Improved phase noise performance using orthogonal ternary codes over spectral polarization and amplitude coding networks

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Abstract. This study proposes an improved hybrid scheme of spectral polarization coding (SPC) and spectral amplitude coding (SAC) based on a specified orthogonal ternary sequence. In a previous SPC scheme, the entire wavelength was assigned either a vertical or a horizontal state of polarization. However, this study assigns positive, negative, or null chip values to individual wavelengths to create an orthogonal ternary sequence based on the bipolar Walsh-Hadamard matrix. This approach reduces the number of wavelength collisions in the photodetector and hence reduces the phase-induced intensity noise (PIIN). Neglecting the effects of shot noise and thermal noise, we consider only PIIN with a degree of polarization $P=0$. The proposed scheme improves the bit error rate by 40% and 100% over SPC and complementary unipolar SAC schemes. The number of simultaneous active users supported by the hybrid scheme for the worst case ($P=1$) is improved by 41.3% over the complementary unipolar SAC coding scheme for the ideal case ($P=0$).

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Subject terms: optical code-division multiple-access; hybrid spectral polarization and amplitude coding; fiber Bragg grating; polarization beamsplitter; multiple-access interference; phase-induced intensity noise.

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1 Introduction

An optical code-division multiple-access (OCDMA) scheme based on spectral-amplitude coding (SAC) was originally proposed as a means of increasing the maximum permissible number of simultaneous active users by reducing the codeword length and eliminating the multiple access interference (MAI) effect.1–5 Traditional SAC schemes can be classified as either conventional unipolar SACs or complementary unipolar SACs. A conventional unipolar SAC transmits optical pulses only on data bit 1, and sends nothing on data bit 0. In contrast, a complementary unipolar SAC transmits a specific codeword on data bit 1 and its complementary codeword on data bit 0. In SAC schemes, a crucial problem is that of the phase-induced intensity noise (PIIN) arising when mixed incoherent light fields are incident on a photodetector. The increased PIIN limits the permissible number of simultaneous active users.6,7 A fundamental approach for overcoming the PIIN effect is to reduce the number of wavelength collisions that take place in the photodetector.

Since only the central spectrum of the incoherent source was usefully flat, the bit error rate (BER) performance and spectral efficiency of supercode configured by Dennis et al.8,9 was severely degraded due to the resulting occupation of a double spectral bandwidth. To improve the spectral efficiency and overcome the PIIN problem, the current authors configured a complementary bipolar spectral amplitude coding (SPC) scheme.10 In their approach, the spectral amplitude is combined with polarization coding as the specific signature address code, and the Walsh-Hadamard code is employed as the signature address to allocate to each specified wavelength an individual vertical or horizontal state of polarization. Unfortunately, on setting the degree of polarization $P=1$ for the worst case, we find that the BER performance of the previous SPC (i.e., complementary bipolar) scheme only matches that of conventional complementary unipolar SAC scheme with $P=0$.

In the current study, a hybrid SPC-SAC scheme is presented to enhance the performance of the previous SPC scheme. The specified orthogonal ternary sequence used in the proposed scheme is transformed from the original Walsh-Hadamard matrix and is constructed by assigning positive (+), negative (−), and null (0) chip values to individual wavelengths. As in the previous SPC scheme,10 a positive chip value (+1) is assigned to the vertical state of polarization (SOP), while a negative chip value (−1) is assigned to the horizontal SOP. In addition, null chip values are assigned to certain wavelengths, i.e., those wavelengths are assigned neither a vertical nor a horizontal SOP. The main difference between the current approach and the SAC scheme presented previously by the current authors10 is the use of null wavelengths, which significantly reduces the number of wavelength collisions in the photodetector, and hence reduces the PIIN.

Although it is well known that the PIIN in high-data-rate and long-haul networks is affected by the degree of polarization (DOP), previous studies of such networks have generally neglected its influence. By contrast, the present study...
specifies specifically takes account of the influence of the DOP on the PIIN, so that the proposed scheme is suitable for implementation in both high-data-rate and long-haul networks.

The remainder of this paper is organized as follows. Section 2 presents the proposed specified orthogonal ternary matrix, which is transformed from the original Walsh-Hadamard code matrix. Section 3 describes the encoder and decoder of the proposed hybrid SPC/SAC scheme based on the specified orthogonal ternary code and presents an illustrative example to demonstrate the cancellation of MAI in the proposed scheme. Section 4 evaluates the system performance in terms of the BER and the maximum number of permissible simultaneous active users. The performance improvement provided by the current scheme is evaluated by comparing the simulation results obtained for the current scheme with those obtained from the unipolar and bipolar SAC approaches. In particular, the effect of the degree of polarization on the PIIN is investigated. Finally, Sec. 5 provides some concluding remarks.

2 Specified Orthogonal Ternary Sequence Matrix

The original Walsh-Hadamard matrices, $H$, have the form

$$H_1 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad \text{and} \quad H_n = \begin{bmatrix} H_{n-1} & H_{n-1} \\ H_{n-1} & -H_{n-1} \end{bmatrix},$$

where $n = 2, 3, 4, \ldots$.

