High speed and secure optical CDMA-based passive optical networks

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A B S T R A C T
One bi-directional passive optical network (PON) based on optical code-division multiple access with interference elimination is proposed. By combining with wavelength division multiplexing (WDM) technique, the proposed scheme alleviates the noise arising during photo-detecting process in the PON. Therefore, the bit error rate performance is improved, which is demonstrated by the results of performance analysis. In addition, simple and low cost encoding/decoding structures with small sizes in the optical line terminal are proposed, and they can cooperate with the dynamic codeword assignment scheme to provide a more secure signal transmission in the PONs.

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1. Introduction

Code-division multiple access techniques was investigated for optical network applications during the last 20–25 years. These techniques have advantages that many users are allowed to access the common channel asynchronously and securely, and high statistical multiplexing gain can be offered even in bursty traffic since dedicated time or wavelength slots do not have to be allocated [1]. These characteristics distinguish optical code-division multiple access (OCDMA) from other multiplexing schemes such as time division multiple access (TDMA) and wavelength division multiple access (WDM).

Due to the bursty nature of the traffic, OCDMA techniques are very suitable for access networks and possibly metropolitan area networks (MANs), and there are a number of literatures concerned this topic [2–5]. Among various optical code-division multiple access (OCDMA) techniques, the spectral-amplitude-coding (SAC) is very promising due to the excellent ability for multiple access interference (MAI) elimination and potential low cost [6].

In the SAC-based passive optical network (PON), the beat noise is an important factor since it affects the bit error rate greatly [4]. To reduce the beat noise in the spatial/spectral OCDMA PONs, the spatial division multiplexing technique is used in [4]. In the PON where spatial coding is not used, wavelength division multiplexing (WDM) technique can be combined with the SAC scheme to amend this noise-induced performance degradation and the resulting scheme is called WDM/SAC scheme [7]. In addition, the ability against eavesdropping is also an important merit for the proposed scheme. In [8] it is pointed that the two-code keying schemes are more secure than the on–off keying ones. Though the SAC scheme proposed in [3] using shifted prime (SP) codes is also two code-keying scheme, it has an additional advantage to improve the ability against eavesdropping which is not mention in the original paper.

In this paper, one novel SAC-based PON is proposed. By employing shifted prime (SP) codes in [3] with WDM technique, the resulting codes named WS–SP codes are constructed and the structure of the associated coding devices are simpler for the cost reduction in OLT and ONUs. In addition, to improve the ability against eavesdropping, the two codewords used for two-code keying by each...
ONU are re-assigned at each epoch of codeword assignment (That is, the codeword assigned to each user is changed with a period \( T_0 \) and remains unchanged during each period.) In the previous SAC scheme employing two-code keying, the two codewords of each ONU (or user) are always complement to each other and eavesdroppers just need to guess one of the two codewords of one ONU to obtain the data. Due to the characteristic of SP codes, each SP codeword can be paired with any codeword in the same code subgroup for two-code keying by each ONU. Therefore, both two codewords of one ONU should be correct for the success of eavesdropping and this shows the proposed PON has improved degree of security.

The rest of this paper is organized as follows: Section 2 is devoted to the proposed network architecture and WS-SP codes. In Section 3, the performance of the proposed scheme is evaluated in terms of noises and splitting losses, and finally, the conclusion is given in Section 4.

2. Network architecture and WS-SP codes

In the tradition bi-directional WDM-PON, there may be one AWG used to connect the OLT and the ONUs, as the LARNET architecture in [13]. For the proposed SAC-based PON, the network architecture is almost the same, and, according to the wavelength bands used for coding, the ONUs can be divided into \( N \) ONU groups and they are indexed as ONU group \( \#n(n=0,1,...,N-1) \). However, due to the code property, the SAC codewords used in each ONU group can be divided into \( p+1 \) codeword groups (\( p \) is a prime and \( p^2 \) is equal to the SAC codeword length) and any two codewords in each codeword group can be assigned to the same ONU. Here the maximum number of ONUs using the codewords in each codeword group is denoted \( M \), and, therefore, there are \( (p+1)M \) ONUs in each ONU group and they are connected to one \( 1 \times (p+1)M \) coupler. The OLT in the central office is connected to these \( 1 \times (p+1)M \) coupler via one \( 1 \times N \) AWG. At each epoch of codeword assignment, each ONU is assigned two SAC codewords (for both downstream and upstream transmission) and the information bits transmitted between the OLT and one specific ONU are encoded optically with the codewords of this ONU. That is, if the information bit is "1" (or "0"), then the 1st (or 0th) codeword is transmitted instead. The codeword assignment at each epoch may be different, and can be announced by protocols of higher level than the physical layer. This enhances the security of the transmission in the OCDMA-based PONs.

