Design and Analysis of Three-dimensional M-sequence Bipolar OCDMA Spectral Amplitude Code

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Research Article

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Abstract:

This paper has been focused to utilize the m-sequence code in spectral/time/spatial OCDMA domain in a bipolar mode (Three Dimensional modes). The scheme has elegantly incorporated the design of an encoder and a decoder such that the system efficiently generates the code in three-dimensional bipolar mode. The decoder design is such that it effectively suppresses the multiple user interference (MUI) of three-dimensional code. System analyses are carried for defining the BER performance variation with users acceptability and received power. The observed results demonstrate that the cardinality of m-sequence three-dimensional bipolar code is larger than the existing 3D Pascal code, 2D-MDW, 3D-PDC, 2D-PDC, 1D-CWH and 1D-MS codes. The received power in proposed system is -5.8dBm is lesser than the 3D Pascal Code at 10^{-18} similarly the users adoption in system more than 210% can be accomplished as compared to 3D Pascal code.

Keywords: Optical code division multiple access(OCDMA),m-sequence code, Multiple access interference(MAI), Phase induced intensity noise(PIIN),Complementary wash hadamard code (CWH), Perfect difference code (PD).two dimensional code (2D) Code, three dimensional(3D) Code.

Introduction:

In the last few decades, the Optical code division multiple access technique has become a prominent technology in the simultaneous transmission of data by multiple users within the same bandwidth with high confidentiality of codes [1-3]. The OCDMA system uses the codes to transmit the data of several users. Coding approach may utilize the time spreading, frequency hopping, spectral amplitude and spatial coding schemes [4]. A single code is assigned to a user for information processing. The aforementioned coding schemes are assigned to users either in uni polar or bipolar mode, in the system to enhance the security. In unipolar code, the code is assigned to the information '1' bit, and there is no code for null information ('0' bit). On the other side, the bipolar scheme applies the two separate codes for the data '0' and '1' bit [5]. This work aims to focus on the development of bipolar code so that it could enlarge the confidentiality of code against the eavesdroppers.

The multiple access interference (MAI) that arises due to the simultaneous transmission of multiple users in the channel degrades the OCDMA code performance. This MAI can be eliminated through the construction of codes with uniform in phase cross-correlation by the efficient decoding scheme at the receiver end [6-7].

The Multiservice code (MS) and Modified Double Weight codes (MDW) are based on the constant in phase cross-correlation in one-dimensional uni-polar mode (1D) [8-9]. The m-sequence and 1D-CWH code in the bipolar scheme also follows the in-phase cross-correlation. As seen, the performances of these one-dimensional coding schemes degrade in handling, a large number of users. Moreover, the designing of codes under such condition becomes sophisticated and not useful to tackle the problem of higher multiple access interference in the channel.

To alleviate the problem that emerges in 1-D schemes, 2-D codes such as 2D MM, 2D-DPD and 2D –MDW codes have been proposed in the literature [10-12]. The three dimensional-PD and PSCAL code also reported with uni polar mode [13-14]. These codes exist with a uni polar coding pattern. To develop a more secured system, a scheme should be adopted that can support a large number of users with the bipolar property. In this regard, this work is focused to develop the code for three-Dimensional mode in bipolar domain. Moreover, a decoding scheme is also projected to assuage the multiple inferences in the channel.

The paper explores the work into five sections. Section 1 explains the proposed work. The mathematical section covers section 2. Section 3 analyses the result and discussion part and the paper concluded with the conclusion.

Proposed approach

m-sequence three-dimensional bipolar code is an enhancement of the one dimensional m-sequence bipolar code [5]. The code construction is done by extending the one dimensional Bipolar m-sequence code in spectral, time spreading and spatial domain. The code is expressed by the $(M \times N \times P, K_1, K_2, K_3, \lambda_a, \lambda_c)$. Where M is the number of wavelengths, N is the temporal length and P is the spatial length. K_1 , K_2 and K_3 are their corresponding weight numbers and λ_a, λ_b is the auto and cross-correlations.

