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Optical-Wireless Enhanced Code-Shift-Keying with IM/DD

Shota TAKAYANAGI
College of Engineering
Ibaraki University, Japan
Email: 15nm718r@vc.ibaraki.ac.jp

Hiromasa HABUCHI
College of Engineering
Ibaraki University, Japan
Email: habuchi@mx.ibaraki.ac.jp

Yusuke KOZAWA
Department of Electrical Engineering
Tokyo University of Science, Japan
Email: kozawa@rs.tus.ac.jp

***Abstract*—In this paper, the extended pseudo orthogonal M-sequence is proposed for the optical-wireless code-shift-keying (CSK) system. The extended pseudo orthogonal M-sequence is a new optical pseudo-noise (PN) code which consists of the modified pseudo orthogonal M-sequence sets (MPOMS) and the bi-orthogonal code. The performance of the CSK systems is enhanced by increasing the number of the optical PN codes. As the conventional optical PN code, the bi-orthogonal code and the pseudo-orthogonal extended prime code set can generate the number of the optical PN codes same as the code length. The extended pseudo orthogonal M-sequence can achieve the performance enhancement of the CSK systems because of its generation of the large number of the codes per the code length. The CSK system using the extended pseudo orthogonal M-sequence has better performance than the CSK systems using the conventional PN code.**

I. Introduction

Optical-wireless communications (OWC) with intensity modulation and direct detection (IM/DD) have attracted much attention for indoor wireless communications. As one of modulation methods in OWC, the code-shift-keying (CSK) [1]-[4] has been studied in recent years. The CSK systems make a transmission signal by selecting one code from the plural optical pseudo-noise (PN) codes according to information data. The performance of the CSK systems depends on the ratio of the number of the optical PN codes, N, and the transmitted code length, L_T, that is, N/L_T. Increasing N/L_T can improve the information transmission efficiency and the bit error rate (BER) performance on the CSK systems. Therefore, one of the significant issues is to design an optical PN code for achieving $N/L_T{\geq}1$. The pseudo-orthogonal extended prime code set [7] which consists of the generalized modified prime sequence code (GMPSC) [8] and the bi-orthogonal code can achieve $N/L_T{=}1$. The information transmission efficiency of the CSK system using the bi-orthogonal code [5] [6] is identical to that of the CSK system using the pseudo-orthogonal extended prime code set. Although the BER performance of both CSK systems is the same in an additive white Gaussian noise (AWGN) channel, the former system differs from the latter system in BER in the optical-wireless channel [7]. Since the optical-wireless CSK system using the pseudo-orthogonal extended prime code set performs data demodulating with two stages, the BER performance of this system is better than that of the bi-orthogonal modulation system. The code design that can realize $N/L_T = 1$ and the data demodulation with two phases are essential for enhancing the optical-wireless CSK systems.

In this paper, we propose a new optical-wireless PN code which meets $N/L_T{>}1$ and enables two stages demodulation. The new code, called the extended pseudo orthogonal M-sequence, consists of the modified pseudo orthogonal M-sequence sets (MPOMS) [9] [10] and the bi-orthogonal code. In this paper, we focus on the information transmission efficiency property and BER performance of the CSK systems. We evaluate the CSK system using the proposed PN code in the indoor optical-wireless channel.

II. Structure of optical PN code

In this section, we explain the constitution of MPOMS, the bi-orthogonal code, and the extended pseudo orthogonal M-sequence. Table I shows the notation for the following discussion.

TABLE I NOTATION

L	Code length of MPOMS & the proposed code
L_T	Transmitted code length as optical signal
M	The number of pulses
N	The number of available codes
R	The information transmission efficiency

A. Modified pseudo orthogonal M-sequence sets

MPOMS is generated based on $\{-1{,}1\}$-valued M-sequence with the code length $L-1$. By applying cyclic shift to $\{-1{,}1\}$-valued M-sequence, we obtain $2M-1$ sequence codes. Next, we add an balanced chip to the end of each sequence code so that the number of binary minus-ones equals the number of binary ones. Hence, we obtain sequence codes with the code length L, which are called $\boldsymbol{M_o}$ in this paper. The sequence codes which are constructed by replacing the -1 of $\boldsymbol{M_o}$ by zero are called as $\boldsymbol{M_A}$. The sequences which reversed zero and 1 of each code in $\boldsymbol{M_A}$ are called $\boldsymbol{M_B}$. We regard $\boldsymbol{M_A}$ and $\boldsymbol{M_B}$ as MPOMS which consists of $4M-2$ codes in total with the code length L. These codes have the following characteristics;