Due to the codeword property, several encoders and decoders in the OLT can share the optical components partially and they are grouped (e.g. the group codec in Fig. 1) for the compactness of the coder implementation. To distribute the encoded signals in each wavelength band to proper ONUs from the OLT, the AWG demultiplexes the signals in each wavelength band and transmits them to the \( 1 \times (p+1)M \) coupler in each ONU group. Then, each \( 1 \times (p+1)M \) coupler broadcasts the received signals to each ONU belonging to the same ONU group and the decoder in each ONU obtains the information bits via decoding process.

The SP code \( X_{ef} \)’s with length \( L = p^2 \) used in this paper can be obtained from one modified stuffed shifted prime (MSSP) code with the same parameter \( p \) in [12] by eliminating the extra codeword and the last \( p+1 \) chips of each remaining MSSP codewords. For example, Table 1 shows the SP codewords for \( p = 3 \), and, from [12], the cross-correlation between \( X_{ef} \) and \( X_{ef'} \) is

\[
X_{ef} \oplus X_{ef'} = \begin{cases} 
  p, & e = e', f = f', \\
  0, & e = e', f \neq f', \\
  1, & e \neq e'.
\end{cases}
\]

![Fig. 1. The architecture of passive optical network.](image-url)
Table 1
The SP codewords for \( p = 3 \).

<table>
<thead>
<tr>
<th>( e )</th>
<th>( f )</th>
<th>( \mathbf{C}_f )</th>
<th>( \mathbf{X}_{ef} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>2</td>
<td>010</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>010</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>001</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0</td>
<td>001</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>010</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>001</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>111</td>
<td>000</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>111</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0</td>
<td>000</td>
</tr>
</tbody>
</table>

and thus

\[
\mathbf{X}_{ef} \circ \mathbf{X}_{e'f'} - \mathbf{X}_{ef_1} \circ \mathbf{X}_{e'f'} = \begin{cases} p, & e = e', f_1 = f', \\ -p, & e = e', f_2 = f', \\ 0, & \text{otherwise.} \end{cases}
\]

Table 2
The WS–SP codes for \( L = 9 \) and \( N = 2 \).

<table>
<thead>
<tr>
<th>Group # 0</th>
<th>( \mathbf{Y}_{1,1} )</th>
<th>( \mathbf{Y}_{1,0} )</th>
<th>( \mathbf{Y}_{0,1} )</th>
<th>( \mathbf{Y}_{0,0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathbf{Y}_{1,1} )</td>
<td>100100100</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{1,0} )</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{0,1} )</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{0,0} )</td>
<td>010001100</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{2,1} )</td>
<td>010000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{2,0} )</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{1,1} )</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{1,0} )</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{0,1} )</td>
<td>010001100</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{0,0} )</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{2,1} )</td>
<td>111000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{2,0} )</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{1,1} )</td>
<td>000000000</td>
<td>000000000</td>
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<td>000000000</td>
</tr>
<tr>
<td>( \mathbf{Y}_{1,0} )</td>
<td>000000000</td>
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</tr>
<tr>
<td>( \mathbf{Y}_{0,1} )</td>
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</tr>
<tr>
<td>( \mathbf{Y}_{0,0} )</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
<td>000000000</td>
</tr>
</tbody>
</table>

where \( \circ \) is the dot-product of two vectors. Since the ONUs can use the code property in Eq. (2) for MAI elimination, any two distinct SP codewords with the same value of \( e \) can be assigned to one specific ONU for two-code keying of information bits. However, the two codewords used for decoding in conventional SAC schemes are always complement to each other. Therefore, this coding scheme has the advantage of security enhancement in the SAC-based optical networks since the eavesdroppers need to guess two codewords used for decoding.

