Abstract

In this paper, improved code-shift keying (CSK) systems with a functional pseudonoise (PN) code are considered for use in indoor optical-wireless channels. In CSK, increasing the number of optical PN codes improves the data rate. It is also effective for increasing the number of simultaneously transmitting optical PN codes. This method is named N-parallel CSK (N-CSK), which indicates the transmission of $N$ codes. In order to enhance the data rate of CSK systems, optical PN code design has become one of the key areas of study. As such functional codes, in this paper we consider EPOM and POEPC, which can be generated by fusing two kinds of optical PN codes. CSK systems can implement two-stage demodulation, which demodulates every optical PN code. It is expected that two-stage demodulation will improve the bit error rate (BER) performance of CSK systems. In this paper, we combine two-stage demodulation with CSK systems: CSK using EPOM and N-CSK using POEPC. It was found that the BER of CSK systems can be improved by utilizing two-stage demodulation.

1. Introduction

As well as the growth of indoor wireless communications, optical-wireless communications (OWC) have been studied for various applications. Since OWC have higher information capacity than conventional radio communications, they are expected to be used as state-of-the-art technologies. The modulation scheme is a key factor in realizing higher-performance OWC systems. Many researchers have studied modulation schemes such as OOK (on-off-keying), PPM (pulse position modulation), MPPM (multipulse PPM), VPPM (variable PPM), DCSK (digital color-shift keying), and CSK (code-shift keying). In particular, CSK is attracting considerable interest because of its potential for system extensibility and high-information transmission efficiency [1]-[3].

CSK systems transmit information by selecting one or $N$ codes from multiple optical pseudonoise (PN) codes. Thus, the performance of CSK depends on the optical PN code design. As conventional optical PN codes for CSK, the optical orthogonal code (OOC) [4], the modified prime sequence code (MPSC) [5], and the generalized MPSC (GMPSC) [6] have been proposed. We proposed the pseudo-orthogonal extended prime code set (POEPC) [7], [8] and the extended pseudo-orthogonal M-sequence (EPOM) [9]. Note that POEPC and EPOM are generated by combining two kinds of optical PN codes. POEPC, which is an orthogonal sequence code, consists of GMPSC and a bi-orthogonal code. EPOM, which is a non-orthogonal sequence code, consists of modified pseudo-orthogonal M-sequence sets (MPOMs) [10] and a bi-orthogonal code.

There are two methods to enhance the data rate of CSK: (a) increasing the number of optical PN codes that the transmitter can generate and (b) increasing the number of transmission optical PN codes that the transmitter uses simultaneously, named N-parallel CSK (N-CSK). In method (a), when we denote the optical code length and the number of codes as $L$ and $M$, respectively, an optical PN code with a large $M/L$ can enhance the performance of CSK. MPSC and GMPSC achieve $M/L = 1/\sqrt{L}$, and POEPC achieves $M/L = 1$. For the optical orthogonal code, the maximum $M/L$ becomes 1. Moreover, $M/L$ can be larger than 1 when including non-orthogonal codes. For example, EPOM achieves $M/L = L/4$. Hence, EPOM can enhance the performance of CSK using method (a) when $L > 4$. On the other hand, since the number of coinciding marks between any two orthogonal codes is zero, an orthogonal code is desirable for method (b). Therefore, optical PN codes having orthogonality, such as GMPSC and POEPC, are effective for N-CSK.

In this paper, we consider improved CSK systems with a functional optical PN code in an indoor optical-wireless channel. In particular, we focus on CSK using EPOM and N-CSK using POEPC. Moreover, we combine these CSK systems with a two-stage demodulation method in order to enhance the bit error rate (BER) performance of the CSK systems in the presence of background noise and scintillation. We investigate the effect of two-stage demodulation on CSK using EPOM and N-CSK using POEPC.
2. System Overview

Table 1 shows the notation for the following discussion.

<table>
<thead>
<tr>
<th>m</th>
<th>Number of marks in a code</th>
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<tbody>
<tr>
<td>L</td>
<td>Transmission code length as optical signal</td>
</tr>
<tr>
<td>M</td>
<td>Number of available codes</td>
</tr>
<tr>
<td>N</td>
<td>Number of simultaneous transmission codes</td>
</tr>
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</table>

2.1 Structure of POEPC

POEPC consists of GMPSC and a bi-orthogonal code.