Applying an exhaustive search method in which addition or subtraction operations are applied to specified row pairs of $H$, the proposed specified orthogonal ternary matrix $ST$ is created and assigned as the codeword matrix. In the current study, the simple specified pairing rule is as follows:

for $i \leq N/4$,
\[ c_{2i-1} = (h_i + h_{N-2(i-1)}) \times \frac{1}{2}, \quad c_{2i} = (h_i - h_{N-2(i-1)}) \times \frac{1}{2} \quad (2a) \]

and for \( i > N/4, \)

\[ c_{2i-1} = (h_i + h_{2i-1}) \times \frac{1}{2}, \quad c_{2i} = (h_i - h_{2i-1}) \times \frac{1}{2}, \quad (2b) \]

where \( c_{2i}, c_{2i}, i = 1, 2, \ldots, N/2, \) with \( N = 2^i, i = 3, 5, 7, \ldots, \)

the specified orthogonal ternary codes, and where \( h_i \) denotes the \( i \)th row of the \( N \times N \) Walsh-Hadamard matrix. Here \( N \) denotes the codeword length. Since the rows of the specified orthogonal ternary matrix are generated via a process of linear transformation (i.e., the transformation process is based on basic addition, subtraction, and multiplication operations), the matrix \( ST \) retains an inherent quasi-orthogonal property and is therefore suitable for application in a SAC scheme. In addition, from Eq. (1), \( c_k \) includes four null wavelengths, which indicates that the number of wavelength collisions and has a cross-correlation of just \( N/8 \) at the photodetector, thereby reducing the PIIN.

The specified pairing rule in Eq. (2) is demonstrated in the following construction of the design of an \( 8 \times 8 \) specified orthogonal ternary matrix. As shown in Table 1, the first and eighth rows of the Hadamard matrix \( H \) are initially selected as a pair and used to populate the first and second rows of the specified orthogonal ternary sequence matrix \( ST \). Specifically, row 1 of \( ST \) is populated by adding rows 1 and 8 of \( H \) and then multiplying the result by \( 1/2 \). Similarly, row 2 of \( ST \) is populated by subtracting row 8 of \( H \) from row 1 and then multiplying the result by \( 1/2 \). For convenience, this process is described as follows: 

\[ ((\text{row } 1 + \text{row } 8)/2, (\text{row } 1 - \text{row } 8)/2) \]

is transferred to (row 1, row 2) \( ST \). Similarly, 

\[ ((\text{row } 2 + \text{row } 6)/2, (\text{row } 2 - \text{row } 6)/2) \]

is transferred to (row 3, row 4) \( ST \), and 

\[ ((\text{row } 3 + \text{row } 5)/2, (\text{row } 3 - \text{row } 5)/2) \]

is transferred to (row 5, row 6) \( ST \), and 

\[ ((\text{row } 4 + \text{row } 7)/2, (\text{row } 4 - \text{row } 7)/2) \]

is transferred to (row 7, row 8) \( ST \). The results of the transformation procedure are shown in Table 1.

As shown in Table 1, the specified orthogonal ternary matrix \( ST \) can be expressed in \((C^{(1)}_V, C^{(2)}_H)\) form as

\[
\begin{bmatrix}
1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \\
1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \\
1 & 1 & 0 & 0 & 0 & 0 & -1 & -1 \\
0 & 0 & -1 & -1 & 1 & 1 & 0 & 0 \\
1 & 0 & -1 & 0 & 0 & -1 & 0 & 1 \\
0 & -1 & 0 & 1 & 1 & 0 & -1 & 0
\end{bmatrix}
\]

The (matrix) can be further decomposed into the \((C^{(1)}_V, C^{(2)}_H)\) form, i.e.,

\[
ST = C^{(1)}_V \cdot C^{(2)}_H
\]

where the subscripts \( V \) and \( H \) denote vertical and horizontal SOPs, respectively.

Comparing these results with Eqs. (3) and (1) of Ref. 10, developed by the authors in their previous proposal for an SPC scheme, it can be seen that the present tuple \((C^{(1)}, C^{(2)})\) replaces the original tuple \((C, \bar{C})\). Here, the \( k \)th row of \((C^{(1)}, C^{(2)})\) is denoted as \((c_k^{(1)}, c_k^{(2)})\) and represents the signature code of the \( k \)th user. In Eq. (3), \( C^{(1)}_V - C^{(1)}_H \) indicates that the user is transmitting data bit 1, where a positive chip value (+) indicates that a vertical SOP is assigned to this wavelength, a negative chip value (−) indicates that a horizontal SOP is assigned, and a null chip value implies that the wavelength is assigned neither a vertical nor a horizontal SOP. Conversely, the complement \( ST = C^{(1)}_H - C^{(1)}_V \) is assigned when the data bit 0 is transmitted. In this case, \( C^{(1)}_V \) indicates that a horizontal SOP is assigned to the wavelength, while \( C^{(2)}_H \) indicates that a vertical SOP is assigned.

By mapping the specified orthogonal ternary sequence matrix to wavelength allocations characterized by mutually orthogonal SOPs (i.e., vertical and horizontal SOPs), the codeword sets shown in Table 2(a and b) can be generated for data bit 1 and data bit 0, respectively. Note in Table 2 that \( c_k \) denotes the \( k \)th row of the specified orthogonal ternary matrix, \( ST \).

\[
\begin{bmatrix}
1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \\
1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
0 & 0 & 1 & 0 & 1 & 0 & 0 & 1
\end{bmatrix}
\]

3 The Hybrid SPC-SAC System Configuration

A polarization beamsplitter (PBS), quarterwave plate (QWP), and fiber Bragg grating (FBG) have been successfully configured to establish a path routing function for optical cross-connectors (OXCs). By extending the same concept, these have been combined to perform encoding and decoding functions in previous SPC schemes. Here, the same mechanism using a PBS is applied as shown in Table 1 of Ref. 10. In the current study, since the new specified orthogonal ternary coding is employed, a slight modification of the coding configuration, requiring an additional null-wavelength transmission FBG array, is presented. Moreover, the system performance in terms of the signal-to-PIIN ratio (SNRPIIN) is derived in the next section.

