An Efficient Spectral Amplitude Coding (SAC) Technique for Optical CDMA System using Wavelength Division Multiplexing (WDM) Concepts

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***Abstract*—This article introduces an improved method for Optical Code Division Multiple Access system (OCDMA). In this scheme, a hybrid technique is used in which Wavelength Division Multiplexing (WDM) is merged with Spectral Amplitude Coding (SAC) to efficiently diminish Multiple Access Interference (MAI) and alleviate the impact of Phase Induced Intensity Noise (PIIN) appearing in photo-detecting process. The proposed technique SAC-OCDMA/WDM MP (SW-MP) is implemented by using Matrix Partitioning (MP) code family, which is constructed via merging mathematics sequence and algebraic approaches. The key notion is to create the code patterns in SAC domain, then diagonally replicate it in the wavelength domain as blocks which preserves the same code patterns of a given code weight. The SW-MP code family preserves convenient code length property which gives flexibility in transmitter-receiver design. It is reported that the proposed scheme has potential to remove MAI proficiently and improve the system performance significantly.**

Keywords—Optical Code Division Multiple Access System (OCDMA); Multiple Access Interference (MAI); Spectral Amplitude Coding (SAC); Wavelength Division Multiplexing (WDM); SAC-OCDMA/WDM MP (SW-MP) code; Cross Correlation (CC)

I. Introduction

Lately WDM system is measured as a promising technique to expand the optical network capacity without changing the backbone fiber optics. Researchers in both academia and industry sectors have proposed various designs that integrate WDM into access networks by [1]-[2]. OCDMA technique has been deemed as a promising technique for light communication networks [3]. Out of the entire OCDMA techniques, SAC system has gained a lot of consideration due to its ability to eliminate MAI completely via balance detection technique [4]-[6]. On the other hand, PIIN considers as an intrinsic noise that impairs the system performance and it occurs when various light fields are occurrence on a receiver, because of the square-law detection. Several systems have been proposed to be integrated with OCDMA scheme for the sake of MAI elimination and provide full cardinality in optic network [7]. In this regard temporal/spatial OCDMA network is presented in [7] to improve cross correlation and autocorrelation properties. In [8]-[10], optical pulses are used to mark one chip in time-wavelength domain to improve the MAI cancellation property. Some schemes have been proposed utilizing differential detection to diminish the MAI [11]-[13]. Nevertheless, these schemes are suffering from different problems somehow or other to eliminate an MAI impact on the end system. Eventually tough interference took place which reduces the involvement of high number of users. In SAC system, fiber Bragg grating (FBG) could be utilized as the major part of both transmitter and receiver structures of each use at large number of users, FBG sizes will become unworkable. To overcome size problem, a two dimensional coding techniques might be used but at the cost of extra passive optical components [14]. In this paper, an SW-MP technique is built by merging WDM and SAC system which keeps MAI cancellation characteristic and PIIN mitigation in OCDMA network. The SW-MP code words are described by the code length L, the number of users N, the code weights W, and the cross correlation λ_c. The SW-MP scheme is built with $\lambda_c \leq 1$ aiming to remove MAI impact. Despite an MAI effect can be removed via balanced detection scheme, PIIN attributed to spontaneous emission from optical source plays a significant role in system degradation too and should be addressed as well [15]. An effective way to reduce the PIIN is by reducing the interference at the optical layer itself, which means the value of λc should be kept to the minimum. The remaining parts of this paper are arranged as follows. Section 2 shows the mathematical steps of MP code construction. The mathematical models of MP code and SW-MP code systems are described in Section 3. The system design and description of SW-MP are demonstrated in Section 4. In Section 5, codes comparison and evaluation is discussed. The performance analysis of the SW-MP in the OCDMA network is explained in Section 6. Hypothetical analysis and mathematical findings are drawn in Section 7. Lastly, the summary of the paper is given in Section 8.

II. MATHEMATICAL MODEL OF SW-MP CODE

A. Explanations

Let $AS = (W, W-1, W-2, W-3, \ldots\ldots, 1)$ represents an arithmetic sequence. The sum of W elements of the arithmetic sequence (AS) can be calculated by "(1)".

$$S_w = \frac{W}{2}(W+1) \tag{1}$$

The value of S_w is the number of columns of matrix partition (MP). Table 1 shows the mapping procedure of *MS* to *MP*. Every component in *MS* will be linked to matching block in MP. The block length is computed as follows:

$$L_g = W - g + 1 \tag{2}$$

Where, $g = 1, 2, 3, \ldots, N$ is the number of groups.