We denote \( S_{r,m}^{(0)} \) and \( S_{r,m}^{(1)} \) as the 0th and 1st SP codewords for the two-code keying of one ONU. That is, if the information bit transmitted to/from this ONU is “1” (or “0”), then \( S_{r,m}^{(1)} \) (or \( S_{r,m}^{(0)} \)) is transmitted instead of the encoded signal. Since the maximum number of codeword pairs is \( (p - 1)/2 \) for a fixed value of \( e \), the value of \( M \) is \( (p - 1)/2 \) and the Eq. (2) can be rewritten as follows:
(1) $S_{e,m} \circ (d) S_{e,m}^r = -S_{e,m} \circ (d) S_{e,m} $
\[
p. \quad e = e', \quad m = m', \quad d = 1, \\
p. \quad e = e', \quad m = m', \quad d = 0, \\
0. \quad \text{otherwise}.
\] (3)

By implementing Eq. (3) and setting the threshold to 0 in the decoders of the ONUs, MAI is eliminated and the original transmitted information bits are recovered theoretically at the outputs of the decoders. The decoding procedure is the same for the upstream transmission from ONUs to the OLT, except that the upstream codewords are used instead of downstream ones.

The SAC scheme mentioned above is a "pure" SAC scheme using SP codes. To alleviate the effect of noises, this SAC scheme can adopt WDM/SAC(WS) technique in [7], scheme using SP codes. To alleviate the effect of noises, this SAC scheme can adopt WDM/SAC(WS) technique in [7], and the resulting codes are called WS–SP codes below. Furthermore, to prevent the interference between the signals in upstream and downstream directions, the coding process for either direction should take place in separate wavelength bands. Thus the following procedure can be used to generate the upstream and downstream code-words. Let $E_{0i} = \{e_{00}, e_{01}, \ldots, e_{0,n-1}\}$ be a vector whose $n$th element is one and others are zero. The 0th and 1st WS–SP codewords of the ONU #($n$, $e$, $m$) for upstream transmission can be obtained [7]

\[
\begin{align*}
(0)^{(0)} Y_{n,e,m}^U &= S_{e,m} \oplus E_n \oplus [0,1], \\
(1)^{(0)} Y_{n,e,m}^U &= S_{e,m} \oplus E_n \oplus [1,0],
\end{align*}
\]
\[
\begin{align*}
(0)^{(1)} Y_{n,e,m}^U &= S_{e,m} \oplus E_n \oplus [0,1], \\
(1)^{(1)} Y_{n,e,m}^U &= S_{e,m} \oplus E_n \oplus [1,0],
\end{align*}
\]

respectively, where $\oplus$ is Kronecker product [7]. That is, the encoding of $(0)^{(d)} Y_{n,e,m}^U$ is equivalent to the encoding of $(0)^{(d)} S_{e,m}$ at the $n$th upstream encoded subband. The 0th and 1st WS–SP codewords for downstream transmission are

\[
\begin{align*}
(0)^{(0)} Y_{n,e,m}^D &= S_{e,m} \oplus E_n \oplus [1,0], \\
(1)^{(0)} Y_{n,e,m}^D &= S_{e,m} \oplus E_n \oplus [0,1],
\end{align*}
\]
\[
\begin{align*}
(0)^{(1)} Y_{n,e,m}^D &= S_{e,m} \oplus E_n \oplus [0,1], \\
(1)^{(1)} Y_{n,e,m}^D &= S_{e,m} \oplus E_n \oplus [1,0],
\end{align*}
\]

respectively. That is, the encoding of $(0)^{(d)} Y_{n,e,m}^D$ is equivalent to the encoding of $(0)^{(d)} S_{e,m}$ at the $n$th downstream encoded subband. Thus when both the downstream and upstream encoded bands are considered, the total code length of WS–SP code is $2N$, which is more flexible than that of the original SP code. From Eqs. (6) and (7), the following property can be obtained:

\[
(1)^{(0)} Y_{n,e,m}^D \circ (d) Y_{n',e',m'}^U - (0)^{(0)} Y_{n,e,m}^D \circ (d) Y_{n',e',m'}^U
\]
\[
\begin{align*}
\begin{cases}
p. \quad n = n', \quad e = e', \quad m = m', \quad d = 1, \\
p. \quad n = n', \quad e = e', \quad m = m', \quad d = 0, \\
0. \quad \text{otherwise}.
\end{cases}
\]
(8)