Similarly to the previous SPC scheme as shown in Fig. 1 of Ref. 10, adaptive polarization mode dispersion (PMD) compensators are introduced in front of the star coupler and the receivers of the current configuration so that the correct SOP (vertical or horizontal) is launched into the decoder for each wavelength. PMD compensators have been successfully applied in previous studies to enhance the performance of wavelength-division multiplexing (WDM).
However, PMD compensators fall outside of the current scope and are therefore not discussed in detail here. A common approach for PMD compensation is to assign a fixed SOP to a reference wavelength inside the transmitting-signal spectrum in order to estimate the PMD effect over the optical fiber channel for \( f \). The difference between the variable and reference SOPs is then used as a feedback signal for polarization tracking to tune the adaptive polarization controller and delay line in order to adjust the principal states of the polarization and the differential group delay. This PMD compensation technique enables the proposed SPC scheme to be feasibly implemented on high-data-rate and long-haul networks such as optical access networks.

### 3.1 The Mechanism of the Proposed Encoder

As shown in Fig. 1, the proposed scheme implements complementary ternary coding using a symmetric pair of hybrid SPC-SAC encoders linked by a switch whose operation is controlled by the logic state of the transmitted data bits. When the user transmits a data bit 1, this switch directs the unpolarized light to the upper branch of the encoder. Conversely, when a data bit 0 is transmitted, the unpolarized light is switched to the lower branch. Taking user 6 for illustrative purposes, the codewords \( c^{(1)}_6 \) and \( c^{(2)}_6 \) prewritten with the FBGs have the same wavelength but orthogonal SOPs in the upper and lower branches of the encoder (i.e., the proposed design comprises one original and one complementary encoder).

Figure 1 shows the detailed mechanisms and configuration of the upper branch of the present original encoder when a data bit 1 is transmitted. Note that the encoding procedure is exactly the same as that used in the previous SPC scheme reported by the current authors in Ref. 10, except for the tuple \( (C^{(1)}, C^{(2)}) \), which replaces the original tuple \( (C, \bar{C}) \). Assuming a user capacity of \( N=8 \), and using the codeword for user 6 (shown in Table 2) for illustrative purposes, the original encoding procedure involves the five steps shown below. Note that the expressions in parentheses denote a simultaneous operation in the complementary arm (i.e., the lower arm) of the original encoder.

1. The PBS allocates the orthogonal horizontal and vertical SOPs to the upper and lower arms of the original encoder, respectively.
2. The horizontal linear SOP wavelengths of \( \lambda_3, \lambda_4, \lambda_5, \) and \( \lambda_6 \) are transformed to a left circular SOP via a Table 2 Specified orthogonal ternary codewords.

<table>
<thead>
<tr>
<th>Codeword (user)</th>
<th>( \lambda_1 )</th>
<th>( \lambda_2 )</th>
<th>( \lambda_3 )</th>
<th>( \lambda_4 )</th>
<th>( \lambda_5 )</th>
<th>( \lambda_6 )</th>
<th>( \lambda_7 )</th>
<th>( \lambda_8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Data bit 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_1 )</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( C_4 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>( C_5 )</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( C_6 )</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( C_7 )</td>
<td>+</td>
<td>0</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>( C_8 )</td>
<td>0</td>
<td>–</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>(b) Data bit 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_1 )</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>0</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( C_4 )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>( C_5 )</td>
<td>–</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>( C_6 )</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( C_7 )</td>
<td>–</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>( C_8 )</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>0</td>
<td>+</td>
<td>0</td>
</tr>
</tbody>
</table>
The mechanism of the proposed decoder

The spectral lightwave signals $\mathbf{R}$ encoded by each hybrid SPC-SAC encoder are summed and then transmitted to the network receivers via a $K \times K$ star coupler. The summed signal spectrum for all of the simultaneous active users $\mathbf{R}$ is composed of vertical and horizontal polarization states and is given by

$$\mathbf{R} = \mathbf{R}_V + \mathbf{R}_H,$$

where

$$\mathbf{R}_V = \sum_{k=1}^{K} b_k \mathbf{c}_k^{(1)} + (1 - b_k) \mathbf{c}_k^{(2)}$$

and

$$\mathbf{R}_H = \sum_{k=1}^{K} b_k \mathbf{c}_k^{(2)} + (1 - b_k) \mathbf{c}_k^{(1)}.$$

In the current correlation filter process, the decoding procedure involves six steps, as shown in Fig. 2. Note that in the following discussion, the expressions in parentheses denote a simultaneous operation in the complementary decoder arm. The symbols $\mathbb{1}$ to $\mathbb{8}$ in this figure indicate the sequence in which these steps are performed. The polarization states are indicated as $(V)$ and $(H)$ in each correlation procedure. As shown in Fig. 2, to compensate for the group delay caused by long-haul transmission when the incident light is reflected by the FBG array, the decoder gratings are arranged in reverse order relative to those in the encoder so that asynchronous transmission can be more easily implemented. The process is as follows:

1. PBS1 allocates the orthogonal horizontal and vertical SOPs to the upper and lower arms, respectively.
2. Passing through QWP1 and following the part reflected by the $j$th coded sequence $\mathbf{c}_j^{(1)}$ (or $\mathbf{c}_j^{(2)}$) prewritten in the upper (lower) FBG, the reflected correlation results are expressed as $\mathbf{R}_H \cdot \mathbf{c}_j^{(1)}$ in the upper arm and $\mathbf{R}_V \cdot \mathbf{c}_j^{(2)}$ in the lower arm after passing back through QWP1.
3. Passing through QWP1 and following the part transmitted by the coded sequence $\mathbf{c}_j^{(1)}$ (or $\mathbf{c}_j^{(2)}$) prewritten in the upper (lower) FBG and passing through QWP2, the transmitted correlation results are expressed as $\mathbf{R}_H \cdot \mathbf{c}_j^{(2)}$ in the upper arm and $\mathbf{R}_V \cdot \mathbf{c}_j^{(1)}$ in the lower arm.
4. Passing through PBS2 and allocating the orthogonal horizontal and vertical SOPs to the upper and lower arms, respectively, the transmitted correlation results
of $\mathbf{R}_V \cdot \mathbf{c}_j^{(1)} + \mathbf{R}_H \cdot \mathbf{c}_j^{(2)}$ are obtained in the upper photodetector (PD1). Similarly, the reflected correlation results $\mathbf{R}_V \cdot \mathbf{c}_j^{(2)} + \mathbf{R}_H \cdot \mathbf{c}_j^{(1)}$ are obtained in the lower photodetector (PD2).