TABLE. I. MAPPING ELEMENTS IN AS TO BLOCKS IN MP MATRIX

$Block_w$	$Block_1$	$Block_2$	$Block_3$	….	$Block_{(w-1)}$
$\leftarrow W-(W-1)\rightarrow$	$\leftarrow W \rightarrow$	$\leftarrow W-1\rightarrow$	$\leftarrow W-2\rightarrow$	-------	$\leftarrow W-(W-2)\rightarrow$

B. MP Code Family Construction Steps

- Step1: Construct the AS as follows:

$$AS = (W, W-1, W-2, W-3, W-4, \ldots, 1)$$

The elements of AS indicate the number of blocks (h) of MP matrix.

- Step 2: Compute b value as follows in "(3)"

$$B_1 \le b \le B_2 \tag{3}$$

Where,

$$B_1 = 2 + (h-1)\left(W - \frac{h-2}{2}\right) \tag{4}$$

$$B_2 = 1 + h\left(W - \frac{h-1}{2}\right) \tag{5}$$

If the calculation of B_1 surpasses the L value; b takes the value 1 (i.e., if $B_1 > L$ then b, B_1, B_2 will be given the value 1).

- Step 3: Compute L's value using "(6)"

$$L = \frac{W \times N}{2} \tag{6}$$

- Step 4: Compute the position of "1s" c at the first row of each block as follows in "(7)".

$$c = (h, b) \tag{7}$$

- Step 5: Compute the positions of CC "1s" d in every block as follows by "(8)".

$$d = (h + b - B_1 + 1, b) \tag{8}$$

- Step 6:The $\frac{W(N-2)}{W-1}$ #0s# values were filled every row.

C. Code Examples

Apply above steps and as mentioned in [16] the following code patterns were built:

$$MP = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix} \tag{9}$$

III. MATHEMATICAL MODEL OF SW-MP SYSTEM

An SW-MP is a scheme where the entire code created in SAC domain (MP) and replicated diagonally in WDM domain as blocks (SW-MP) [17]. Each block keeps the similar number of users for specified weight of SAC code as displayed in Fig. 1. In this SW-MP system, the code sequences are separated into g blocks, where g = 1, 2, 3, …. Each user is labeled as user #(z,t) and given a code sequence $C_{z,t}$, z = 1,2,3…, g and t =1,2,3…, N. The code length L is computed using "(10)".

$$L = g\frac{W \times N}{2} \tag{10}$$

Equations (11) and (12) associated with c and d respectively and determine the positions of "1s" at every row of each block and the positions of CC "1s" in each block, respectively.

$$c = (h + (g-1)N, b + (g-1)L) \tag{11}$$

$$d = (h + m - B_1 + (g-1)N + 1, b + (g-1)L) \tag{12}$$

(3)

$$\begin{bmatrix} (SW-MP)_1 & 0 & 0 & \cdots & 0 \\ 0 & (SW-MP)_2 & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & 0 \\ 0 & 0 & \cdots & 0 & (SW-MP)_N \end{bmatrix}$$

Fig. 1. Matrix representation of SW-MP code.

To explain the SW-MP structure we dealt with code patterns when *W=2, N=6 and g*=2.

In Sections 2.2 and 3, we applied Steps 1-2 and 5 and "(12-13)" to compute the place of "1s" in the first row of each block and the locations of CC "1s" in every block respectively (as in Table 1). Therefore, the points coordinates attained for c are (1,2), (1,3), (2,1) using "(7)" and (4,5), (4,6) by applying "(12)". While for d are (2,2), (3,3), (3,1) utilizing "(8)" and (5,5), (6,6), (6,4) by applying "(12)".

TABLE. II. SW-MP CODE SEQUENCES FOR W=2, G = 2 AND N = 6

z	T	MP code words $C_{z,t}$					
1	1	0	1	1	0	0	0
1	2	1	1	0	0	0	0
1	3	1	0	1	0	0	0
2	4	0	0	0	0	1	1
2	5	0	0	0	1	1	0
2	6	0	0	0	1	0	1

IV. SYSTEM DESIGN AND DESCRIPTION

For W = 4 the transmitter section is built in Fig. 2 based on the SW-MP code sequence. Representing digital data in the form of presence or absence is called on-off shift keying where it used in this work to modulate the data of the targeting user#1 from Table 2, 011000. The modulated data is then guided to an arranged fiber Brag grating. Each pulse of the desirable user is assigned specific wavelengths (λ_2, λ_3,). The center wavelengths of the FBGs depend on the positions of "1s" in the code sequences.