Then the decoder of the ONU #($n$, $e$, $m$) can compute Eq. (8) for interference elimination and information bit extraction in case of downstream transmission. The decoding procedure is the same for the upstream transmission from ONUs to the OLT, except that the upstream codewords are used instead of downstream ones. In addition, since the encoded wavelength bands of upstream and downstream WS–SP codes for the ONUs in the same groups are separated, the interference between the transmitted signals in these two directions can be alleviated.

Table 2 shows the upstream and downstream WS–SP codes generated from SP codewords in Table 1 for $N = 2$ (with $(0)^{(0)} S_{e,m} = X_{e,2m}$ and $(1)^{(0)} S_{e,m} = X_{e,2m+1}$. At this epoch of codeword assignment.) Note that this is just one case out of the totally $\Phi c = p(p-1)(p+1)$ possible codeword assignments of one ONU, and the period of codeword assignment $T_c$ can be increased as long as the value of $\Phi c$ or $p$ is increased. The exact value of $T_c$, needed by the networks also depends on the required degree of security and the techniques of eavesdropping nowadays [8].

For the proposed SAC coding scheme using WS–SP codewords in Table 2, the corresponding center wavelength of the $i$th chip for one WS–SP codeword is denoted as $\lambda_i$, and the value of each chip in each codeword determines if the amplitude of the corresponding wavelength is nonzero or not. It can be found that each codeword (no matter downstream or upstream) can be divided into $4(=2N)$ segments equally and each segment acts like the total coded spectra in conventional SAC schemes. These segments can be treated as coarse wavelengths with line-widths $L$ times wider than that of each individual wavelength chip. Therefore, the upstream (or downstream) WS–SP codewords use the first (or the last) $N$ coarse wavelengths. This is similar to the conventional bi-directional WDM networks such as that in [11]. However, the wavelength assignments for upstream and downstream transmissions are interleaved in [11].

3. The codec in the OLT and ONUs

The group codec #$e$ using WS–SP code for $p = 3$ and $e = 0$ in Table 2 is shown in Fig. 2, and it contains one group encoder, one group decoder, one information distrib...
bution unit (IDU) and one information processing unit (IPU). Suppose that each wavelength chip has spectral width \(\Delta k(\Delta \lambda = -k - k_1)\) and the center wavelength of the first wavelength chip is \(k_0\), the spectrum width of broadband light source (e.g. super luminescent diode (SLD) ) should be \(L\Delta k\) with center wavelength \(k_0 + (L - 1)\Delta k/2\). In the following the specification of the optical filters for the encoding part of the codec is described. As for the decoding part of the codec, the center wavelengths of the optical filters should be decreased \(\Delta k_2(\Delta \lambda_2 = -N\Delta \lambda_1)\) for the segregation of upstream and downstream transmission. Two kinds of optical filters are used in the codec: One is \(1 \times L\) (fine) AWG with free spectral range \(\text{FSR} = \Delta \lambda_1\) and channel bandwidth \(\Delta \lambda_2\) [9], and the center wavelengths of the first output port at the AWG are \(k_0 \pm \text{a FSR} (a\text{ is an integer}). The other is conventional \(1 \times N\) demultiplexer (demux) with channel bandwidth \(\Delta \lambda_2\), and the center wavelength of the first output port at the demultiplexer is \(k_0 + (N - 1)\Delta k/2\). Both the encoder and decoder have one AWG and \(N\) demultiplexers and each AWG is connected to \(N\) demultiplexers according to the SP codewords \(X_{ij}\). If the \(j\)th chip of \(X_{ij}\) is 1, then the \(j\)th output port of AWG should be connected to the \(j\)th demultiplexer. For example, when \(X_{00} = \{00101001\}\), the output ports \#0, \#3 and \#6 are connected to the 0th demultiplexer. Note that due to the characteristics of SP codes, each AWG output port is not connected to more than one demultiplexer. Thus the power imbalance problem does not occur for each SP codeword, and the power adjustment of encoded signals is not needed, which may induce additional power loss.