5. The transmitted correlation results $\mathbf{R}_V \cdot \mathbf{c}_j^{(1)} + \mathbf{R}_H \cdot \mathbf{c}_j^{(2)}$ pass through the null-wavelength transmission FBG array via PBS3. Hence, the null wavelengths, which result from a null chip (i.e., $\lambda_1, \lambda_2, \lambda_7$, and $\lambda_8$ in the codeword for user 6), are filtered out so that only the positive chips “1” (i.e., $\lambda_3$ and $\lambda_4$) and the negative chips “1” (i.e., $\lambda_3$ and $\lambda_4$) impinge in PD1.

6. Impinging on the differential photodetector, the detected power units PD1-PD2 are obtained and expressed as $(\mathbf{R}_V \cdot \mathbf{c}_j^{(1)} + \mathbf{R}_H \cdot \mathbf{c}_j^{(2)}) - (\mathbf{R}_V \cdot \mathbf{c}_j^{(2)} + \mathbf{R}_H \cdot \mathbf{c}_j^{(1)})$.

As discussed previously, the current tuple $(\mathbf{C}_1, \mathbf{C}_2)$ replaces the tuple $(\mathbf{C}, \mathbf{C})$ in the previous SPC scheme. Furthermore, the current decoding procedure differs slightly from that employed in the previous scheme in that it employs an additional null-wavelength transmission FBG array. Taking the codeword for user 6 (0, 0, −1, −1, 1, 1, 0, 0) for illustration purposes, the absent (null) wavelengths of $\lambda_1, \lambda_3, \lambda_7$, and $\lambda_8$ are assigned neither a vertical nor a horizontal state of polarization. Therefore, the null-wavelength transmission FBG array rejects the wavelengths arising from this transmitted part of FBG 1 (i.e., $\lambda_1, \lambda_3, \lambda_7$, and $\lambda_8$) and prevents them from impinging on photodetector 1 (i.e., PD1).

Following the sixth step (i.e., 8) of the decoding procedure, and rearranging terms, the $j$th detected power units can be expressed as

$$(\mathbf{R}_V \cdot \mathbf{c}_k^{(1)} + \mathbf{R}_H \cdot \mathbf{c}_j^{(2)}) - (\mathbf{R}_V \cdot \mathbf{c}_k^{(2)} + \mathbf{R}_H \cdot \mathbf{c}_j^{(1)}) = (\mathbf{R}_V + \mathbf{R}_H) \cdot (\mathbf{c}_k^{(1)} - \mathbf{c}_k^{(2)}) = \mathbf{R} \cdot (\mathbf{c}_k^{(1)} - \mathbf{c}_k^{(2)}),$$

where $\mathbf{c}_k^{(1)}$ and $\mathbf{c}_k^{(2)}$ are the $i$th user’s coding patterns with vertical and horizontal SOPs in the spectral domain, respectively. It can be seen that Eq. (5) represents a correlation function for $\mathbf{R}$ and $\mathbf{c}_k^{(1)} - \mathbf{c}_k^{(2)}$. In other words, the proposed decoder performs a complementary ternary function and therefore differs from the complementary bipolar function presented previously.10

### 3.3 Illustration of MAI Cancellation in Hybrid SPC-SAC Coding

The detected power units obtained by balanced detection $(I_{PD1} - I_{PD2})$ are given by

$$I_{PD1} - I_{PD2} = \sum_{k=1}^{K} [(2b_k - 1)(\mathbf{c}_k^{(1)} \cdot \mathbf{c}_j^{(1)} + \mathbf{c}_k^{(2)} \cdot \mathbf{c}_j^{(2)}) - (2b_k - 1) \times (\mathbf{c}_k^{(2)} \cdot \mathbf{c}_j^{(1)} + \mathbf{c}_k^{(1)} \cdot \mathbf{c}_j^{(2)})].$$

At the receiver (decoder) end, the in-phase correlations of the $k$th user’s signal coming from the star coupler and the $j$th user’s signal (i.e., the signal of the desired user) are $\mathbf{c}_k^{(1)} \cdot \mathbf{c}_j^{(1)} + \mathbf{c}_k^{(2)} \cdot \mathbf{c}_j^{(2)}$ and $\mathbf{c}_k^{(1)} \cdot \mathbf{c}_j^{(2)} + \mathbf{c}_k^{(2)} \cdot \mathbf{c}_j^{(1)}$ at PD1 and PD2, respectively, for $N=2^2$, $i=3, 5, 7, \ldots$, and are written as

$$\mathbf{c}_k^{(1)} \cdot \mathbf{c}_j^{(1)} + \mathbf{c}_k^{(2)} \cdot \mathbf{c}_j^{(2)} = \sum_{i=1}^{N} \mathbf{c}_k^{(1)}(i) \mathbf{c}_j^{(1)}(i) + \mathbf{c}_k^{(2)}(i) \mathbf{c}_j^{(2)}(i)$$

$$= \begin{cases} N/2 & \text{for } k = j, \\ 0 & \text{for } k = j - 1, \text{ if } j \text{ is even}, \\ 0 & \text{for } k = j + 1, \text{ if } j \text{ is odd}, \\ N/8 & \text{otherwise}, \end{cases}$$