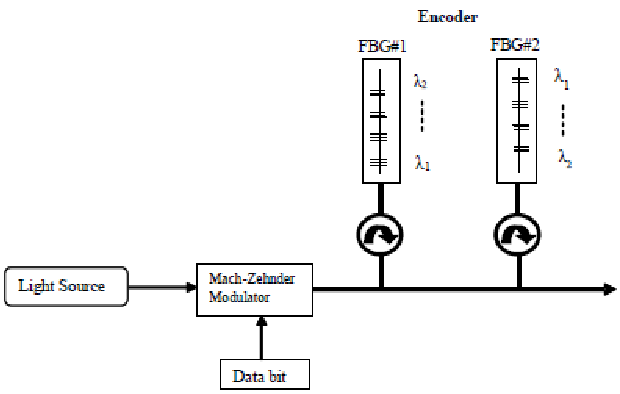

Fig. 2. Implementation of the SW-MP transmitter side.

The basic principle of the work of SW-MP detection procedure in which only pulses of desired users and pulses of overlapping users having the same frequencies in the same group are detected and removed. The configuration of the *SW-MP* receiver for hybrid SAC OCDMA is shown in Fig. 3. In this figure, the optical pulses are passed to an arranged fiber Brag grating. Each pulse of the desirable user is assigned specific wavelengths ($\lambda_{2,}$ $\lambda_{3,}$). The position of the FBGs depends on the pulse value and only the pulse '1' is represented.

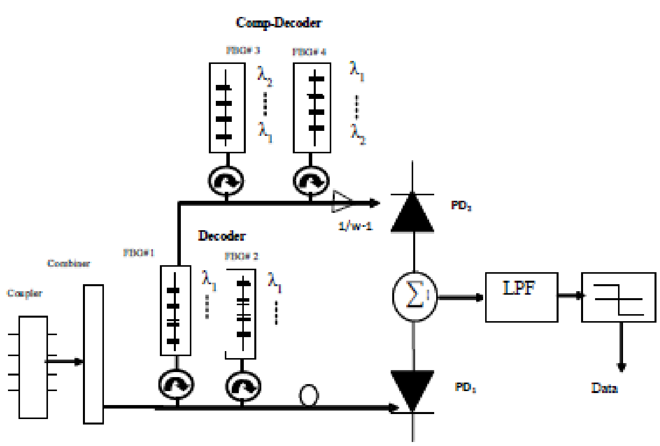

Fig. 3. Implementation of the SW-MP receiver.

In Fig. 3, the incoming pulse is deciphered by the decoder who has similar spectral response to the desired encoder for the data to be processed (Decoder). The intended signal spectrum and overlapping spectra from other interferers are detected as production from the decoder which is W power units for the desired user accompanied by λ power units for interferers.

The complementary decoder (Comp-Decoder) branch detects the complementary spectrum of the intended user (from Table 2, (λ_1,)). Then the received signal is passing over FBG pieces and the output passed to balanced photo-detectors. From the FBGs, different center wavelengths are placed along a piece of fiber and the wavelength elements of spectral codes are spread out in time. So, second fibers with FBGs in reverse positions are needed in each encoder and decoder in order to compensate the time spreading. To separate the unwanted signal from the wanted signal, a subtraction process is took place to deduct the interference signals from the required signal to yield the wanted signal. Code patterns reside in different groups pass via the decoder without being detected (user *#4*, user *#5*, and user *#6* from Table 2). The advantage of the *SAC/WDM* (*SW-MP*) decoder design over conventional SAC techniques is that only code sequences in the same group are passed to balanced photo-detectors. In addition, the receiver complexity is reduced by using less filters.