K_1 , K_2 and K_3 are as

$$K_1 = \frac{(m+1)}{2} = \frac{M}{2}, K_2 = \frac{(n+1)}{2} = \frac{N}{2}, K_3 = \frac{(p+1)}{2} = \frac{P}{2}$$

$$M=m+1, N=n+1, P=p+1$$

m-sequence three-dimensional bipolar code can be constructed using the three code sequence (m, n and p) of one-dimensional Bipolar code [6]. $X = [x_0 x_1 \dots x_{M-1}]$, $\bar{X} = [\bar{x}_0 \bar{x}_1 \dots \bar{x}_{M-1}]$, $Y = [y_0 y_1 \dots y_{N-1}]$, $\bar{Y} = [\bar{y}_0 \bar{y}_1 \dots \bar{y}_{N-1}]$ and $Z = [z_0 z_1 \dots z_{P-1}]$, $\bar{Z} = [\bar{z}_0 \bar{z}_1 \dots \bar{z}_{P-1}]$ represents the three (m, n and p-sequence) bipolar codes. Table 1 shows the code construction. M, N and P are the length of codes in one-dimensional bipolar m, n and p-sequence code.

For expression of cross-correlation of this three-dimensional bipolar code the characteristics matrix $A^{(d)}$ for $d \in (0, 1, \dots, 7)$ are given by $A^{(0)} = X^T Y Z$, $A^{(1)} = X^T \bar{Y} Z$, $A^{(2)} = \bar{X}^T Y Z$, $A^{(3)} = \bar{X}^T \bar{Y} Z$, $A^{(4)} = X^T Y \bar{Z}$, $A^{(5)} = X^T \bar{Y} \bar{Z}$, $A^{(6)} = \bar{X}^T Y \bar{Z}$, $A^{(7)} = \bar{X}^T \bar{Y} \bar{Z}$.

Where $\bar{X}$, $\bar{Y}$ and $\bar{Z}$ denotes the complementary code sequence of X, Y and Z

The cross-correlation between the $A^{(d)}$ and $A_{g,h,l}$ is defined as

$$R^{(d)} = \sum_{k=0}^{P-1} \sum_{j=0}^{N-1} \sum_{i=0}^{M-1} a_{i,j,k}^{(d)} b_{i,j,k}(g, h, l) \quad (1)$$

In a similar manner cross-correlation between the $A^{(d)}$ and $\bar{A}_{g,h,l}$ is defined as

$$\bar{R}^{(d)} = \sum_{k=0}^{P-1} \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} a_{i,j,k}^{(d)} \bar{b}_{i,j,k}(g, h, l) \quad (2)$$

Where $a_{i,j,k}^{(d)}$ is the (i,j,k)th entry of $A^{(d)}$, $b_{i,j,k}(g, h, l)$ is the (i,j,k)th entry of $A_{g,h,l}$ and $\bar{b}_{i,j,k}(g, h, l)$ is the (i,j,k)th entry of $\bar{A}_{g,h,l}$ with $g = 0, 1, 2, \dots, M-1$, $h = 0, 1, 2, \dots, N-1$ and $l = 0, 1, 2, \dots, P-1$. The $A_{g,h,l}$ is code corresponds to '1' bit and $\bar{A}_{g,h,l}$ denotes the code corresponds to '0' information bits for user (g,h,l).

The cross-correlation of $A^{(d)}$ and $A_{g,h,l}$ and $A^{(d)}$ and $\bar{A}_{g,h,l}$ shown in table.2 and table.3

For analysing the MUI cancellation property in '1' information bit, table.2 divides into two parts. From the upper portion of the table.2, Where $R^{(3)}(g, h, l)$ has non zero value only when $g \neq 0 \cap h \neq 0$. $R^{(3)}(g, h, l)$ is used to eliminate the influence caused by $A_{(g,h,l)}$ from $R^{(0)}(g, h, l)$, $R^{(1)}(g, h, l)$ and $R^{(2)}(g, h, l)$ with $g \neq 0 \cap h \neq 0$. The new cross correlation is defined by

$$R^0(g, h) - R^1(g, h) - R^2(g, h) + R^3(g, h) = \begin{cases} K_1 K_2 K_3 & \text{for } g = 0 \quad h = 0 \quad l = 0 \\ \frac{K_1 K_2 K_3}{2} & \text{for } g = 0 \quad h = 0 \quad l \neq 0 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

Similarly from the lower portion of the table.2, the new cross correlation is given by

$$R^4(g, h) - R^5(g, h) - R^6(g, h) + R^7(g, h) = \begin{cases} 0 & \text{for } g = 0 \quad h = 0 \quad l = 0 \\ \frac{K_1 K_2 K_3}{2} & \text{for } g = 0 \quad h = 0 \quad l \neq 0 \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