(7a)

$$\mathbf{c}_k^{(1)} \cdot \mathbf{c}_j^{(2)} + \mathbf{c}_k^{(2)} \cdot \mathbf{c}_j^{(1)} = \sum_{i=1}^{N} \mathbf{c}_k^{(1)}(i) \mathbf{c}_j^{(2)}(i) + \mathbf{c}_k^{(2)}(i) \mathbf{c}_j^{(1)}(i)$$

$$= \begin{cases} 0 & \text{for } k = j, \\ 0 & \text{for } k = j + 1, \text{ if } j \text{ is odd}, \\ N/8 & \text{otherwise}. \end{cases}$$

(7b)

In Eqs. (7a) and (7b) for the proposed specified orthogonal ternary sequence, the first term denotes the matching scenario (i.e., $k=j$), and an autocorrelation value of $N/2$ is obtained. The second and third terms are characterized by an orthogonality property, since the adjacent specified ternary sequence is created by a linear transformation, as shown in Table 1. The fourth term denotes the nonadjacent and nonmatching scenario and indicates that the number of wavelength collisions is given by $N/8$ in the general case. For a user capacity of $N=8$, as considered in the present study, the number of wavelength collisions is therefore equal to 1. This result confirms the suitability of the rule given in Eq. (2) for constructing the present specified ternary codeword from the Walsh-Hadamard code. The construction is performed using a simple transformation rule and results in a minimum number of light-wave chip pulses. Hence, the proposed hybrid SPC-SAC scheme with a specified ternary codeword not only retains orthogonality via its use of balanced photodetectors, but also guarantees minimal wavelength collision in the photodetector and therefore reduces the PIIN.

Table 3 is an illustration of MAI cancellation, which shows the transmitting signature code for users 1 to 8 with data bits 1 or 0. When a user transmits data bit 1, the transmitted signal is given by $\mathbf{c}_k^{(1)}$ for $\mathbf{R}_V$ and $\mathbf{c}_k^{(2)}$ for $\mathbf{R}_H$. Conversely, when transmitting data bit 0, the transmitted signal is denoted by $\mathbf{c}_k^{(1)}$ for $\mathbf{R}_H$ and $\mathbf{c}_k^{(2)}$ for $\mathbf{R}_V$. As shown, the number of simultaneous active users is 8 and the received signal spectrum is $\mathbf{R}$. A PBS splits the received signal into $\mathbf{R}_V$ and $\mathbf{R}_H$, corresponding to the reflected wavelengths $\mathbf{c}_k^{(1)}$ and $\mathbf{c}_k^{(2)}$, respectively, and these wavelengths are then launched into PD1 and PD2.

For the matched codec (e.g., user 4) and the transmission of data bit 1, the detected power units are $\mathbf{R}_V \cdot \mathbf{c}_6^{(1)} + \mathbf{R}_H \cdot \mathbf{c}_6^{(2)} = 10$ at PD1 and $\mathbf{R}_V \cdot \mathbf{c}_6^{(1)} + \mathbf{R}_H \cdot \mathbf{c}_6^{(1)} = 6$ at PD2. Applying differential detection, the detected power units are 4, and the data bit 1 is recovered. Similarly, for the matched codec (e.g., user 6), the detected power units are $\mathbf{R}_V \cdot \mathbf{c}_6^{(1)} + \mathbf{R}_H \cdot \mathbf{c}_6^{(2)} = 6$ at PD1 and $\mathbf{R}_V \cdot \mathbf{c}_6^{(2)} + \mathbf{R}_H \cdot \mathbf{c}_6^{(1)} = 10$ at PD2.
Therefore, following differential detection, −4 power units are detected, corresponding to the transmission of data bit 0. In other words, MAI is completely canceled in the proposed hybrid SPC-SAC scheme.

### 4 Performance of Hybrid SPC-SAC Scheme

In evaluating the performance of the proposed hybrid SPC-SAC scheme, the present study adopts a similar analysis model to that applied for the conventional SAC scheme. The symbols that appear in the following discussions are defined in Refs. 4 and 7. The present evaluations assume that each light source is unpolarized and that the optical source has an ideal flat spectrum with a magnitude of \( P_{\text{sr}} / \Delta \nu \), where \( P_{\text{sr}} \) is the effective power from a single source at the receiver and \( \Delta \nu \) is the optical source bandwidth in hertz.

#### 4.1 Signal Power Evaluation

Referring to Eq. (12) of Ref. 4 and to Eq. (15) of Ref. 7, and applying Eq. (4), the detected photocurrent from \( K \) simultaneous active users with a chip length of \( N \) per user at the \( j \)'th upper photodetector (PD1) is given by

\[
I_1 = \mathcal{R} \int_0^\infty G_1(\nu) d\nu = \frac{\mathcal{R} P_{\text{sr}}}{N} \sum_{i=1}^K b_i [c_k^{(1)}(i)c_j^{(1)}(i) + c_k^{(2)}(i)c_j^{(2)}(i)]
\]

\[
+ \frac{\mathcal{R} P_{\text{sr}}}{N} \sum_{i=1}^K \sum_{k=1}^N (1 - b_k) [c_k^{(2)}(i)c_j^{(1)}(i) + c_k^{(1)}(i)c_j^{(2)}(i)]. \tag{8}
\]