V. System Performance

To study the system based on Fig. 4 and 5 for SW-MP, let C_x (i) represents the ith element of the xth *SW-MP* code words; based on XOR subtraction scheme the code properties is formed as follows [18]-[19]:

$$\sum_{i=1}^{L} C_x(i)C_y(i) = \begin{cases} W, & x = y \\ 1, & x \neq y \\ 0, & x \neq y \end{cases} \begin{matrix} \text{In the same group (g=1)} \\ \text{Not in the same group } (g \geq 2) \end{matrix} \quad (13)$$

$$\sum_{i=1}^{L} (C_x(i) \oplus C_y(i))C_x(i) = \begin{cases} 0, & x = y \\ W-1, & x \neq y \\ 0, & x \neq y \end{cases} \begin{matrix} \text{In the same group (g=1)} \\ \text{Not in the same group } (g \geq 2) \end{matrix} \quad (14)$$

The stipulation of x and y exist in the same group (i.e., g =1) means that the two code sequences maybe located in SW-MP(1) or SW-MP$_{(2)}$ or SW-MP$_{(m)}$ as shown in Fig. 1. The stipulation of x and y not reside in the same group (i.e., $g \geq 2$) means that one user maybe located in SW-MP$_{(1)}$ and the other user is resided in SW-MP$_{(2)}$ or SW-MP$_{(m)}$. Hence, the XOR process of $(C_x(i) \oplus C_y(i))\, C_x(i)$ is valid for $x \neq$y. Still, the CC of $(C_x(i) \oplus C_y(i))$ is only valid for $x \neq$y in "(14)" while from "(14)", the CC of $(C_x(i).C_y(i))$ is W when $x = y$. Consequently, an MAI impact is removed as the CC $\sum_{i=1}^{L}(C_x(i) \oplus C_y(i))C_x(i)$ can be deducted from $\sum_{i=1}^{L} C_x(i)C_y(i)$ when $x \neq$ y. Therefore, the decoder that calculates "(15)" declines the MAI arriving from intrusive users and gets the desired data.

Hence,

$$\sum_{i=1}^{L} C_x(i)C_y(i) - \frac{\sum_{i=1}^{L}\left(C_x(i) \oplus C_y(i)\right)C_x(i)}{W-1} = \begin{cases} W, & x = y \\ 0, & x \neq y \end{cases} \quad (15)$$

When $x \neq$y the lower branch in "(16)" equals zero which means an XOR subtraction technique is able to remove an MAI impact smoothly. To study the system performance we compute the coherence time of a thermal source (τ_c) as follows [20]:

$$\tau_c = \frac{\int_0^\infty G^2(v)dv}{\left[\int_0^\infty G(v)dv\right]^2} \quad (16)$$

Where, $G(v)$ is the single sideband power spectral density (PSD) of the optic source. The variance of photocurrent caused by the recognition of un-polarized thermal source, which produces by spontaneous emission and given as follows [4]-[5]:

$$\langle i^2\rangle = \langle I_{shot}{}^2\rangle + \langle I_{PIIN}{}^2\rangle + \langle I_{thermal}{}^2\rangle \tag{17}$$

Where, $I_{shot}{}^2$ denotes shot noise, $I_{PIIN}{}^2$ symbolizes intensity noise and $I_{thermal}{}^2$ represents the thermal noise. Hence, "(18)" will be written as follows:

$$\langle \mathrm{i}^2\rangle = 2\mathrm{eIB} + \mathrm{I}^2\mathrm{B}\tau_{\mathrm{c}} + 4\mathrm{K_B T_n B R_L} \tag{18}$$

Where,

- electronic charge symbolizes by e
- average photocurrent symbolizes by I
- equivalent electrical bandwidth of the receiver denotes B;
- Boltzmann's constant denotes by KB
- Absolute receiver noise temperature denotes by Tn
- load resistor of receiver denotes by R_L.

$$r(v) = \frac{P_{sr}}{\Delta v}\sum_{n=1}^{N} d_n \sum_{i=1}^{L} c_n(i)\, rec(i) \tag{19}$$

Where, P_{sr} represents the active power of a broad-band source at the receiver and d_n is the data bit of the nth user that is "1" or "0". The *rec (i)* function in "(19)" is written as follows as in [16]-[17]:

$$rec(i) = u\left[v - v_o - \frac{\Delta v}{2L}(-L+2i-2)\right] - u\left[v - v_o - \frac{\Delta v}{2L}(-L+2i)\right] \tag{20}$$