The final MUI cancellation is performed with the eq -3 and eq-4 then the new cross-correlation equation is

$$[R^0(g,h) - R^1(g,h) - R^2(g,h) + R^3(g,h)] - [R^4(g,h) - R^5(g,h) - R^6(g,h) + R^7(g,h)] = \begin{cases} K_1 K_2 K_3 & \text{for } g=0 \quad h=0 \quad l=0 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

In a similar way, from the above-mentioned cross-correlation cancellation method, table3 can be used to eliminate the MAI caused by '0' information bits. In table.2, $\bar{R}^{(3)}(g,h,l)$ is used to eliminate the influence caused by $\bar{A}_{(g,h,l)}$ from $\bar{R}^{(0)}(g,h,l)$, $\bar{R}^{(1)}(g,h,l)$ and $\bar{R}^{(2)}(g,h,l)$ with $g \neq 0 \cap h \neq 0$. The new cross-correlation is defined by

$$\bar{R}^0(g,h) - \bar{R}^1(g,h) - \bar{R}^2(g,h) + \bar{R}^3(g,h) = \begin{cases} 0 & \text{for } g=0 \quad h=0 \quad l=0 \\ \frac{K_1 K_2 K_3}{2} & \text{for } g=0 \quad h=0 \quad l \neq 0 \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

Similar manner the lower portion of the table.3 defines the new cross-correlation is given as

$$\bar{R}^4(g,h) - \bar{R}^5(g,h) - \bar{R}^6(g,h) + \bar{R}^7(g,h) = \begin{cases} K_1 K_2 K_3 & \text{for } g=0 \quad h=0 \quad l=0 \\ \frac{K_1 K_2 K_3}{2} & \text{for } g=0 \quad h=0 \quad l \neq 0 \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

Then from the eq-6 and eq-7 the new cross-correlation is given as

$$[\bar{R}^0(g,h) - \bar{R}^1(g,h) - \bar{R}^2(g,h) + \bar{R}^3(g,h)] - [\bar{R}^4(g,h) - \bar{R}^5(g,h) - \bar{R}^6(g,h) + \bar{R}^7(g,h)] = \begin{cases} -K_1 K_2 K_3 & \text{for } g=0 \quad h=0 \quad l=0 \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

System design explanation

The three Dimensional m-sequence bipolar system is shown in figure.1 where M, N, P are transmitter and receiver pair. Users supported by this system are 'MNP'.

The encoder design of three dimensional code is shown in figure.2. It consists of the broadband light source, Optical switch for bipolar modulation, Fibre bragg gratings, N optical delay line and optical splitter, P optical switch. It uses the fiber bragg grating FBGt1 and FBGt2 with equal gratings number to reflect back the similar spectral components for run trip delays compensation.

Initially, optical source spectrum reaches to one encoder by the incoming information bit 0 or 1. If the incoming information bit is 1 then the upper encoder is selected otherwise lower encode for 0 bit is assigned. In the selected encoder, the optical pulse spectrally encoded by the two sets of FBGs which generates the code sequence X_g ($\bar{X}_g$, in case of 0 bit). After the spectral encoding, optical delay lines provide a time spreading sequence Y_h ($\bar{Y}_h$, in the case

of 0 bit). Then finally for spatial encoding purpose optical spectrum process to the splitters and switches which corresponds to the Z_l ($\bar{Z}_l$, in case of 0 bit).

Figure. 3 shows the structure of the receiver. The receiver consists the two optical combiners, four correlators, four balanced detectors with each having two FBGs and photodiode, and an integrator.

The optical combiner combines the incoming signal and first de correlate the spatial code sequence Z_l and complementary code sequence $\bar{Z}_l$. The output of the optical combiner process to the correlators which is made of optical delay line corresponds to the code sequence Y_h and $\bar{Y}_h$. Correlators 1 and correlator 3 decode the code sequence Y_h and correlator 2 and correlator 4 decode the code sequences $\bar{Y}_h$. All correlators acquire the K_2 optical delay lines. Finally, for decoding of spectral component, each balanced detector consists the two set of FBGs and two p-i-n diodes. FBGr1 to FBGs8 follows the same number of grating and it can be utilized to reflect back similar spectral components which correspond to the X_s . Again to compensate the different round trip delays of the matched spectral components, the position of gating in FBGs 0,1,2 and 4 are similar but contrary to that in FBGs 3,5, 6 and 7.