where \( \mathcal{R} \) denotes the responsivity of the photodetector. Here and below, \( G_1(\nu) \) and \( G_2(\nu) \) are the single-sideband power spectral densities (PSDs) of the received signal at the upper and lower photodetectors (PD1 and PD2), respectively; \( c_k^{(1)}(i) \) and \( c_k^{(2)}(i) \) are the \( i \)'th wavelength elements of \( c_k^{(1)} \) and \( c_k^{(2)} \), respectively, where \( c_k^{(1)}(i) \) and \( c_k^{(2)}(i) \) denote the \( i \)'th chip of the \( k \)'th user codeword coming from the star coupler with vertical and horizontal SOPs. The \( j \)'th desired sequence (i.e., the \( j \)'th decoder) prewritten with vertical and horizontal SOPs is represented by \( c_j^{(1)}(i) \) and \( c_j^{(2)}(i) \). Similarly, the detected photocurrent coming from \( K \) simultaneous active users with a chip length of \( N \) per user at the \( j \)'th lower photodetector (PD2) is given by

\[
I_2 = \mathcal{R} \int_0^\infty G_2(\nu) d\nu = \frac{\mathcal{R} P_{\text{sr}}}{N} \sum_{i=1}^K \sum_{k=1}^N (1 - b_k) [c_k^{(1)}(i)c_j^{(1)}(i) + c_k^{(2)}(i)c_j^{(2)}(i)]
\]

\[
+ \frac{\mathcal{R} P_{\text{sr}}}{N} \sum_{i=1}^K \sum_{k=1}^N b_k [c_k^{(2)}(i)c_j^{(1)}(i) + c_k^{(1)}(i)c_j^{(2)}(i)]. \tag{9}
\]

Hence, the \( j \)'th differential detected photocurrent, obtained by subtracting the lower photocurrent from the upper photocurrent (PD1–PD2), is given by
\[ I_1 - I_2 = \Re \int_0^\infty G_1(v)dv - \Re \int_0^\infty G_2(v)dv \]
\[ = \frac{9P_{sw}}{N} \sum_{i=1}^{N} \sum_{k=1}^{K} (2b_k - 1)[c_k^{(1)}(i)c_j^{(1)}(i) + c_k^{(2)}(i)c_j^{(2)}(i)] \]
\[ = \frac{9P_{sw}}{N} \sum_{i=1}^{N} \sum_{k=1}^{K} (2b_k - 1)[c_k^{(2)}(i)c_j^{(1)}(i) + c_k^{(1)}(i)c_j^{(2)}(i)] \]
\[ + c_k^{(1)}(i)c_j^{(2)}(i)]. \quad (10) \]

Substituting the results of Eq. (7a) and Eq. (7b) into Eq. (10) gives
\[ I_1 - I_2 = \begin{cases} \left( \frac{9P_{sw}}{2} \right) & \text{for } k = j \text{ and } b_k = 1, \\ -\left( \frac{9P_{sw}}{2} \right) & \text{for } k = j \text{ and } b_k = 0, \\ 0 & \text{for } k \neq j, \end{cases} \quad (11) \]

where \( P_{sw} \) is the effective power of the broadband source at the receiver. For the user-unmatched case where \( k \neq j \) in Eqs. (7a) and (7b), the detected upper and lower photocurrent units are equal. Equation (11) shows that MAI is completely eliminated, in theory, for an optical source with an ideal flat spectrum.

### 4.2 PIIN Power Evaluation

This study only evaluates the PIIN that results from several thermal sources with a phase variation at each frequency. The PIIN results obtained from the present scheme are compared with those obtained from a conventional SCA scheme for evaluation purposes. Referring to Eq. (19) of Ref. 4, the thermal noise is independent of the effective power of the broadband source at the receiver (\( P_{sw} \)), and the shot noise is proportional only to \( P_{sw} \). However, the PIIN is proportional to \( P_{sw}^2 \). The effective power \( P_{sw} \) from each user is large (e.g., \( P_{sw} \) is more than \(-10 \text{ dBm} \)). Both the shot noise and the thermal noise are negligible compared to the PIIN. Hence, the PIIN is the main limitation on the system performance [as assessed in terms of the signal-to-noise ratio (SNR)]. The variance of the photodetector current is expressed as
\[ \langle i^2 \rangle = \langle I^2 \rangle + (P^2)B\tau_c, \quad (12) \]

where \( I, B, \tau_c, \) and \( P \) denote the average photocurrent, the noise-equivalent electrical bandwidth of the receiver, the coherence time of the source, and the DOP, respectively. Lutz\(^4\) obtained a DOP of \( P=0.03 \) by placing a depolarizer in front of the photodetector. Accordingly, this study assumes that the DOP \( P \) in Eq. (12) is negligible, so that \( \langle i^2 \rangle \approx \langle I^2 \rangle B\tau_c \).

This study adopts the analysis model presented in Ref. 7 and assumes \( G(v) \) to be the single-sideband PSD of the received signal. Therefore, the source coherence time \( \tau_c \) can be expressed as
\[ \tau_c = \frac{1}{\int_0^\infty G^2(v)dv} \left[ \int_0^\infty G(v)dv \right] \]. \quad (13)

Since \( I=\Re \int_0^\infty G(v)dv \), the variances of the upper and lower photocurrents resulting from the PIIN are independent and can be written as
\[ \langle i_{\text{PIIN}}^2 \rangle = \langle I^2 \rangle + \langle I^2 \rangle = B\Re^2 \int_0^\infty G_1^2(v) + G_2^2(v)dv, \quad (14) \]

where \( B \) denotes the noise-equivalent electrical bandwidth of the receiver.