Where, v_o is the central optical frequency and Δ_v is the optical source bandwidth in H_z. The unit step function $u[v]$ is written as:

$$u[v] = \begin{cases} 1, & v \ge 0 \\ 0, & v < 0 \end{cases} \tag{21}$$

The overall power occurrence at the Photodiode1 and Photodiode 2 as shown in Fig. 3 of the gth receiver during one bit period is formed as follows:

$$\begin{aligned}
\int_0^\infty G_1(v)dv &= \int_0^\infty \frac{P_{sr}}{\Delta V}\sum_{f=1}^{N} d_f \sum_{i=1}^{L} C_f(i) C_g(i) \begin{pmatrix} u\left[v - v_o - \frac{\Delta v}{2L}(-L+2i-2)\right] \\ -u\left[v - v_o - \frac{\Delta v}{2L}(-L+2i)\right] \end{pmatrix} dv \\
&= \frac{P_{sr}}{\Delta V}\frac{\Delta v}{L}\sum_{f=1}^{N} d_f \sum_{i=1}^{L} C_f(i) C_g(i) \\
&= \frac{P_{sr}W}{L} d_g + \frac{P_{sr}}{L}\sum_{f=1, f\neq g}^{N} d_f
\end{aligned} \tag{22}$$

$$\begin{aligned}
\int_0^\infty G_2(v)dv &= \int_0^\infty \frac{P_{sr}}{\Delta V}\sum_{f=1}^{N} d_f \sum_{i=1}^{L} \frac{c_f(i)\left(C_f(i)\oplus C_g(i)\right)}{W-1} \begin{pmatrix} u\left[v - v_o - \frac{\Delta v}{2L}(-L+2i-2)\right] \\ -u\left[v - v_o - \frac{\Delta v}{2L}(-L+2i)\right] \end{pmatrix} dv \\
&= \frac{P_{sr}}{\Delta V}\frac{\Delta v}{L}\sum_{f=1}^{N} d_f \sum_{i=1}^{L} \frac{C_f(i)\left(C_f(i)\oplus C_g(i)\right)}{W-1} \\
&= \frac{P_{sr}}{L}\sum_{f=1, f\neq g}^{N} d_f
\end{aligned} \tag{23}$$

The current I of preferred user is computed by taking the difference of two photodiodes as follows:

$$I = I_1 - I_2 \tag{24}$$

The currents at Photodiode1 and Photodiode 2 are denoted by I_1 and I_2, respectively.

$$\begin{aligned}
I &= \Re\int_0^\infty G_1(v)dv - \Re\int_0^\infty G_2(v)dv \\
&= \Re\left(\frac{P_{sr}W}{L}d_g + \frac{P_{sr}}{L}\sum_{f=1, f\neq g}^{N} d_f - \frac{P_{sr}}{L}\sum_{f=1, f\neq g}^{N} d_f\right) \\
&= \Re\left(\frac{P_{sr}W}{L}d_g\right)
\end{aligned} \tag{25}$$

The photo-detectors responsivity is $\Re$ and represented by

$$\Re = \frac{\eta e}{h V_c} \tag{26}$$

Here, η is the quantum efficiency and h is the Planck's constant. The shot noise power can be written as:

$$\begin{aligned}
\left\langle I_{shot}^2\right\rangle &= 2eB\,\Re\left[\int_0^\infty G_1(v)dv + \int_0^\infty G_2(v)dv\right] \\
&= 2eB\,\Re\left(+\frac{P_{sr}}{L}\sum_{f=1, f\neq g}^{N} d_f + \frac{P_{sr}}{L}\sum_{f=1, f\neq g}^{N} d_f\right) \\
&= 2eB\,\Re\frac{P_{sr}}{L}\left(Wd_g + 2\sum_{f=1, f\neq g}^{N} d_f\right) \\
&= 2eB\,\Re\frac{P_{sr}}{L}\left(W + 2(N-1)\right) \\
\left\langle I_{shot}^2\right\rangle &= 2eB\,\Re\frac{P_{sr}}{L}\left[2(N-1) + W\right]
\end{aligned} \tag{27}$$