The operation of the receiver is described. At the receiver side, the upper combiner receives the signal corresponds to the spatial code $\bar{Z}_l$. The lower optical combiner is located for receiving $\bar{Z}_l$ for providing the cancellation information.

The optical signal from two combiners split in two. The upper combiner carries the signal to the 1 and 2 correlators and lower combiner carries the signal to the 3 and 4 correlator.

If Y_h is [11101000] the length of delay line 1,2,3 and 4 are designed to delay the optical signal first, second third and five times of the chip duration. In similarly the delay lines 5-8 are designed to provide the delay in the optical signal for four, six, seven and eight times of the chip duration represent the '0' alignment. Each balanced detector consists the two sets of FBGs. The function of the balanced detector explains as. The output signal from correlator 1 split in two-part and the signal delivered to the FBGr1 of the upper balanced detector and this signal reflects back to code corresponds to the 1s code sequence. The matched signal is also passed to FBGr2 for delay compensation and reaches to PD0. The unmatched section is processed to the PD2 via delay lines. The delay line is applied to compensate the delay due to FBGr1 and FBGr2.

The signal portion matched to the time spreading, spatial and spectral code sequence of the receiver can reach PD0, the output current is proportional to the $R^{(0)}(g,h,l)$ for '1' information bit and $\bar{R}^{(0)}(g,h,l)$ for '0' information bit. Similarly, The output current from PD1 to the PD7 is proportional to $R^{(1)}(g,h,l)$, $R^{(2)}(g,h,l)$, $R^{(3)}(g,h,l)$, $R^{(4)}(g,h,l)$, $R^{(5)}(g,h,l)$, $R^{(6)}(g,h,l)$, $R^{(7)}(g,h,l)$ for '1' information bit and $\bar{R}^{(1)}(g,h,l)$, $\bar{R}^{(2)}(g,h,l)$, $\bar{R}^{(3)}(g,h,l)$, $\bar{R}^{(4)}(g,h,l)$, $\bar{R}^{(5)}(g,h,l)$, $\bar{R}^{(6)}(g,h,l)$, $\bar{R}^{(7)}(g,h,l)$ for '0' information bit. So output current generated from four balanced detectors for '1' information and '0' information bit are proportional to $R^{(0)}(g,h,l) - R^{(2)}(g,h,l)$, $R^{(1)}(g,h,l) - R^{(3)}(g,h,l)$, $R^{(4)}(g,h,l) - R^{(6)}(g,h,l)$, $R^{(5)}(g,h,l) - R^{(7)}(g,h,l)$ and $\bar{R}^{(0)}(g,h,l) - \bar{R}^{(2)}(g,h,l)$, $\bar{R}^{(1)}(g,h,l) - \bar{R}^{(3)}(g,h,l)$, $\bar{R}^{(4)}(g,h,l) - \bar{R}^{(6)}(g,h,l)$, $\bar{R}^{(5)}(g,h,l) - \bar{R}^{(7)}(g,h,l)$. Finally the generated output currents after eliminating the MUI is proportional to the $[R^0(g,h) - R^1(g,h) - R^2(g,h) + R^3(g,h)] - [R^4(g,h) - R^5(g,h) - R^6(g,h) + R^7(g,h)]$ and $[\bar{R}^0(g,h) - \bar{R}^1(g,h) - \bar{R}^2(g,h) + \bar{R}^3(g,h)] - [\bar{R}^4(g,h) - \bar{R}^5(g,h) - \bar{R}^6(g,h) + \bar{R}^7(g,h)]$ corresponds to the '1' and '0' information bit.

Mathematical Analysis

The gaussian approximation is considered for analysis and [3, 4].PIIN noise, thermal noise and shot noise are acquired for calculation. The SNR for an electrical signal is the average signal power to noise power, $SNR = [I/R]$. The following assumptions are made

- (a) Each light source spectrum is flat over the bandwidth $[V_o - \Delta V/2, V_o + \Delta V/2]$ where V_o is the central frequency and ΔV is the optical source bandwidth in Hertz.
- (b) Each power spectral component has an identical spectral width.
- (c) Each user has nearly equal power at the transmitter
- (d) Each user bitstream is synchronized