GMPSC has m groups and each group includes m \{0,1\}-valued codes with code length m^2(=L/2). In POEPC, one group of GMPSC, denoted G_n (1 ≤ n ≤ m), is used. G_n is written as follows:

\[ G_n = \begin{bmatrix} g_{n,1} \\ g_{n,2} \\ \vdots \\ g_{n,m} \end{bmatrix} = \begin{bmatrix} g_{n,11} & g_{n,12} & \cdots & g_{n,1m^2} \\ g_{n,21} & g_{n,22} & \cdots & g_{n,2m^2} \\ \vdots & \vdots & \ddots & \vdots \\ g_{n,m1} & g_{n,m2} & \cdots & g_{n,m^2m^2} \end{bmatrix} \]  

(1)

The generation method of G_n is described in [6] in detail. For example, when m=4 and n=2, G_2 is written as:

\[ G_2 = \begin{bmatrix} g_{2.1} \\ g_{2.2} \\ g_{2.3} \\ g_{2.4} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \]  

(2)

Since any group of GMPSC has the same characteristics [8], the group of GMPSC can be chosen arbitrarily.

The bi-orthogonal code is based on the \{-1,+1\}-valued m×m Hadamard matrix \(H_m\) and the negative version of \(H_m\), denoted \(-H_m\). \(H_m\) can be written as:

\[ H_m = \begin{bmatrix} H_m & H_m \\ H_m & -H_m \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1m} \\ h_{21} & h_{22} & \cdots & h_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ h_{m1} & h_{m2} & \cdots & h_{mm} \end{bmatrix} \]  

(3)

The bi-orthogonal code \(B_m\) is expressed as:

\[ B_m = \begin{bmatrix} H_m \\ -H_m \end{bmatrix} \]  

(4)

For example, when m = 4, \(B_4\) is expressed as:

\[ B_4 = \begin{bmatrix} B_{4,1} \\ B_{4,2} \\ B_{4,3} \\ B_{4,4} \\ B_{4,5} \\ B_{4,6} \\ B_{4,7} \\ B_{4,8} \end{bmatrix} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \\ -1 & +1 & -1 & +1 \\ -1 & -1 & +1 & +1 \\ -1 & +1 & +1 & -1 \end{bmatrix} \]  

(5)

In order to generate the POEPC codes, each bi-orthogonal code is replaced by:

\[ h_{ij} \rightarrow h_{ij}, h_{ij}, h_{ij}, \ldots, h_{ij} \]  

(6)

For example, \(B_{4,4}\) in Eq. (5) is changed as follows.

\[ B_{4,4}' = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \]  

(7)

One POEPC code can be generated by combining one GMPSC with one of the expanded bi-orthogonal codes as shown in Eq. (7). POEPC \(P_{n,m}\) is generated by:

\[ P_{n,m} = \begin{bmatrix} g_{n,1} & g_{n,2} & \cdots & g_{n,m^2} \end{bmatrix} \begin{bmatrix} h_{m,1} & 0 & \cdots & 0 \\ 0 & h_{m,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & h_{m,m^2} \end{bmatrix} \]  

(8)

POEPC \(P_{2,4}\), which consists of \(G_2\) and \(B_4'\), is expressed as:

\[ P_{2,4} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & -1 \end{bmatrix} \]  

(9)
Before POEPC is transmitted, we convert it into a \{0, 1\}-valued signal. Hence, POEPC is multiplied by a Manchester code having two successive pulses of opposite polarity and its minus values are removed. In the case of \{00010000 – 1, –10000100\} in Eq. (9), the transmission signal is given as

\[
\begin{bmatrix}
0000100000001010000000010000
\end{bmatrix}
\] (10)

### 2.2 Structure of EPOM

EPOM consists of an MPOMs and a bi-orthogonal code. The MPOMs is based on a \{0, 1\}-valued M-sequence with code length \(L/2 – 1\). By applying a cyclic shift to the \{0, 1\}-valued M-sequence, we obtain \(L/2 – 1\) different sequence codes. We add a balanced chip to the end of each sequence code so that the number of binary zeros equals the number of binary ones. Thus, we obtain \(L/2 – 1\) different sequence codes with code length \(L/2\), which are collectively denoted as \(M_A\). The sequence codes in \(M_A\) with ‘0’ and ‘1’ reversed are denoted as \(M_B\). We regard \(M_A\) and \(M_B\) as MPOMs that consist of \(L – 2\) codes in total with code length \(L/2\). For example, when \(L = 16\), the MPOMs are expressed as