Referring to Eq. (14) of Ref. 4 and Eq. (10) of Ref. 7 and applying the derivation procedure presented in Eqs. (18) to (22) of Ref. 10, the variance of the differential photocurrent resulting from the PIIN can be expressed as
\[ \langle \delta I_{\text{PIIN}}^2 \rangle = \langle I_1^2 \rangle + \langle I_2^2 \rangle \]
\[ = B\Re^2 \int_0^\infty G_1^2(v) + G_2^2(v)dv \]
\[ = \frac{B\Re^2P_{sw}^2}{\Delta \nu} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{m=1}^{K} \left[ b_k b_m S_{k,m} + b_k (1 - b_m) D_{k,m} \right] \]
\[ \times [c_k^{(1)}(i)c_j^{(1)}(i) + c_k^{(2)}(i)c_j^{(2)}(i)] + \frac{B\Re^2P_{sw}^2}{\Delta \nu} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{m=1}^{K} \left[ 1 - b_k b_m D_{k,m} + (1 - b_k)(1 - b_m) S_{k,m} \right] \]
\[ \times [c_k^{(1)}(i)c_j^{(2)}(i) + c_k^{(2)}(i)c_j^{(1)}(i)], \quad (15) \]

where, by definition,
\[ S_{k,m}(i) = c_k^{(1)}(i)c_m^{(1)}(i) + c_k^{(2)}(i)c_m^{(2)}(i), \]
\[ D_{k,m}(i) = c_k^{(2)}(i)c_m^{(1)}(i) + c_k^{(1)}(i)c_m^{(2)}(i). \]

As seen in Eqs. (20) and (21) of Ref. 10, in the previous SPC scheme, \( c_k^{(1)}(i) + c_k^{(2)}(i) \) always yields a sequence of 1’s for different values of the parameter \( i \). However, in this study, \( c_k^{(1)}(i) + c_k^{(2)}(i) \) in Eq. (15) generates different results for different values of \( i \), i.e., \( c_k^{(1)}(1) + c_k^{(2)}(1) \) may be different from \( c_j^{(1)}(2) + c_j^{(2)}(2) \), which in turn may be different from \( c_j^{(1)}(3) + c_j^{(2)}(3) \), etc. Therefore, the present PIIN analysis is more complicated than that in the previous SPC scheme. To analyze the worst case of Eq. (15) (i.e., when the maximal PIIN occurs), it is assumed that all of the simultaneously active users transmit a data bit 1 and that the probabilities of data bit 1 and 0 transmission are equal. Note that these assumptions are consistent with those adopted in Ref. 4.

Under these assumptions, the \( \sum_{i}^{N} [\sum_{k}^{K} S_{k,m}(i)] \) terms of Eq. (15) can be rearranged into the form
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### Table 4 Detailed analysis of PIIN resulting from various cases.

<table>
<thead>
<tr>
<th>Origin of PIIN</th>
<th>Desired user (match, (=c_j))</th>
<th>Other users (nonmatch, (\neq c_j))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Term in Eq. (16)</td>
<td>First ((k=m=j))</td>
<td>Second ((k\neq m \text{ but } k=j \text{ or } m=j))</td>
</tr>
<tr>
<td>Relation of indices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correlation (R_{\omega(k,m)}) for (k)th and (m)th users (single arm)</td>
<td>(N/2)</td>
<td>(N/8)</td>
</tr>
<tr>
<td>No. of terms in (\sum \sum) of Eq. (16)</td>
<td>1</td>
<td>(K-1)</td>
</tr>
<tr>
<td>Ratio of numbers of encoded wavelengths, PD1/PD2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Resulting PIIN (product of thee preceding rows)</td>
<td>(N/2)</td>
<td>(N/(K-1))</td>
</tr>
</tbody>
</table>

In Table 4, the second row shows the order of the terms in Eq. (16). Equation (15) can be divided into the cases of matching (\(=c_j\)) and not matching (\(\neq c_j\)) the desired decoder. Therefore, the matching case of Eq. (15) is indicated by the first term (i.e., \(k=m=j\)) and the second term (i.e., \(k\neq m\), but \(k=j \text{ or } m=j\)) of Eq. (16). Similarly, the nonmatching case of Eq. (15) is indicated by the third term (i.e., \(k=m \neq j\)) and the fourth term (i.e., \(k\neq m \neq j\)) of Eq. (16). In order to derive the maximal PIIN (i.e., the most severe wavelength collision), the first and second terms of Eq. (16) and Eq. (17) are multiplied by a ratio of 1 under the matching case \((=c_j)\), because all the encoded wavelengths impinge on a pair of photodetectors. Similarly, the third and fourth terms of Eq. (16) and Eq. (17) are multiplied by a factor of \(1/2\) because one-quarter of the total encoded wavelengths impinge on the upper photodetector (PD1), while one-quarter of them impinge on the lower photodetector (PD2) under the nonmatching case \((\neq c_j)\). Therefore, the PIIN predicted by Eq. (17) overestimates the interference, and it can be viewed as an upper-bound approximation (i.e., the scenario of maximal PIIN).

#### 4.3 Evaluation of the Signal-to-PIIN Ratio

Dividing Eq. (11) by Eq. (17), the SNR under the assumption of a Gaussian approximation is given by

\[
\text{SNR} = \frac{\langle I_{\text{out}} - I_{\text{out0}} \rangle^2}{\langle I_{\text{PIN}}^2 \rangle} = \frac{16 \Delta \nu}{B(K^2 + 3K + 4)},
\]

where \(\Delta \nu\) is the optical bandwidth and \(K\) is the number of active users.

Table 5 summarizes the SNR results obtained when the PIIN is considered under a DOP set equal to zero for the ideal case. The SNR results of the proposed hybrid SPC-SAC scheme are found to be approximately 6 and 3 dB better than those of the conventional complementary unipolar scheme and the previous SPC scheme, respectively. As expected, the spectral efficiency is twice that of the previous unipolar supercode scheme based on Walsh-Hadamard code.