The power spectral density (PSD) of the received signals can be given

$$r(f) = \frac{P_{sr}}{K_2 K_3 \Delta f} \sum_{w=1}^W d(w) \sum_{k=0}^{P-1} \sum_{j=0}^{N-1} \sum_{i=0}^{M-1} a_{i,j,k}(W) \times F(f,i) \quad (9)$$

For convenience analysis, we define the $F(f,i)$ as

$$F(f,i) = \left\{ u \left[f - f_0 - \frac{\Delta f(-M+2i)}{2M} \right] - u \left[f - f_0 - \frac{\Delta f(-M+2i-2)}{2M} \right] \right\} \quad (10)$$

In case of information '1' bit

The output current of photodiode PD0 to PD7 which suffer due to cross-correlation between the $A^{(d)}$ and $A_{g,h,l}$, is defined as

$$I_0(f) = \Re \int_0^\infty G_0(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^W d(w) R^0(i, j, l) F(f, i)$$

From eq -10 and table-2

$$\Delta = \frac{K_1 K_2 K_3 (W-1)}{(MNP-1)}$$

$$= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{K_1 K_2 K_3 + \frac{\Delta(N-1)}{2} + \frac{\Delta(M-1)}{2} + \frac{\Delta(M-1)(N-1)}{4} + \frac{\Delta(P-1)}{2} + \frac{\Delta(N-1)(P-1)}{4} + \frac{\Delta(M-1)(P-1)}{4}}{\frac{\Delta(M-1)(N-1)(P-1)}{8}} \right\}$$

$$I_1(f) = \Re \int_0^\infty G_1(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^W d(w) R^1(i, j, l) F(f, i)$$

$$= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(N-1)}{2} + \frac{\Delta(M-1)(N-1)}{4} + \frac{\Delta(N-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\}$$

$$I_2(f) = \Re \int_0^\infty G_2(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^W d(w) R^2(i, j, l) F(f, i)$$

$$= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)}{2} + \frac{\Delta(M-1)(N-1)}{4} + \frac{\Delta(M-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\}$$

$$I_3(f) = \Re \int_0^\infty G_3(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^W d(w) R^3(i, j, l) F(f, i)$$

$$= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)(N-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\}$$

$$I_4(f) = \Re \int_0^\infty G_4(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^W d(w) R^4(i, j, l) F(f, i)$$

$$= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(P-1)}{2} + \frac{\Delta(M-1)(N-1)(P-1)}{4} + \frac{\Delta(M-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\}$$

$$I_5(f) = \Re \int_0^\infty G_5(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^W d(w) R^5(i, j, l) F(f, i)$$

$$= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)(N-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\}$$

$$I_6(f) = \Re \int_0^\infty G_6(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^W d(w) R^6(i, j, l) F(f, i)$$

$$= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)(M-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\}$$

$$I_7(f) = \Re \int_0^\infty G_7(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^W d(w) R^7(i, j, l) F(f, i)$$

$$= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\}$$

The average photocurrent output at the receiver due to '1' information bit

$$I_r = \int_0^\infty \{ [G_0(f) - G_2(f)] - [G_1(f) - G_3(f)] \} - \{ [G_4(f) - G_6(f)] - [G_5(f) - G_7(f)] \}$$

$$I_r = [I_0(f) - I_2(f)] - [I_1(f) - I_3(f)] - [I_4(f) - I_6(f)] - [I_5(f) - I_7(f)]$$

In case of information '0' bit

The output current of photodiode PD0 to PD7 which suffer due to cross-correlation between the $A^{(d)}$ and $\overline{A_{g,h,l}}$, is defined as, from eq-9 and 10 and table.3.