$$\boldsymbol{M_o} = \boldsymbol{M_A} - \boldsymbol{M_B} \tag{1}$$

$$\boldsymbol{M_A}\boldsymbol{M_o}^T = \left(\frac{L}{2}\right)\boldsymbol{E} \tag{2}$$

$$\boldsymbol{M_B}\boldsymbol{M_o}^T = \left(-\frac{L}{2}\right)\boldsymbol{E} \tag{3}$$

where $\boldsymbol{E}$ is a unit matrix and $\boldsymbol{M_o^T}$ is transposed matrix of $\boldsymbol{M_o}$. For example, when L=8[chip], $\boldsymbol{M_o}$, $\boldsymbol{M_A}$, and $\boldsymbol{M_B}$ are expressed as

$$\boldsymbol{M_o} = \begin{bmatrix} M_{o1} \\ M_{o2} \\ M_{o3} \\ M_{o4} \\ M_{o5} \\ M_{o6} \\ M_{o7} \end{bmatrix} = \begin{bmatrix} +1 & +1 & +1 & -1 & +1 & -1 & -1 & -1 \\ +1 & +1 & -1 & +1 & -1 & -1 & +1 & -1 \\ +1 & -1 & +1 & -1 & -1 & +1 & +1 & -1 \\ -1 & +1 & -1 & -1 & +1 & +1 & +1 & -1 \\ +1 & -1 & -1 & +1 & +1 & +1 & -1 & -1 \\ -1 & -1 & +1 & +1 & +1 & -1 & +1 & -1 \\ -1 & +1 & +1 & +1 & -1 & +1 & -1 & -1 \end{bmatrix} \tag{4}$$

$$\boldsymbol{M_A} = \begin{bmatrix} M_{A1} \\ M_{A2} \\ M_{A3} \\ M_{A4} \\ M_{A5} \\ M_{A6} \\ M_{A7} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{5}$$

$$\boldsymbol{M_B} = \begin{bmatrix} M_{B1} \\ M_{B2} \\ M_{B3} \\ M_{B4} \\ M_{B5} \\ M_{B6} \\ M_{B7} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix}. \tag{6}$$

From the example mentioned above, $\boldsymbol{M_A}$ and $\boldsymbol{M_B}$ have four pulses respectively, note that the relation $M = L/2$ can be defined.

B. Bi-orthogonal code

The bi-orthogonal code is generated based on {-1,+1}-valued Hadamard matrix $\boldsymbol{H_M}$ and the negative version of $\boldsymbol{H_M}$, denoted $-\boldsymbol{H_M}$. $M \times M$ Hadamard matrix, $\boldsymbol{H_M}$, can be written as

$$\boldsymbol{H_M} = \begin{bmatrix} \boldsymbol{H_{\frac{M}{2}}} & \boldsymbol{H_{\frac{M}{2}}} \\ \boldsymbol{H_{\frac{M}{2}}} & -\boldsymbol{H_{\frac{M}{2}}} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1M} \\ h_{21} & h_{22} & \cdots & h_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{MM} \end{bmatrix}. \tag{7}$$

The initial value of Hadamard matrix, $\boldsymbol{H_1}$, is 1. Therefore, Hadamard matrix $\boldsymbol{H_2}$ is expressed as

$$\boldsymbol{H_2} = \begin{bmatrix} H_1 & H_1 \\ H_1 & -H_1 \end{bmatrix} = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix}. \tag{8}$$

When MPOMS and the extended pseudo orthogonal M-sequence have code length L on the transmission signal, the code length of the bi-orthogonal code needs $L/2 (= M)$. The bi-orthogonal code with code length $L/2$, $\boldsymbol{B_M}$, is expressed as

$$\boldsymbol{B_M} = \begin{bmatrix} B_{M,1} \\ B_{M,2} \\ \vdots \\ B_{M,M} \\ B_{M,M+1} \\ B_{M,M+2} \\ \vdots \\ B_{M,2M} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1M} \\ h_{21} & h_{22} & \cdots & h_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{MM} \\ -h_{11} & -h_{12} & \cdots & -h_{1M} \\ -h_{21} & h_{22} & \cdots & -h_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ -h_{M1} & -h_{M2} & \cdots & -h_{MM} \end{bmatrix}. \tag{9}$$