\[
M_A = \begin{bmatrix}
M_{A1} \\
M_{A2} \\
M_{A3} \\
M_{A4} \\
M_{A5} \\
M_{A6} \\
M_{A7}
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 0 & 1 & 0 & 0 & 0 \\
1 & 1 & 0 & 1 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 0 & 1 & 0 & 1 & 1 \\
1 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 0 & 1 & 1 & 1 & 0 & 1 \\
0 & 1 & 1 & 1 & 0 & 1 & 0
\end{bmatrix} \quad (11)
\]

\[
M_B = \begin{bmatrix}
M_{B1} \\
M_{B2} \\
M_{B3} \\
M_{B4} \\
M_{B5} \\
M_{B6} \\
M_{B7}
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 1 & 1 \\
0 & 0 & 1 & 0 & 1 & 1 & 1 \\
0 & 1 & 0 & 1 & 1 & 0 & 0 \\
1 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 \\
1 & 0 & 0 & 0 & 1 & 0 & 1
\end{bmatrix} \quad (12)
\]

The MPOMs code named \(M_p (A1 \leq p \leq A(L/2 – 1) or B1 \leq p \leq B(L/2 – 1))\) has \(m\) positive marks. In order to generate EPOM, \(M_p\) is combined with one of the bi-orthogonal codes. The \(K\)th (\(1 \leq K \leq m\)) mark of \(M_p\) is multiplied by the \(K\)th value of the selected bi-orthogonal code. For example, when we combine \(M_{A2}\) in Eq. (11) with \(B_{4,6}\) in Eq. (5), EPOM becomes

\[
\begin{bmatrix}
-1 & +1 & 0 & -1 & 0 & 0 & +1 & 0
\end{bmatrix} \quad (13)
\]

Before EPOM is transmitted, it is multiplied by a Manchester code having two successive pulses of opposite polarity and its minus values are removed. In the example in Eq. (13), the transmission code becomes

\[
\begin{bmatrix}
-1 & 1 & 0 & -1 & 0 & 0 & 0 & 1 & 0
\end{bmatrix} \quad (14)
\]

### 2.3 Transmitter and receiver

Figure 1 illustrates the structure of the N-CSK system. The mixed PN code in Fig.1 is POEPC or EPOM. Note that the value of \(N\) in Fig.1 equals 1 when EPOM is generated. As described in the preceding section, EPOM is a non-orthogonal code. Therefore, using EPOM with N-CSK brings about significant deterioration of its performance.

The transmitter possesses two optical PN codes: \(PN_{#1} = \{PN_{1,1}, PN_{1,2}, \ldots, PN_{1,J}\}\) and \(PN_{#2} = \{PN_{2,1}, PN_{2,2}, \ldots, PN_{2,J}\}\). At the transmitter, source data is divided into a (DATA1+DATA2) segment with DATA1 \((log_2 I[\text{bit}])\) as the front part of the segment and DATA2 \((log_2 J[\text{bit}])\) as the rear part of the segment. When POEPC is used for the system, GMSPS \((I = L/8)\) is used as \(PN_{#1}\) and a bi-orthogonal code \((J = L/4)\) is used as \(PN_{#2}\). The \(N\) codes are selected from \(PN_{#1}\) and \(PN_{#2}\) in accordance with DATA1 and DATA2, respectively. The \(N\) POEPC codes are generated from GMSPS and the bi-orthogonal code by the method described in the preceding section. The \(N\)
POEPC codes are summed. On the other hand, in the case of EPOM, an MPOMs \((J=L/2)\) is used as PN\#1 for DATA\#1 and a bi-orthogonal code \((J=L/2)\) is used as PN\#2 for DATA\#2. The mixed PN code is multiplied by a Manchester code and its minus values are removed. This on-off signal is transmitted to the receiver through an optical-wireless channel.

At the receiver, a chip-level avalanche photodiode (APD) \([11]\) implements photoelectric conversion. The received signal branches off into two routes for two-stage demodulation. In the first demodulation, the on-off signal received from the APD is integrated over a two-chip interval. The integrated signal is correlated with PN\#1. For example, when the transmitter adopts EPOM and group 2 of GMPSC, correlator 1 has the reference code \(g_{2,1}\). The output values from the \(M\) correlators are compared with each other. When \(N>1\), the \(N\) GMPSC codes that give a larger correlation value than the other \(M-N\) correlation values are estimated. Similarly, when the transmitter adopts EPOM, the integrated signal is correlated with the reference signal at the correlator. Each correlator has a \([-1,1]\)-valued MPOMs as the reference signal. The \([-1,1]\)-valued MPOMs is constructed by replacing ‘0’ in the MPOMs by ‘-1’. The MPOMs giving the largest correlation value is estimated. DATA\#1 is extracted from the estimated PN\#1. In the second demodulation, the received signal is multiplied by a Manchester code and integrated over a two-chip interval. The \(N\) PN\#2 are estimated by correlation detection. In this detection step, the estimated PN\#1 are utilized. Each correlator has a reference signal that combines the estimated PN\#1 with a bi-orthogonal code. The polarity of the marks in the estimated PN\#1 is altered by the polarity values of the bi-orthogonal code. When \(N>1\), the \(N\) bi-orthogonal codes giving a larger correlation value than the other \(M-N\) correlation values are estimated. DATA\#2 is extracted from the estimated PN\#2. The combiner allocates the estimated DATA\#1 as the front part of the target data. The estimated DATA\#2 corresponds to the rear part of the target data.