$$\begin{aligned}
I'_0(f) &= \Re \int_0^\infty G'_0(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^w d(w) \overline{R}^0(i, j, l) F(f, i) \\
&= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\} \\
I'_1(f) &= \Re \int_0^\infty G'_1(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^w d(w) \overline{R}^1(i, j, l) F(f, i) \\
&= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)(M-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\} \\
I'_2(f) &= \Re \int_0^\infty G'_2(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^w d(w) \overline{R}^2(i, j, l) F(f, i) \\
&= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)(M-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\} \\
I'_3(f) &= \Re \int_0^\infty G'_3(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^w d(w) \overline{R}^3(i, j, l) F(f, i) \\
&= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)(N-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\} \\
I'_4(f) &= \Re \int_0^\infty G'_4(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^w d(w) \overline{R}^4(i, j, l) F(f, i) \\
&= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(P-1)}{2} + \frac{\Delta(M-1)(N-1)(P-1)}{4} + \frac{\Delta(M-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\} \\
I'_5(f) &= \Re \int_0^\infty G'_5(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^w d(w) \overline{R}^5(i, j, l) F(f, i) \\
&= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)(N-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\} \\
I'_6(f) &= \Re \int_0^\infty G'_6(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^w d(w) \overline{R}^6(i, j, l) F(f, i) \\
&= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{\Delta(M-1)}{2} + \frac{\Delta(M-1)(N-1)}{4} + \frac{\Delta(M-1)(P-1)}{4} + \frac{\Delta(M-1)(N-1)(P-1)}{8} \right\} \\
I'_7(f) &= \Re \int_0^\infty G'_7(f) df = \int_0^\infty \frac{\Re P_{sr}}{K_2 K_3 \Delta f} \times \sum_{w=1}^w d(w) \overline{R}^7(i, j, l) F(f, i) \\
&= \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ K_1 K_2 K_3 + \frac{\Delta(N-1)}{2} + \frac{\Delta(M-1)}{2} + \frac{\Delta(M-1)(N-1)}{4} + \frac{\Delta(P-1)}{2} + \frac{\Delta(N-1)(P-1)}{4} + \frac{\Delta(M-1)(P-1)}{4} \right\}
\end{aligned}$$

The average photocurrent output at the receiver due to '0' information bit

$$I'_r = \int_0^\infty \{[G'_0(f) - G'_2(f)] - [G'_1(f) - G'_3(f)]\} - \{[G'_4(f) - G'_6(f)] - [G'_5(f) - G'_7(f)]\} \\ I'_r = [I'_0(f) - I'_2(f)] - [I'_1(f) - I'_3(f)] - [I'_4(f) - I'_6(f)] - [I'_5(f) - I'_7(f)]$$

The resulted current at the receiver end is given as

$$I_{Bipolar} = I_r - I'_r \\ I_{Bipolar} = \frac{2\Re P_{sr} K_1}{M} \quad (11)$$

Noise can be given as

$$\langle i_{noise}^2 \rangle = \langle i_{PIIN}^2 \rangle + \langle i_{shot}^2 \rangle + \langle i_{thermal}^2 \rangle \\ I^2 = I_r^2 B_r \tau_c + 2e B_r I_r + \frac{4K_b T_n B_r}{R_L} \quad (12)$$

$$\tau_c = \frac{\int_0^\infty [S^2(f)] df}{\left[\int_0^\infty S(f) df \right]^2}$$

Where S(f) is the single-sideband power spectral density (PSD) of the light incident to the photodiode. Then PIIN noise is given as

$$\langle I_{PIIN}^2 \rangle = B_r \Re^2 \int_0^\infty \left[\begin{aligned} &G_0^2(f) + G_1^2(f) + G_2^2(f) + G_3^2(f) + G_4^2(f) + G_5^2(f) + G_6^2(f) + G_7^2(f) - 2G_0(f)G_1(f) - 2G_0(f)G_4(f) \\ &+ 2G_0(f)G_5(f) + 2G_1(f)G_4(f) - 2G_1(f)G_5(f) - 2G_4(f)G_5(f) - 2G_2(f)G_3(f) - 2G_2(f)G_6(f) \\ &+ 2G_2(f)G_7(f) + 2G_3(f)G_6(f) - 2G_3(f)G_7(f) - 2G_6(f)G_7(f) \end{aligned} \right] df \quad (13)$$

$$\int_0^\infty G_0^2(f) df = \frac{P_{sr}^2}{K_2^2 K_3^2 \Delta f^2} \int_0^\infty \left[\sum_{w=1}^w R^0(i, j, l) F(f, i) \right]^2 df = \frac{MI_0^2}{K_1 \Delta f \Re^2}$$