For example, when L=8[chip] and $M = 4$, $\boldsymbol{B_4}$ is expressed as

$$\boldsymbol{B_4} = \begin{bmatrix} B_{4,1} \\ B_{4,2} \\ B_{4,3} \\ B_{4,4} \\ B_{4,5} \\ B_{4,6} \\ B_{4,7} \\ B_{4,8} \end{bmatrix} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \\ -1 & -1 & -1 & -1 \\ -1 & +1 & -1 & +1 \\ -1 & -1 & +1 & +1 \\ -1 & +1 & +1 & -1 \end{bmatrix}. \tag{10}$$

C. Extended pseudo orthogonal M-sequence

The extended pseudo orthogonal M-sequence is constructed by combining one of MPOMS, denoted M_p ($A1 \le p \le AM$ or $B1 \le p \le BM$), with one of the bi-orthogonal codes, denoted $B_{M,q}$ ($1 \le q \le 2M$). The K-th ($1 \le K \le M$) pulse of M_p is multiplied by the K-th value of $B_{M,q}$. For example, the first pulse of M_p is multiplied by the first value of $B_{M,q}$. Thus, the combined sequence codes $Y_{p,q}$, called the extended pseudo orthogonal M-sequence, are generated. For example, when we combine M_{A2} in Eq. (5) with $B_{4,6}$ in Eq. (10), the combined code $Y_{A2,6}$ can be written as

$$Y_{A2,6} = [\ -1 \quad +1 \quad 0 \quad -1 \quad 0 \quad 0 \quad +1 \quad 0\ ]. \tag{11}$$

Since the transmitter in our system has $2M$ MPOMS and $2M$ bi-orthogonal codes, $4M^2$ sequence codes ($Y_{p,q}$) can be generated at the transmitter. Note that $Y_{p,q}$ have to be converted into the transmission signal before the code is transmitted. The transmission signal is an $\{0, +1\}$-valued signal with the code length $2L (= L_T)$. $Y_{p,q}$ is multiplied by Manchester code having 2 chip length ($2T_c$) and removed its minus values for the sake of transforming $Y_{p,q}$ to the on-off signal. As a result, the code length of the transmission signal becomes L_T. Figure 1 illustrates the transformation from $Y_{A2,6}$ to the on-off signal as the example. In this case, the transmission signal is expressed as follows.

$$[\ \overbrace{1\,0}^{-1}\ \overbrace{0\,1}^{1}\ \overbrace{0\,0}^{0}\ \overbrace{1\,0}^{-1}\ \overbrace{0\,0}^{0}\ \overbrace{0\,0}^{0}\ \overbrace{0\,1}^{1}\ \overbrace{0\,0}^{0}\ ]. \tag{12}$$

III. Code-Shift-Keying system

Figure 2 illustrates the system model of the CSK system using the extended pseudo orthogonal M-sequence.

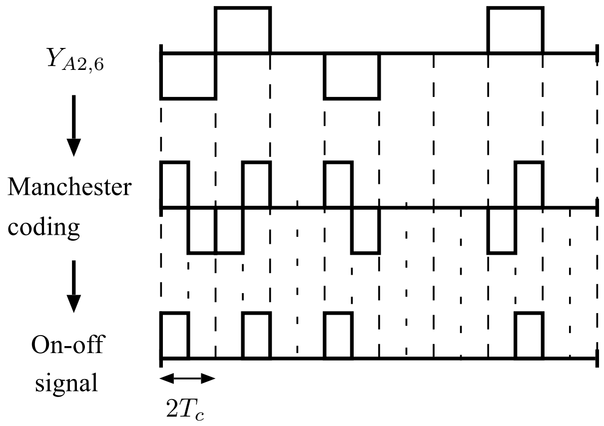

Fig. 1. Transformation to on-off signal

A. Transmitter

By the data converter at the transmitter, source data are divided into two data; DATA1 ($\log_2(2M)$[bit]) and DATA2 ($\log_2(2M)$[bit]). At the transmitter, the CSK system prepares $2M$ codes with the code length L from MPOMS so that there are $\boldsymbol{M_A}$ and $\boldsymbol{M}_B$ which is inversion of $\boldsymbol{M_A}$. The CSK system also prepares $2M$ bi-orthogonal codes with the code length $L/2$. One of $2M$ MPOMS $\{(M_{A1}),\cdots,(M_{AM}),(M_{B1}),\cdots,(M_{BM})\}$ is selected according to DATA1. Also, one of $2M$ bi-orthogonal codes $\{(B_{M,1}),\cdots,(B_{M,M}),(B_{M,M+1}),\cdots,(B_{M,2M})\}$ is selected according to DATA2. As we described in a previous section, M pulses of MPOMS are multiplied by the $\{-1,+1\}$-values of the bi-orthogonal code like Eq. (11), which makes $Y_{p,q}$. After applying Manchester coding to $Y_{p,q}$ and removing minus values of the code, the on-off signal such as Eq. (12) is implemented in optical intensity modulation and transmitted to the receiver.