The Gaussian approximation is also used in the calculation of the BER, i.e.,

\[
\text{BER} = \frac{1}{2} \text{erfc}\left[\sqrt{\frac{\text{SNR}}{8}}\right].
\]

In Fig. 3, for \(\Delta \nu=6.25\) THz, \(B=80\) MHz, and a given error probability of \(10^{-9}\), it can be seen that the number of simultaneous active users is improved by 40% and 100% relative to the previous SPC coding and conventional complementary unipolar schemes, respectively, under a DOP of zero for the ideal case.

In Eq. (12), the degree of polarization, \(P\), is defined by...
The degree of polarization, $P$, varies between 0 and 1. From Eq. (12), and as shown in Fig. 4, it is clear that the BER performance of the proposed SPC-SAC scheme is characterized by an upper bound of $P=1$ for the worst case and a lower bound of $P=0$ for the ideal case. As discussed earlier, Lutz achieved a degree of polarization $P=0.03$ by positioning a depolarizer in front of the photodetector.\cite{14} In Fig. 4, it can be seen that the curve for $P=0.03$ virtually coincides with that of the proposed SPC-SAC scheme for the ideal case ($P=0$). In addition, setting the DOP to 1 (i.e., $P=1$) for the worst case, the BER performance of the proposed scheme is found to be superior to that of the complementary unipolar SAC scheme based on Walsh-Hadamard code. Surprisingly, the performance of the previous SPC

$$P^2 = \frac{(s_1)^2 + (s_2)^2 + (s_3)^2}{(s_0)^2}.$$  (20)

In Eq. (20), $s_0, s_1, s_2,$ and $s_3$ are the Stokes parameters and are expressions of the SOPs. Note that the bracket $\langle \rangle$ denotes the average value of these parameters over wavelength, time, or space. The degree of polarization, $P$, is dependent on the light source and is also known to vary during long-haul network transmission. A higher signal-to-PIIN ratio can be obtained by positioning a depolarizer in front of the photodetector to eliminate its polarization-dependent properties.\cite{14-16} Hence, the average values of $s_1, s_2,$ and $s_3$ in Eq. (20) approach zero, and the degree of polarization (DOP) is reduced (e.g., $P=0.03$). In other words, the depolarizer theoretically eliminates the polarization sensitivity of the photodetector in the proposed SPC scheme.

From Eqs. (12) and (20), it is clear that the individual factors of the DOP can be separated and discussed independently. The first term, $P^2B_\tau$, represents the PIIN of the proposed SPC scheme. The second term, i.e., $P^2f^2B_\tau$, evaluates the effect of the degree of polarization on the PIIN. Having calculated the total PIIN by summing these terms, it is possible to determine the SNR (i.e., the signal power divided by the PIIN power) and subsequently to establish the corresponding BER (BER $= \frac{1}{2} \text{erfc}[(\text{SNR}_{\text{PIN}}/8)^{1/2}]$).

The degree of polarization, $P$, varies between 0 and 1. From Eq. (12), and as shown in Fig. 4, it is clear that the BER performance of the proposed SPC-SAC scheme is characterized by an upper bound of $P=1$ for the worst case and a lower bound of $P=0$ for the ideal case. As discussed earlier, Lutz achieved a degree of polarization $P=0.03$ by positioning a depolarizer in front of the photodetector.\cite{14} In Fig. 4, it can be seen that the curve for $P=0.03$ virtually coincides with that of the proposed SPC-SAC scheme for the ideal case ($P=0$). In addition, setting the DOP to 1 (i.e., $P=1$) for the worst case, the BER performance of the proposed scheme is found to be superior to that of the complementary unipolar SAC scheme based on Walsh-Hadamard code. Surprisingly, the performance of the previous SPC

<table>
<thead>
<tr>
<th>Applied scheme (Walsh-Hadamard)</th>
<th>Constructed matrix</th>
<th>Codeword length</th>
<th>Weight</th>
<th>User capacity</th>
<th>SNR_{PIN}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional unipolar SAC scheme</td>
<td>$N=2^m$, $m&gt;2$</td>
<td>$N$</td>
<td>$N/2$</td>
<td>$N-1$</td>
<td>$N/4$</td>
</tr>
<tr>
<td>Complementary unipolar SAC scheme</td>
<td>$N=2^m$, $m&gt;2$</td>
<td>$N$</td>
<td>$N/2$</td>
<td>$N-1$</td>
<td>$N/4$</td>
</tr>
<tr>
<td>Previous SPC scheme (complementary bipolar scheme)</td>
<td>$N=2^m$, $m&gt;2$</td>
<td>$N$</td>
<td>$N$</td>
<td>$N$</td>
<td>$N/2$</td>
</tr>
<tr>
<td>Hybrid SPC-SAC scheme (complementary bipolar scheme)</td>
<td>$N=2^m$, $m&gt;2$</td>
<td>$N$</td>
<td>$N/2$</td>
<td>$N$</td>
<td>$N/8$</td>
</tr>
</tbody>
</table>
scheme is found to be as good as that of the complementary unipolar SAC scheme on setting the DOP to 1 for the worst case. For a given error probability of $10^{-9}$, the number of simultaneous active users supported by the hybrid SPC-SAC coding scheme for the worst case ($P=1$) is 41.3% higher than that supported by the complementary unipolar SAC coding scheme for the ideal case ($P=0$).

5 Discussion and Conclusions

This study has constructed a hybrid SPC-SAC scheme based on an orthogonal ternary matrix. Compared with the conventional SAC scheme, the use of adaptive compensators for practical realizations are needed for a further development. Especially, a simpler PMD and DGD compensation technique for the proposed hybrid SPCSAC scheme will be worth investigating in the next stage of work.

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