Similarly other factors are given as

$$\int_0^\infty G_1^2(f) df = \frac{MI_1^2}{K_1 \Delta f \Re^2}, \quad \int_0^\infty G_2^2(f) df = \frac{MI_2^2}{K_1 \Delta f \Re^2}, \quad \int_0^\infty G_3^2(f) df = \frac{MI_3^2}{K_1 \Delta f \Re^2}, \quad \int_0^\infty G_4^2(f) df = \frac{MI_4^2}{K_1 \Delta f \Re^2}$$

$$\int_0^\infty G_5^2(f) df = \frac{MI_5^2}{K_1 \Delta f \Re^2}, \quad \int_0^\infty G_6^2(f) df = \frac{MI_6^2}{K_1 \Delta f \Re^2}, \quad \int_0^\infty G_7^2(f) df = \frac{MI_7^2}{K_1 \Delta f \Re^2}$$

$$\int_0^\infty G_0(f)G_1(f) df = \frac{P_{sr}^2}{K_2^2 K_3^2 \Delta f^2} \int_0^\infty \left[\sum_{w=1}^w R^0(i, j, l) F(f, i) \right] \times \left[\sum_{w=1}^w R^1(i, j, l) F(f, i) \right] df = \frac{MI_0 I_1}{K_1 \Delta f \Re^2}$$

As same as other factors are given as

$$\begin{aligned}
\int_0^\infty G_0(f)G_4(f)df &= \frac{MI_0I_4}{K_1\Delta f\Re^2}, \int_0^\infty G_0(f)G_5(f)df = \frac{MI_0I_5}{K_1\Delta f\Re^2}, \int_0^\infty G_1(f)G_4(f)df = \frac{MI_1I_4}{K_1\Delta f\Re^2} \\
\int_0^\infty G_1(f)G_5(f)df &= \frac{MI_1I_5}{K_1\Delta f\Re^2}, \int_0^\infty G_4(f)G_5(f)df = \frac{MI_4I_5}{K_1\Delta f\Re^2}, \int_0^\infty G_2(f)G_3(f)df = \frac{MI_2I_3}{K_1\Delta f\Re^2} \\
\int_0^\infty G_2(f)G_6(f)df &= \frac{MI_2I_6}{K_1\Delta f\Re^2}, \int_0^\infty G_2(f)G_7(f)df = \frac{MI_2I_7}{K_1\Delta f\Re^2}, \int_0^\infty G_3(f)G_6(f)df = \frac{MI_3I_6}{K_1\Delta f\Re^2} \\
\int_0^\infty G_3(f)G_7(f)df &= \frac{MI_3I_7}{K_1\Delta f\Re^2}, \int_0^\infty G_6(f)G_7(f)df = \frac{MI_6I_7}{K_1\Delta f\Re^2}
\end{aligned}$$

Then from eq-13 and above factors the PIIN noise become

$$\begin{aligned}
\langle i_{PIIN}^2 \rangle &= B_r I_r^2 = B_r \Re^2 \frac{M}{K_1 \Delta f \Re^2} \left\{ I_1^2 + I_2^2 + I_3^2 + I_4^2 + I_5^2 + I_6^2 + I_7^2 - 2I_0I_1 - 2I_0I_4 + 2I_0I_5 + 2I_1I_4 - 2I_1I_5 \right. \\
&\quad \left. - 2I_4I_5 - 2I_2I_3 - 2I_2I_6 + 2I_2I_7 + 2I_3I_6 - 2I_3I_7 - 2I_6I_7 \right\} \\
\langle i_{PIIN}^2 \rangle &= \frac{MB_r}{K_1 \Delta f} \left\{ (I_0 - I_1 - I_4 + I_5)^2 + (I_2 - I_3 - I_6 + I_7)^2 \right\} \quad (14)
\end{aligned}$$

$$\langle i_{shot}^2 \rangle = 2eB_r I_{Total}$$

$$\langle i_{shot}^2 \rangle = 2eB_r (I_0 + I_1 + I_2 + I_3 + I_4 + I_5 + I_7) \quad (15)$$

After placing all current components in eq-14.

$$\begin{aligned}
\langle i_{shot}^2 \rangle &= 2eB_r \frac{\Re P_{sr}}{K_2 K_3 M} \left\{ \frac{K_1 K_2 K_3 + \frac{2\Delta(N-1)}{4} + \frac{2\Delta(M-1)}{8} + \frac{2\Delta(P-1)}{8} + \frac{4\Delta(M-1)(N-1)}{4} + \frac{4\Delta(N-1)(P-1)}{4} \right\} \\
\langle i_{thermal}^2 \rangle &= \frac{4K_b T_n B_r}{R_L}
\end{aligned}$$