Once all users conveying bit "1" and by approximating the summation from "(21)" via applying the average value as $\sum_{f=1}^{N} C_f \cong \frac{NW}{L}$. Based on the properties of SW-MP code, the PIIN noise power is given as [4]-[5]:

$$\begin{aligned}
\langle I_{PIIN}^2\rangle &= BI_1^2\tau_{c1} + BI_2^2\tau_{c2} \\
&= B\Re^2\left[\int_0^\infty G_1^2(v)dv + \int_0^\infty G_2^2(v)dv\right] \\
&= B\Re^2\frac{P_{sr}^2}{\Delta vL}\sum_{i=1}^{L}\left\{C_g(i)\left[\sum_{f=1}^{N} d_f C_f(i)\right]\cdot\left[\sum_{m=1}^{N} d_m C_m(i)\right]\right\} \\
&\quad + \frac{B\Re^2}{P^2}\frac{P_{sr}^2}{\Delta vL}\sum_{i=1}^{L}\left\{\left(C_f(i)\oplus C_g(i)\right)\left[\sum_{f=1}^{N} d_f C_f(i)\right]\left[\sum_{m=1}^{N} d_m C_m(i)\right]\right\} \\
&\cong B\Re^2\frac{P_{sr}^2}{\Delta vL}\sum_{i=1}^{L}\left\{C_g(i)\frac{NW}{L}\left(\sum_{f=1}^{N} C_f(i)\right)\right\} \\
&\quad + \frac{B\Re^2}{P^2}\frac{P_{sr}^2}{\Delta vL}\sum_{i=1}^{L}\left\{\left(C_f(i)\oplus C_g(i)\right)\frac{NW}{L}\left(\sum_{f=1}^{N} C_f(i)\right)\right\} \\
&\cong B\Re^2\frac{P_{sr}^2}{\Delta vL}\frac{NW}{L}\sum_{f=1}^{N}\left(\sum_{i=1}^{L} C_f(i)\cdot C_g(i)\right) \\
&\quad + \frac{B\Re^2}{\quad}\frac{P_{sr}^2}{\Delta vL}\frac{NW}{L}\sum_{f=1}^{N}\left(\sum_{i=1}^{L} C_f(i)\cdot\left(C_f(i)\oplus C_g(i)\right)\right)
\end{aligned}$$

$$\langle I_{PIIN}^2 \rangle \cong B\Re^2 \frac{P_{sr}^2}{\Delta vL}\frac{NW}{L}(W+N-1)+\frac{B\Re^2}{}\frac{P_{sr}^2}{\Delta vL}\frac{NW}{L}(N-1)$$
$$=\frac{B\Re^2 P_{sr}^2 NW}{\Delta vL^2}(W+1+2(N-1)) \quad (28)$$

It should be point out that the probability of transmitting bit '1' in any time of each user is 0.5, then "(27)" and "(28)" become respectively [4]:

$$\langle I_{shot}^2 \rangle = eB\Re\frac{P_{sr}}{L}[2(N-1)+W] \quad (29)$$

and

$$\langle I_{PIIN}^2 \rangle = \frac{B\Re^2 P_{sr}^2 NW}{2\Delta vL^2}\left(W+1+\frac{2(N-1)}{g}\right) \quad (30)$$

To determine the overlapping from the other users hitting on the desired user we have studied two cases depending on the values of g. If g =1 means the two users are reside in the similar group while for the condition g ≥2 means the two users are reside in another groups. Thus, "(28)" is simplified furthermore as:

The thermal noise is given as [4]-[5]:

$$\langle I_{thermal}^2 \rangle = \frac{4K_b T_n B}{R_L} \quad (31)$$

The SNR of the SW-MP scheme is calculated as:

$$SNR = \frac{I^2}{\langle i^2 \rangle} = \frac{(I_2 - I_1)^2}{\langle I_{shot}^2 \rangle + \langle I_{PIIN}^2 \rangle + \langle I_{thermal}^2 \rangle} \quad (32)$$

Thus "(32)" based on "(25)", "(29)", "(30)" and "(31)" can be written as:

$$SNR = \frac{\Re^2 P_{sr}^2 (W-1)^2 / L^2}{(P_{sr}\, e\, B\, \Re/L)[2N+W-2]+\left(B\Re^2 P_{sr}^2 NW/(2\Delta vL^2)\right)\left(W+1+\frac{2(N-1)}{g}\right)+4K_b T_n B/R_L} \quad (33)$$

Using Gaussian approximation as in [4]-[5], the bit error rate (BER) is computed as follows:

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{\text{SNR}}{8}}\right) \quad (34)$$

VI. Comparison and Evaluation

For evaluation objective, the characteristic of the SW-MP and DEU codes are tabulated in Table 3 [18]-[19]. Table 3 shows that SW-MP and DEU codes exist for positive integer W, free cardinality, and ideal CC. In terms of code length and to support 8 users, the code lengths required by SW-MP ($W=3$) and DEU ($W=3$) are 12 and 17, respectively. To conclude SW-MP has short code length compared to DEU for the same parameters; long code length is not practical to be implemented in terms of hardware as the code is susceptible to either very extensive band source or narrow filter bandwidths are necessary.