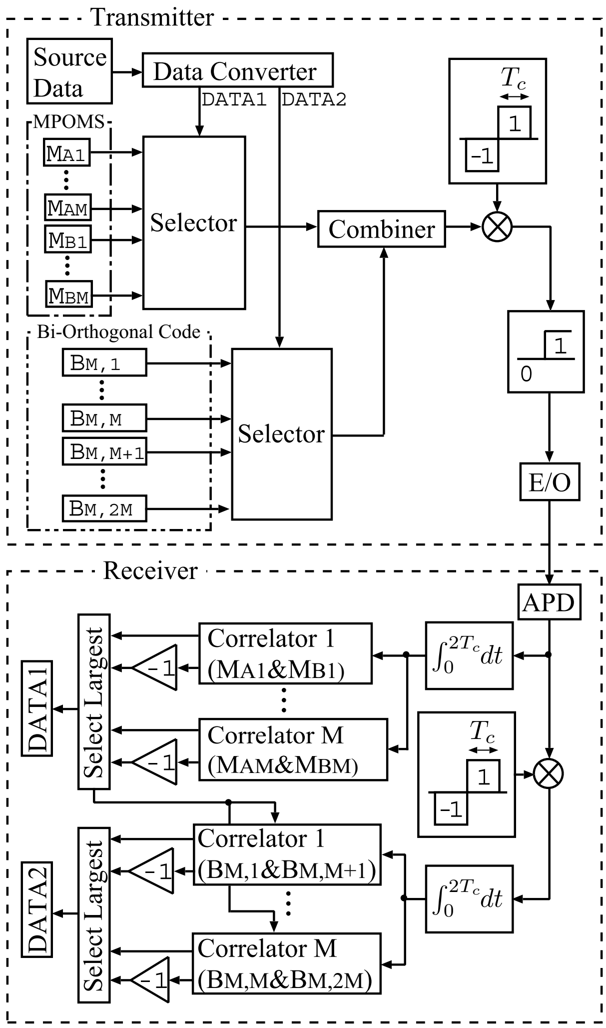

Fig. 2. System model

B. Receiver

At the receiver, the electric signal converted from the on-off signal is obtained by chip-level avalanche photo-diode (APD) [11]. This signal passes two branches to demodulate both DATA1 and DATA2 for performing two stages demodulation. The receiver has M correlators for DATA1 and M correlators for DATA2.

The first demodulation for DATA1 has three steps as follows. Firstly, the received signal by APD is integrated in 2 chips interval ($2T_c$). Secondly, the output of the integrator is correlated with the reference codes, M_o $\{(M_{o1}),\cdots,(M_{oM})\}$. Each correlator outputs the correlation value and its negative value. Therefore, the M correlation values and the M opposite polarity values are obtained. Finally, MPOMS which gives the maximum value is estimated by comparing the $2M$ correlation values. DATA1 are demodulated by the estimated MPOMS.

The second demodulation for DATA2 has three steps as follows. Firstly, the received signal by APD is correlated with Manchester code and integrated in $2T_c$. This method means just reversed procedure in Fig. 1. Secondly, the output of the integrator is correlated with the reference codes combining one of MPOMS estimated by DATA1 with the bi-orthogonal codes $\{(B_{M,1}),\cdots,(B_{M,M})\}$. For example, the correlator 1 for $B_{M,1}$ and $B_{M,M+1}$ in Fig. 2 has the reference code combining the estimated MPOMS with $B_{M,1}$. Similarly, the correlator M for $B_{M,M}$ and $B_{M,2M}$ in Fig. 2 has the reference code combining the estimated MPOMS with $B_{M,M}$. Each correlator outputs the correlation value and its negative value. Therefore, M correlation values and the M opposite polarity values are obtained. Finally, the bi-orthogonal code which gives the maximum value is estimated by comparing the $2M$ correlation values. DATA2 are demodulated by the estimated bi-orthogonal code.