Due to the periodic characteristic of AWG, \(k_0, k_1, k_2, \ldots, k_{L-1}\) and \(k_{L+n}(n = 0, 1, \ldots, N - 1)\) appear at the input port of the 0th demultiplexer, and \(k_{L+n}, k_{L+n+1}\), and \(k_{L+n+n}\) (for one specific value of \(n\)) are obtained at the \(n\)th output port of the 0th demultiplexer, which are corresponding to \(X_{00}\) at the \(n\)th downstream encoded subband. The case for the output ports of the other demultiplexers can be deducted similarly.

In the upper part of the codec (used for encoding procedure), the light from the light source is demultiplexed by the \(1 \times L\) AWG cascaded by \(N\) demultiplexers. Each output port of these demultiplexers are connected to one \(1 \times 1\) optical switch (OSW) and the OSW connected to the \(n\)th output port of the \(j\)th demultiplexer is indexed OSW \(\#(n, f, j, m)\). The output port \(\#(n, f, j, m)\) of the IDU is connected to the control input of AWG \(\#(f, j, m, n)\) and thus the signal \(A_{N,n}\) at the output port \(\#(f, j, m, n)\) of the IDU can be used to control if the wavelength chips arriving at each OSW can be transmitted or not from the encoder. If the codewords \(X_{00,f,1}\) and \(X_{00,f,2}\) at the \(n\)th downstream subband are the 1st and 0th codewords for ONU \#(\(n, f, 0\), \(m\)) (that is, \(X_{00,f,1}\) or \(X_{00,f,2}\) is used to encode the information bit \(d_{00,m}\) when \(d_{00,m} = 1\) (or 0)), then the 0th and 1st WS–SP codewords for downstream transmission can be obtained from Eqs. (6) and (7):

\[
(0)_Y^{(D)} = X_{00,f,1} \otimes E_0 \otimes \{0, 1\},
\]

\[
(0)_Y^{(D)} = X_{00,f,2} \otimes E_0 \otimes \{0, 1\},
\]

respectively. The rule for the values of the signal at the output ports \(\#(f, N + n)\) and \(\#(f, N + n)\) of the IDU are \(A_{N,n} = 1 - d_{00,m}\) and \(A_{N,n} = d_{00,m}\). Since \(2M (= p - 1)\) SP codewords in one code subgroup are used by ONUs at one time, there is only one SP codeword in each code subgroup unused. Thus the IDU output port corresponding to the OSW of this codeword is set to 0 (to prevent the transmission of this codeword.) Since the code \#\(e_0\) is used to generate the codewords of the SP codeword with the same value of \(e\) for all \(N\) downstream encoded subbands, \(N\) IDU output ports are always set to 0 during this epoch of codeword assignment.

Continuing our example in Fig. 2 (\(N = 2\)), suppose that at this epoch of codeword assignment the assignment rule is \(f_1 = 2m\) and \(f_2 = 2m + 1\) for all \(n\). That is, ONU \#(\(n, 0, e_0 = 0\), \(m\)) uses \(Y^{(D)} = X_{00,2m} \otimes E_0 \otimes \{0, 1\}\) and \(Y^{(D)} = X_{00,2m+1} \otimes E_0 \otimes \{0, 1\}\) as the 0th and 1st codewords, respectively. For ONU \#(\(1, 0, m = 0\)) (e.g. \(f_1 = 2m = 0\) and \(f_2 = 2m + 1 = 1\)), \(d_{10,0}\) and \(d_{11,0}\) appear at the output port \#1 and \#(\(N + 1\)) of the IDU, respectively. Therefore, when \(d_{10,0}\) is 1, the control inputs of the OSW \#(\(0, n = 1\)) and OSW \#(\(1, n = 1\)) are \(A_{N,1} = A_{N,1} = 0\) and \(A_{N,1} = A_{N,1} = 0\), respectively, and \(Y^{(D)} = X_{00,2m+1} \otimes E_0 \otimes \{0, 1\}\) is transmitted by the codec. Conversely, when \(d_{11,0}\) is 0, the control inputs of the OSW \#(\(0, n = 1\)) and OSW \#(\(1, n = 1\)) are 0 and 1, respectively, and \(Y^{(D)} = X_{00,2m} \otimes E_0 \otimes \{0, 1\}\) is transmitted by the codec. Note that at this epoch of codeword assignment, the value at the output port \#(\(2N + 1\)) of the IDU is always zero since \(X_{00}\) is not assigned to any ONU at the 0th downstream encoded subband. However, this situation may change at the next epoch of codeword assignment.