TABLE. III. Properties of SW-MP and DEU Codes [18]-[19]

Property	DEU-technique	SW-MP-technique	Remarks
λ	≤1	≤1	• The maximum CC equals one between any two adjacent DEU codes • The maximum cross correlation is zero when g ≥2 for SW-MP codes
Existence	Any integer number	Any integer number	• More flexibility in code weight selection for SW-MP and DEU codes
Size	Free	Free	• Free cardinality for SW-MP and DEU codes
Code length	$L=N(W-1)+1$	$L=\frac{(W\times N)}{2}$	• SW-MP code has short code length compared to DEU code
Number of variables and parameters	W	W, g	• SW-MP has two parameters in construction while DEU has one parameter
Matrix Form	Yes	Yes	• Same steps of construction

VII. Theoretic and Simulation Findings

In this section the process of SAC domain combined with WDM domain is investigated by considering different types of noises such as PIIN, thermal and shot noises using the key parameters listed in Table 4.

TABLE. IV. Elements of SNR and BER Associated with Corresponding Values

Symbol	Translation of symbol	Symbol's value and representation
η	Quantum efficiency of photodiode	0.6
V_c	Line-width of the thermal source	3.75THz
λ_0	Transmission Window	1550 nm
B	Electrical bandwidth	80 MHz
R_b	Data bit rate	155 Mb/s
T_n	Absolute receiver noise temperature	300 K
R_L	Receiver load resistor	1030 Ω
e	The electron charge	1.6×10^{-19} Coulomb's
K_B	Boltzmann's constant is	1.38054×10^{-23}
P_{sr}	Efficient power of a broad-band source	-10 dBm
N	Number of simultaneous users	Vary
W	Code weight	Any integer number
g	Number of groups	Any integer number
L	Code's length	$L=\frac{(W\times N)}{2}$

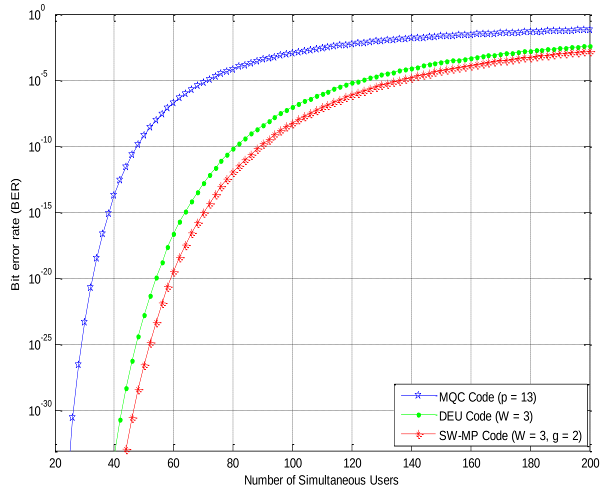

Fig. 4. Bit error rate against simultaneous users at 155Mbits/s.

In Fig. 4, SW-MP is compared as a function of the number of concurrent users versus BER with conventional SAC coding technique MQC and DEU. The comparison has been carried out in a free space setting with different values of parameters when P_{sr} = -10dBm at 155Mbits/s for MQC (p =16), DEU (W =3), and SW-MP (W=3, g =2). As expected, SW-MP code is having good result in terms of performance with regard to DEU even for the same code's weight, which is 3 and this is due to the elimination of the interference from different users when the value of g ≥2. As seen from the result, for lower weight (W=3) the quality of the received signal is satisfactory and the BER = 10^{-9} is attained for almost ≈ 80 and ≈ 90 users for DEU and SW-MP, respectively.

SW-MP outperforms MQC even for higher code's weight, which is 13. This outperformance due to higher SNR in SW-MP as compared with MQC. However, MQC code is utilized for an ideal cross-correlation (λ= 1) where each system employing MQC still suffers from MAI effect, thus preventive the system performance for more improvement. Hence, this boosts the signal's impairment eventually system performance degradation.