### 3. Performance Evaluation

Figure 2 shows the data rates of CSK using EPOM and N-CSK using POEPC. Naturally enough, as \(N\) increases, the data rate of N-CSK using POEPC becomes much higher. The data rate of CSK using EPOM is almost the same as that of N-CSK using POEPC when \(N=2\). Thus, the BER of CSK using EPOM is comparable to that of N-CSK using POEPC \((N=2)\) under the same data rate. The channel is assumed to be an indoor optical-wireless channel with background noise and a weak scintillation process \([8],[12]\). Table 2 shows the numerical conditions used to obtain the BER performances for CSK using EPOM and N-CSK using POEPC.

<table>
<thead>
<tr>
<th>Table 2: Numerical conditions</th>
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<tbody>
<tr>
<td>Chip rate (1664) [Mcps]</td>
</tr>
<tr>
<td>Laser wavelength (830) [nm]</td>
</tr>
<tr>
<td>Background noise (-45) [dBm]</td>
</tr>
<tr>
<td>Logarithm variance of scintillation (0.01)</td>
</tr>
<tr>
<td>Modulation extinction ratio (1.0) [%]</td>
</tr>
<tr>
<td>Quantum efficiency (0.6)</td>
</tr>
<tr>
<td>Excess noise factor (3.9502)</td>
</tr>
<tr>
<td>Energy per photon (23.94939759 \times 10^{-20}) [W]</td>
</tr>
<tr>
<td>Electric charge (1.6021766 \times 10^{-19}) [C]</td>
</tr>
<tr>
<td>APD gain (100)</td>
</tr>
<tr>
<td>Effective ionization ratio (0.02)</td>
</tr>
<tr>
<td>Bulk leakage current (0.1) [nA]</td>
</tr>
<tr>
<td>Surface leakage current (10) [nA]</td>
</tr>
<tr>
<td>Boltzmann constant (1.38 \times 10^{-23}) [J/K]</td>
</tr>
<tr>
<td>Receiver noise temperature (1100) [K]</td>
</tr>
<tr>
<td>Receiver load resistor (1030) [\Omega]</td>
</tr>
</tbody>
</table>

Figure 3 shows the BERs of CSK using EPOM and N-CSK using POEPC when \(L=128\). We evaluated the BERs of the CSK systems under the same chip rate. The BERs of CSK using EPOM and N-CSK using POEPC can be improved by utilizing two-stage demodulation. From Fig.3, we infer that CSK using EPOM and N-CSK using POEPC are both feasible. When the N-CSK system has \(N=1\) or 2, CSK using EPOM is more effective than N-CSK using POEPC. On the other hand, when the N-CSK system has \(N \geq 3\), only N-CSK using POEPC is suitable. We also found that N-CSK using POEPC has a trade-off between the data rate and BER when \(N\) increases.

![Figure 2: Data rates of CSK using EPOM and N-CSK using POEPC when \(N = 1, 2, 3\)](image-url)
Figure 3: BERs of CSK using EPOM and N-CSK using POEPC when $L = 128$ and $N = 1, 2, 3$

4. Conclusions

We considered improved code-shift keying (CSK) systems with a functional pseudonoise (PN) code in an optical-wireless channel. In particular, we focused on CSK using EPOM and N-parallel CSK (N-CSK) using POEPC. Our analysis found that two-stage demodulation can enhance the bit error rate (BER) of these CSK systems. BER of CSK using EPOM is lower than that of N-CSK using POEPC when both systems have the same data rate. Moreover, N-CSK using POEPC has a trade-off between the data rate and BER when $N$ increases. Hence, when CSK using EPOM and N-CSK using POEPC are used with the same data rate, CSK using EPOM is more effective. Upon further improving the data rate, only N-CSK using POEPC will be suitable.

Acknowledgment

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References