Then SNR is given as, from eq-11,12,13 and 14

$$SNR = \frac{\left(\frac{2\Re P_{sr} K_1}{M} \right)^2}{\frac{MB_r}{K_1 \Delta f} \left\{ (I_0 - I_1 - I_4 + I_5)^2 + (I_2 - I_3 - I_6 + I_7)^2 \right\} + 2eB_r (I_0 + I_1 + I_2 + I_3 + I_4 + I_5 + I_7) + \frac{4K_b T_n B_r}{R_L}}$$

The following parameter is considered during the analysis

Photodetector quantum efficiency (η) 0.75

Line-width broadband source (ΔV) 3.75 THz

Operating wavelength (k_0) 1552 nm

Data bit rate (R_b) 1Gbps

Receiver noise temperature (T_n) 300 K

Result and analysis

System capabilities are analyzed by observing the Bit error rate and SNR with the capacity of users and sustainable received power.

BER variation with users

Figure 4 shows the three-dimensional m-sequence bipolar code performance by bit error rate variation with the number of simultaneous users for $M=8, N=16, P=4$ ($m=7, n=15, p=3$). The observed result in proposed System is much better and it can be verified by the outputs where the increment in BER for three-dimensional m-sequence bipolar code is less as compared to the reporting methods. The users which can be accepted in the system at 10^{-12} BER are 310. so the system is capable to handle much more users than the 3D PASCAL ($M=8, N=16, P=4$), 3D-PD ($M=7, N=21, P=3$), 2D-m matrix ($M=127, N=3$) code where number of users are 117, 80 and 63 as shown in Fig.4. For 120 users in system the measured BER is 10^{-37} and BER in other reported system 3D pascal ($M=8, N=16, P=4$), 3D-PD ($M=7, N=21, P=3$) and 2D-m matrix ($M=127, N=3$) Code are 10^{-14} , 10^{-10} and 10^{-04} .

Figure 5 discussed the BER performance criteria with sets of received power for constant users. For 10^{-12} BER proposed system stands with -5.2 dBm less power than the 3D PASCAL code and -7.3 dBm less compare to 3D PD Code. If system is used at the -15 dBm received power then the system shows the 10^{-21} BER and PASCAL code and 3D PD perform the 10^{-09} and 10^{-04} BER.

Current age technology demands high data rate transmission so that system should support the high data rate transmission. As figure.6 shows that the system can acquire the 120 users at 2.5 Gbit/s data rate for 10^{-25} BER and similar users and the same (2.5 Gbits/s) data rate the BER achieved in 3D PASCAL code is 10^{-07} and in 3D PD code is 10^{-02} . For getting 10^{-24} BER in the proposed system possible data rate is 2.5 Gbits/s and in PASCAL code for similar BER, data rate is 0.5 Gbits/s.

The analysis of spectral band-width is also a parameter in optical system. Analysis of spectral width variation with BER is shown in Figure 7. For 4 THz Spectral Width, the BER 10^{-59} in 3D-m sequence bipolar code ($M=8, N=16, P=4$) is obtained and, in 3D PASCAL ($M=8, N=16, P=4$), 3D-PD ($M=7, N=21, P=3$) and 2D-m matrix ($M=127, N=3$) code are 10^{-14} , 10^{-04} and 10^{-03} . It has noticed that spectral width parameter shows the much improvement compare to published results.

Conclusion

The suggested approach elaborated the three-dimensional m-sequence in a bipolar mode is much better against the eavesdropping situation due to the property of bipolar coding system. Extension of one-dimensional m-sequence bipolar code into spectral, time spreading and spatial domain was carried for the proposed three-dimensional method. Results are obtained for various numbers of users, received power, data rates and spectral width. The proposed work shows the larger cardinality and lower effective transmitted power than the existing three dimensional and two dimensional techniques. Moreover, it is seen that the low effective received power (-17.4dBm) is achieved to acquire the BER of 10^{-12} through the proposed system. Analysis of results shows that the system is capable of handling more than 240 users at 10^{-18} BER at the data rate of 1.0 Gbits/s and -10dBm received power, which is much better than the other reported methods.

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Figures

Figure 1

Basic structure of transmitter and receiver.

Figure 2

Architecture of encoder design of 3D m-sequence Bipolar code

Figure 3

Architecture of decoder design of 3D m-sequence Bipolar code .

Figure 4

Variation in BER with number of users.

Figure 5

Variation in BER with received power.

Figure 6

Variation in BER with data rates

Figure 7

Variation in BER with spectral width.

Supplementary Files

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