In Fig. 5, performance of the system with regards to the effective power P_{sr} for 40 users at data rate of 155Mb/s for considering PIIN, shot and thermal noises for MFH (q=16), MQC (p=13), DEU (W=3) and SW-MP (W=3, g =2) codes is evaluated. The figure demonstrates that the P_{sr} of the BER of 10-9 is achieved with Psr ≈ -28 dBm for the SW-MP code while the same BER is obtained as P_{sr} ≈ -18 dBm, P_{sr} ≈ -17 dBm and P_{sr} ≈ -23dBm for the MFH, MQC and DEU codes, respectively. Due to its good property the SW-MP code shows better performance where an MAI impact is minimized when g≥ 2 whereas for MFH and MQC codes are "1", respectively as the number of concurrent users increases. In particular, for DEU code the maximum CC is "1" between any two neighboring users that minimizes the impact of MAI and this sees in better performance compared to MQC and MFH codes.

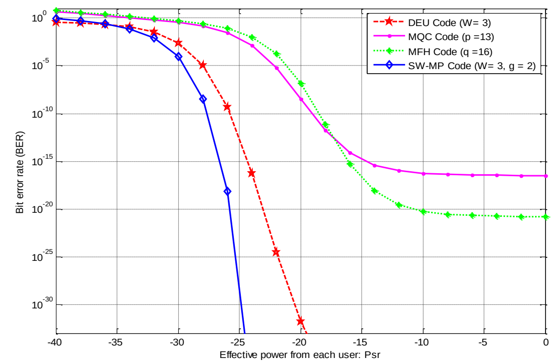

Fig. 5. BER plotted against P_{sr} for 40 users at the data rate 155Mbits/s.

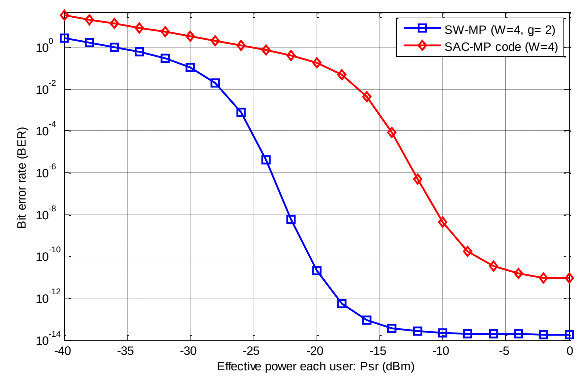

Fig. 6. BER drawn against Psr for 15 users at the data rate 155Mbits/s.

Fig. 6 displays the BER drawn versus P_{sr} for 40 users at a data rate of 155Mbits/s considering the PIIN, thermal and shot noises for SW-MP (hybrid system) and SAC-MP (conventional system) codes. SW-MP is created with the parameters W=4 and g =2 (two groups); SAC-MP code is selected with the weight W=4. The acceptable error for reliable transmission (BER < 10^{-9}) is achieved for the SW-MP code with ≈ -22 dBm whereas the same BER is achieved with ≈ P_{sr} > -8 dBm for SAC-MP code for 40 users. This is because the effect of MAI is diminished when g≥ 2 for SW-MP while for SAC-MP is fixed as the number of concurrent users increases. The figure proves that SW-MP codes outperform SAC-MP codes by the magnitude of almost three times.

VIII. Conclusion

The study in this paper has provided a promising strategy to constructing a code family for optical communication. The main aspects of this code family have been studied extensively. The theory and calculation findings of the system were compared with the codes mentioned in the literature review. The SW-MP technique is a SAC code reiterated diagonally in wavelength domain. The in-phase CC has maximum value of "1" in the similar group and zero with codes in different groups. SW-MP code has several features like the freedom of picking the number of users (free cardinality) than other codes, workable code length and easy to carry out through FBGs. It's reported that the new code family was able to mitigate PIIN noise efficiently and enhance the system performance noticeably. It is mentioned that when the system is highly populated with concurrent users, the SW-MP surpass almost three times the traditional ones and the BER is reduced when the value of g increments.

Furthermore, top of its excellence performing the SW-MP codes need less complexity in terms of hardware for the transmitter-receiver structure.

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