For simplicity, let us consider the case that the signal $Y_{A2,6}$ in Eq. (12) is transmitted. At the integrator in the first demodulation, $Y_{A2,6}$ is integrated in $2T_c$ and becomes

$$\{1,1,0,1,0,0,1,0\}. \tag{13}$$

The reference code of the correlator 1 for M_{A1} and M_{B1} is M_{o1}. Therefore, the correlation values of this correlator 1 are 0 if there are no distortion and no noise. Similarly, if there are no distortion and no noise, the correlation values for $\{M_{A1}, M_{B1}, \cdots, M_{M_{A4}}, M_{B4}\}$ become

$$\{0, 0, 4, -4, 0, 0, 0, 0\}. \tag{14}$$

The third value in Eq. (14) which is the correlation value of M_{A2} becomes the maximum value. Thus, M_{A2} is estimated and DATA1 are demodulated.

Next, let us consider the case of DATA2. $Y_{A2,6}$ is correlated with Manchester code and becomes

$$\{-1, 0, 0, 1, 0, 0, -1, 0, 0, 0, 0, 0, 0, 1, 0, 0\}. \tag{15}$$

Eq. (15) is integrated in $2T_c$ and becomes

$$\{-1, 1, 0, -1, 0, 0, 1, 0\}. \tag{16}$$

When DATA1 are demodulated correctly, the reference codes are expressed as

$$\boldsymbol{Y_{A2}} = \begin{bmatrix} Y_{A2,1} \\ Y_{A2,2} \\ Y_{A2,3} \\ Y_{A2,4} \end{bmatrix} = \begin{bmatrix} +1 & +1 & 0 & +1 & 0 & 0 & +1 & 0 \\ +1 & -1 & 0 & +1 & 0 & 0 & -1 & 0 \\ +1 & +1 & 0 & -1 & 0 & 0 & -1 & 0 \\ +1 & -1 & 0 & -1 & 0 & 0 & +1 & 0 \end{bmatrix}. \tag{17}$$

If there are no distortion and no noise, the correlation values for $\{B_{4,1}, B_{4,5}, \cdots, B_{4,4}, B_{4,8}\}$ become

$$\{0, 0, -4, 4, 0, 0, 0, 0\}. \tag{18}$$

Since the forth value in Eq. (18) which is the correlation value of $Y_{A2,6}$ becomes the maximum value, $B_{4,6}$ is estimated and DATA2 are demodulated.

IV. Performance analysis

In this section, we compare the CSK system using the extended pseudo orthogonal M-sequence with the CSK system using bi-orthogonal code and the CSK system using the pseudo-orthogonal extended prime code set. When we represent the code length of the bi-orthogonal code as L, the code length of the on-off signal is $2L$. The bi-orthogonal code has N=$2L$ codes ($(1+\log_2 L)$[bit]). N/L_T becomes 1. Hence, the information transmission efficiency R is given by

$$R = \frac{1}{2}\left(\frac{1+\log_2 L}{L}\right) [\text{bit/chip}]. \tag{19}$$

The pseudo-orthogonal extended prime code set consists of GMPSC and the bi-orthogonal code. When we represent the code length of the pseudo-orthogonal extended code set as L, $\sqrt{L}$ GMPSC and $2\sqrt{L}$ bi-orthogonal codes are available. In this case, the code length of the on-off signal is $2L$. The number of codes is N=$2L$, and so N/L_T=1. Hence, the CSK system using the pseudo-orthogonal extended prime code set achieves the information transmission efficiency R same as the bi-orthogonal modulation system. On the other hand, the extended pseudo orthogonal M-sequence consists of MPOMS and the bi-orthogonal code. $2M(=L)$ MPOMS and $2M(=L)$ bi-orthogonal code are available. When the code length of the on-off signal is $2L$, the number of codes is N=$4M^2(=L^2)$, and so $N/L_T = L/2$. When $L > 2$, $N/L_T > 1$. Hence, the information transmission efficiency R is given by

$$R = \frac{\log_2 L}{L} [\text{bit/chip}]. \tag{20}$$

The proposed optical PN code has the information transmission efficiency $(2\log_2 L/(1+\log_2 L))$ times as high as the bi-orthogonal code and the pseudo-orthogonal extended prime code set. When $L = 2$, three optical PN codes have the same information transmission efficiency and the same code length. If $L \rightarrow \infty$, the information transmission efficiency of the CSK system using the proposed optical PN code becomes twice as good as that of the CSK systems using the conventional optical PN code.