In the lower part of the codec (used for decoding procedure), the signals from the ONUs are demultiplexed by one AWG cascaded with \(N\) demultiplexers. The connections between the output ports of the AWG and the demultiplexers are the same as that in the upper part of the codec. Each output port of these demultiplexers are connected to one photo-diode (PD) and the PD connected to the \(n\)th output port of the \(j\)th demultiplexer are indexed PD \#(\(f, n\)). The output port \#(\(f, N + n\)) of the information processing unit (IPU) is connected to the output port of PD \#(\(f, n\)) and thus the signal \(B_{N,n}\) at the output port \#(\(f, N + n\)) of the IPU can be used to accomplish the MAI elimination scheme in Eq. (8).

Continuing our example mentioned above, suppose that at this epoch of codeword assignment ONU \#(\(n, 0, e_0 = 1\), \(m = 0\)) uses \(Y^{(D)} = X_{00,2m} \otimes E_0 \otimes \{0, 1\}\) and \(Y^{(D)} = X_{00,2m+1} \otimes E_0 \otimes \{0, 1\}\) (e.g. \(f_1 = 2m\) and \(f_2 = 2m + 1\)) as the 0th and 1st codewords for upstream transmission, respectively. For ONU \#(\(1, 0, m = 0\)) (e.g. \(f_1 = 0\) and \(f_2 = 1\)), the IPU needs to collect \(B_1(= Y^{(D)} \otimes S^{(C)})\) and \(B_{N,1}(= Y^{(D)} \otimes S^{(C)})\) from its output port \#1 and \#(\(N + 1\)) and compute \(B_1 - B_{N,1}\) to accomplish the MAI elimination scheme in Eq. (8). Here \(S^{(C)}\) is the summation signal from all ONUs.

The tunable codec of ONU \#(\(n, e, m\)) using WS–SP code for \(L = 9\) is shown in Fig. 3, which is modified from the encoder and decoder based on fiber Bragg grating (FBG) in [7]. In the upper part of the codec (used for encoding procedure), two FBG encoders consisting of \(p\) FBGs with channel bandwidths \(\Delta \lambda\) and permanent center wavelengths \(\{\lambda_{n,1}, \lambda_{n,2}, \ldots, \lambda_{n,p-1}\}\) (which are independent to the values of \(e\) and \(m\)) are used to produce the codewords.
For the case of upper FBG encoder and wavelengths \( \lambda_{0} \), the wavelengths from the light source enter the upper FBG encoder for \( \lambda_{0} \). \( \lambda_{0} \) is tunable and this can be realized by the lower FBG encoder, wavelengths \( \lambda_{1}, \lambda_{2}, \lambda_{3} \) are reflected by the FBGs in the lower FBG decoder. For the wavelengths passing lower FBG decoder and entering the upper FBG encoder, the wavelengths \( \lambda_{1}, \lambda_{2}, \lambda_{3} \) are reflected by the FBGs in the upper FBG decoder if there are any wavelengths belonging to these three wavelengths. These reflected signals represent the result of \( Y_{0}^{(2)} \) and \( Y_{0}^{(0)} \) and appear at the input port of the upper photo-diode in the decoder. Therefore, the result of \( Y_{0}^{(2)} \) and \( Y_{0}^{(0)} \) is obtained at the output port of the balanced detector.

The \( 1 \times N \) coarse AWG connected between the OLT and the \( 1 \times (p+1)M \) couplers in Fig. 1 has channel bandwidth \( L_{a} \lambda \) and FSR \( N_{a}L_{a} \). The center wavelength of the first AWG output port is \( \lambda_{0} + (L - 1)/2 \lambda \). Due to the periodic characteristic of AWG, both the downstream and upstream signals between the OLT and one specific ONUs can use this AWG simultaneously and use the same fiber for transmission, which is different from the SAC-based PON in [4].

### 4. Performance analysis

In the following analysis, phase-induced intensity noise (PIIN) [10] and thermal noise are taken into account, and only the downstream signal transmission in the PON is considered in the following. Assume each unpolarized light source has flat power spectral density (PSD) over the optical source bandwidth \( \Delta \lambda \) with magnitude \( P_{0}/\Delta \lambda \), where \( P_{0} \) is the effective transmitted power from the light source at one group codec in the OLT without the consideration of splitting loss induced by the coupler of each ONU group in Fig. 1. Note that the value of \( P_{0} \) here has taken various losses such as the insertion losses of optical components into account for simplicity. When bit synchronization is achieved, the PSD of the signal at the input of the ONU decoder is [10, 4]

\[
S(v) = \frac{P_{0}/(p+1)M}{\Delta \lambda} \times \sum_{k=0}^{N-1} \sum_{i=0}^{N-1} (1 - d_{k}) \sum_{i=0}^{N-1} \frac{y_{k}(i)\Pi(i)}{1 - d_{k}}.
\]
where \( \Pi(i) = u[v - v_0 - \frac{A_N}{2N}(-N + 2i)] - u[v - v_0 - \frac{A_N}{2N}(-N + 2i + 2)] \)

\( u(v) \): the unit step function.
\( K \): the number of active ONUs.
\( d_i \): the information bit of the \( i \)th active ONU.
\((d_i)y_0(i)\): the \( i \)th chip of the \( d_i \)th codeword for the \( K \)th active ONU.

Note that the term \( p_{tr}/((p + 1)M) \) in Eq. (11) represents the consideration of splitting loss induced by the \( 1 \times (p + 1)M \) coupler in each ONU group. If the splitting loss is not considered, the term \( p_{tr}/((p + 1)M) \) should be replaced by \( p_{tr} \) in Eq. (11) (and thus Eqs. (12) and (14) in the following) in order to evaluate the corresponding performances. By the use of the results in [10,3], the variance of PIIN at the balanced detector output is

\[
\langle \eta_p^2 \rangle = BR^2 \left[ \int_0^\infty G_0^2(v) dv + \int_0^\infty G^2(v) dv \right]
\]

\[ = BR^2 \left( \frac{p_{tr}/((p + 1)M)^2}{\Delta v} \right) \times \left[ p + 2 \left( K'_{\text{eff}} - \left[ \frac{K'_{\text{eff}}}{p} \right] \right) \right] \left( 2 + \frac{1}{p} \left( K'_{\text{eff}} - \left[ \frac{K'_{\text{eff}}}{p} \right] - 1 \right) \right) \quad (12)
\]

respectively, where \( \left\lfloor \cdot \right\rfloor \) is the floor function, \( R \) is the responsivity of the photo-diodes, and \( B \) is noise-equivalent electrical bandwidth of the decoder. The effective number of interfering active ONUs is [7]

\[ K'_{\text{eff}} = \left[ \frac{K - 1}{N} \right]. \quad (13) \]

The signal power for the balanced detector in the codec of the ONU is

\[ I^2 = \left( \frac{RP_{tr}/((p + 1)M)^2}{pN} \right)^2. \quad (14) \]

Finally the SNR of the balanced detector can be obtained:

\[ \text{SNR} = \frac{I^2}{\langle \eta_p^2 \rangle} = \left( \frac{\langle \eta_p^2 \rangle}{\langle \eta_p^2 \rangle} \right) \quad (15) \]

where \( \langle \eta_p^2 \rangle \) is the variance of thermal noise and can represent in term of the two-sided thermal noise PSD:

\[ \langle \eta_p^2 \rangle = 2ST(f)B. \quad (16) \]