Figure 3 shows the code length of the on-off signal versus the information transmission efficiency between the CSK system using the proposed optical PN code and the CSK systems using the conventional optical PN code. When the CSK system using the proposed optical PN code has the same code length as the CSK systems using the conventional optical PN code, better information transmission efficiency is shown in Fig. 3. In addition, the CSK system using the proposed optical PN code has twice number of the codes as the CSK systems using the conventional optical PN code when both CSK systems achieve the same information transmission efficiency. To make code length larger means increasing the number of the codes, which leads the performance improvement.

Table II shows the numerical conditions in the optical-wireless channel. Figure 4 shows the average received laser power per bit versus BER when three CSK systems achieve same information transmission efficiency. The CSK system using the proposed optical PN code (L = 128) achieves better the BER performance than the CSK systems using the conventional optical PN code (L=64).

TABLE II
THE NUMERICAL CONDITIONS

Name	Value
Bit rate	156×10^6[bps]
Laser wavelength	830[nm]
Background noise	-45[dBm]
Scintillation logarithm variance	0.01
Quantum efficiency	0.6
Excess noise factor	3.9502
Energy per a photon	$23.94939759 \times 10^{-20}$
Electric charge	$1.60217646 \times 10^{-19}$[C]
APD gain	100
Effective ionization ratio	0.22
Bulk leakage current	0.1[nA]
Surface leakage current	10[nA]
Modulation extinction ratio	100
Boltzmann constant	1.38×10^{-23}
Receiver noise temperature	1100[K]
Receiver load resistor	1030[Ω]

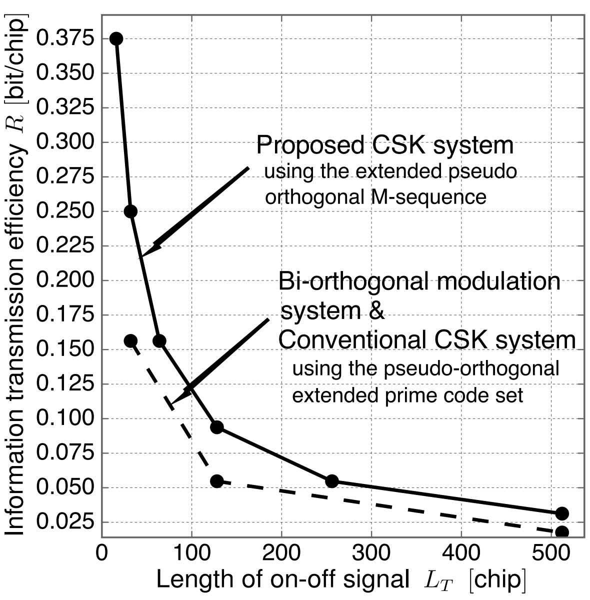

Fig. 3. Code length of on-off signal (L_T) versus information transmission efficiency (R)

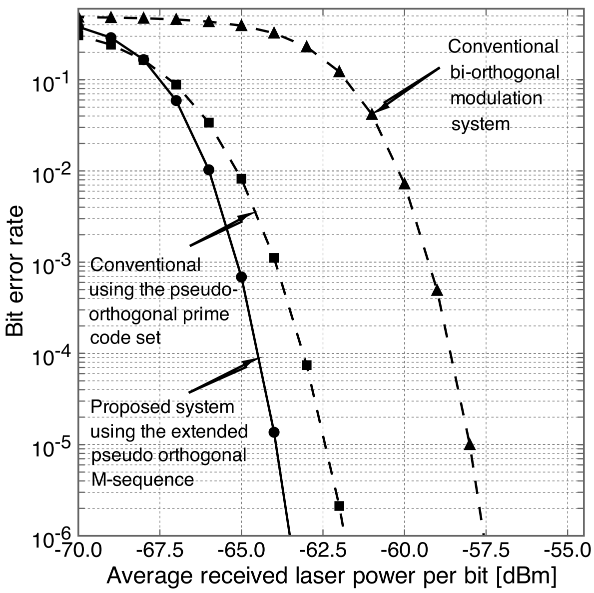

Fig. 4. Average received laser power per bit versus BER when three CSK systems achieve same information transmission efficiency

V. Conclusion

In this paper, we proposed the extended pseudo orthogonal M-sequence as the optical PN code and have adopted it to the optical-wireless CSK system. The extended pseudo orthogonal M-sequence achieves $N/L_T > 1$ when $L > 2$ and can be performed two stages demodulation. The performance of the CSK system using the proposed optical PN code is better than that of the CSK systems using the conventional optical PN code. Future works, we will consider application for visible light communications using the CSK system.

Acknowledgement

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