Therefore, the SNR for the scheme adopting WS–SP codes can be obtained. Since two-code keying is adopted for information transmission when SP and WS–SP codes are used, the bit error rate (BER) can be obtained by BER = \( \text{erfc}(\sqrt{\text{SNR}/2})/2 \). The parameters used here are \( B = 625 \text{ MHz} \) (for bit rate \( R_0 = 1.25 \text{ Gbps} \)), \( S_T(f) = 8 \times 10^{-22} \text{ A}^2/\text{Hz}. \text{R} = 0.8 \text{ A}/\text{W}. \Delta v = 7.5 \text{ THz}, \) and \( v_0 = 193.1 \text{ THz} \). Note that forward error correction is not used in this paper for performance improvement.

When the splitting loss is not considered, the relationship between BER and the number of active ONUs \( K \) can be found in Fig. 4, where the effective transmitted power \( P_{tr} \) is set to 0dBm and the code-length of downstream part \( LN \) is fixed at about 289. It can be found that WS–SP codes obtain lower BER as compared to SP codes. When the number of active ONUs is relatively small, WS–SP codes with different values of \( L \) and \( N \) obtain similar BERs. However, as the number of active ONUs increases, WS–SP codes with larger \( N \) obtain better performance.

Fig. 4. BER v.s. \( K \) when the splitting loss is not considered.
By taking splitting losses into account, the relationship between BER and the number of active ONUs $K$ is obtained in Fig. 5, where other parameters are the same as that in Fig. 4. After comparing Fig. 5 with Fig. 4, it is found that splitting loss only affects the BER seriously when $L$ is large and $K$ is small. This is because when $K$ is small, the effect of PIIN on BERs is enhanced as compared to the case of small $K$. Though it seems that SP codes with $L = 121$ and 169 do not suffer splitting loss too much, they can't support PONs with total number of ONUs greater than 200. However, WS–SP codes can support large number of ONUs and obtain BER improvement under the effect of splitting loss.

Fig. 5. BER v.s. $K$ when the splitting loss is considered.

Fig. 6. BER v.s. $P_t$ for $K = 80$ when the splitting loss is not considered.
When the splitting loss is not considered, the relationship between BER and $P_r$ is shown in Fig. 6, where the number of ONUs is set to 80. Here the BERs of Hadamard code, BIBD code and the codes compared in Fig. 6 are shown for comparison. When $P_tr$ is smaller, the influence of PIIN is less and the BER for each code increases with $P_tr$. This increase gradually disappears because of the domination of PIIN. Though SP codes obtain better BERs than that of Hadamard and BIBD codes when the codelengths are similar, WS–SP codes shows a great BER improvement over SP codes when $P_tr$ is relatively large, and at this time WS–SP codes with larger $N$ obtain better performances.

If splitting losses are considered, then the relationships between BER and $P_r$ for SP and WS–SP codes become the situation in Fig. 7. When $P_r$ is relatively large, both the results in Figs. 6 and 7 are similar. However, when $P_r$ is relatively small, the result in Fig. 7 may be opposite to that in Fig. 6, which is due to the effect of splitting losses. For example, SP codes with larger $L$ obtain worse BERs for low $P_tr$ in Fig. 7, and the WS–SP codes with larger $N$ still obtain lower BERs for low $P_tr$ in Fig. 7. These two observations are both different from that in Fig. 6, and thus the BERs for WS–SP codes are always lower than that of SP codes in Fig. 7. Therefore, it can be concluded that splitting loss reductions are important for relatively lower $P_r$, and WS–SP codes obtain better performances than other “pure” SAC codes even when the advantage of splitting loss reductions is disregarded.

5. Conclusion

One novel code family for OCDMA-based PONs is proposed. This code family has an additional ability against eavesdropping and the corresponding coder implementation is simple. In addition, the corresponding BER performance is improved as compared to other “pure” SAC codes since the proposed codes produce less noise in the photo-diodes of the decoders. Therefore, the proposed scheme is a solution for PONs with enhanced security and improved performance.

References


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