

Indoor Experiment of BER Performance of Optical CDMA System Using Optical ZCZ Code

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Abstract—The optical ZCZ code, which is a set of pairs of binary and bi-phase sequences with zero correlation zone, can provide optical code division multiple access (CDMA) communication system without co-channel interference. We proposed the compact construction of a code generator and a bank of matched filters for this code.

In this paper, we verified that this system can suppress co-channel interference and interference by shifting of optical axis by data multiplex transmission experiment of optical CDMA system using optical ZCZ codes which is called ZCZ-CDMA system, consisting of a infrared light emitting diode(LED), an avalanche photo diode(APD) module and field programmable gate array(FPGA) boards corresponding to 400,000 logic gates.

As a result of data transmission experiment, optical ZCZ-CDMA system can suppress co-channel interference, but can't remove completely co-channel interference, and interference by shifting of optical axis is suppressed from about -30 to 30 degrees.

Keywords—Optical ZCZ code, Optical wireless communication, CDMA system, Shifting of optical axis

I. INTRODUCTION

The optical code division multiple access (CDMA) system can expect a high speed communication to be able to use a wide band [1], [2], [3], [4]. The interference from adjacent light source of desire light source is a problem in the realization of optical CDMA system.

An optical CDMA system using the optical ZCZ code which is called ZCZ-CDMA system, is proposed as a method with the possibility that this problem can be solved without complicating hardware. This optical ZCZ-CDMA system, which is used a set of pairs of binary and bi-phase sequences with zero correlation zone [5], [6] can remove co-channel interference. We proposed the compact construction of a code generators [7], [8] and a bank of matched filters [9], [10] for this ZCZ-CDMA system.

In this paper, we verified that this system can remove co-channel interference and interference by shifting of optical axis by data transmission experiment of optical CDMA system using optical ZCZ codes [11], [12], consisting of a infrared light emitting diode(LED), an avalanche photo diode(APD) module and field programmable gate array(FPGA) boards corresponding to 400,000 logic gates. Especially, we clarified the influence of interference by increase in a multiple number and shifting of optical axis on the BER performance by the experiment.

II. OPTICAL ZCZ CODES WITH $Zcz = 1$

Let $\mathbf{H}_{N_1}$ be the Sylvester-type Hadamard matrix of size $N_1 \times N_1 = 2^{n_1} \times 2^{n_1}$ with $n_1 \geq 2$, written as

$$\mathbf{H}_{N_1} = [h_{N_1}^0, h_{N_1}^1, \dots, h_{N_1}^j, \dots, h_{N_1}^{N_1-1}]^T, \quad (1)$$

$$h_{N_1}^j = (h_{N_1,0}^j, h_{N_1,1}^j, \dots, h_{N_1,i}^j, \dots, h_{N_1,N_1-1}^j), \quad (2)$$

$$h_{N_1,i}^j \in \{1, -1\},$$

where the symbol T denotes the matrix transposition, which is defined by

$$\mathbf{H}_{N_1} = \mathbf{H}_{\frac{N_1}{2}} \otimes \mathbf{H}_2 \quad (3)$$

$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \quad (4)$$

where the operation $\otimes$ denotes the Kronecker product. $h_{N_1}^j$ is called a Hadamard sequence.

A bi-phase sequence a_N^j with length $N = 2N_1$ whose elements take 1 or -1, written as

$$a_N^j = (a_{N,0}^j, a_{N,1}^j, \dots, a_{N,i}^j, \dots, a_{N,N-1}^j), \quad (5)$$

$$a_{N,i}^j \in \{1, -1\},$$

where i denotes $i \bmod N$, and is given by

$$a_{N,i}^j = \alpha_{N,i} \cdot h_{N_1,i \bmod N_1}^j \quad (6)$$

$$\alpha_{N,i} = \begin{cases} h_{N_1,i}^0 & = 1 \\ & ; 0 \leq i \leq \frac{N}{2} - 1 \\ -h_{N_1,i \bmod N_1}^1 & = (-1)^{i+1} \\ & ; \frac{N}{2} \leq i \leq N - 1 \end{cases}.$$

The mean value of this sequence a_N^j is given by

$$\sum_{i=0}^{N-1} a_{N,i}^j = \sum_{i=0}^{N_1-1} h_{N_1,i}^0 h_{N_1,i}^j - \sum_{i=0}^{N_1-1} h_{N_1,i}^1 h_{N_1,i}^j = 0, \quad (7)$$

where $j \neq 0, 1$. Therefore, a bi-phase sequence a_N^j is called a bi-phase balanced sequence.

A binary sequence $\hat{a}_N^{j,d}$ of length N whose elements take 1 or 0, written as

$$\hat{a}_N^{j,d} = (\hat{a}_{N,0}^{j,d}, \hat{a}_{N,1}^{j,d}, \dots, \hat{a}_{N,i}^{j,d}, \dots, \hat{a}_{N,N-1}^{j,d}), \quad (8)$$

$$\hat{a}_{N,i}^{j,d} \in \{1, 0\}, d \in \{1, 0\},$$

where i denotes $i \bmod N$ and data d takes 1 or 0, and is given by

$$\hat{a}_{N,i}^{j,d} = \frac{1 + (-1)^d a_{N,i}^j}{2}. \quad (9)$$

Let A be a set of pairs of bi-phase sequences, a_N^j 's, and binary sequences, $\hat{a}_N^{j,d}$'s, written as

$$A = \{(a_N^1, \hat{a}_N^{1,d}), (a_N^2, \hat{a}_N^{2,d}), \dots, (a_N^j, \hat{a}_N^{j,d}), \dots, (a_N^M, \hat{a}_N^{M,d})\} \quad (10)$$

with M is the number of sequences in a sequence family, and is called family size.

The periodic correlation function between a_N^j and $\hat{a}_N^{j,d}$ except $j = 0, 1$ is given by

$$\begin{aligned} \rho_{a_N^j, \hat{a}_N^{j',d}, i'} &= \sum_{i=0}^{N-1} a_{N,i}^j \hat{a}_{N,(i+i') \bmod N}^{j',d} \\ &= \begin{cases} w = \frac{N}{2} & ; i' = 0, j = j', d = 0 \\ -w = -\frac{N}{2} & ; i' = 0, j = j', d = 1 \\ 0 & ; i' = 0, j \neq j' \\ 0 & ; i' = Zcz = \pm 1 \end{cases} \end{aligned} \quad (11)$$

with $w = \sum_{i=0}^{N-1} \hat{a}_{N,i}^{j,d} < N$, Zcz is zero correlation zone. In this paper, correlation function $\rho_{a_N^j, \hat{a}_N^{j',d}, i'}$ of $j = j'$ and $j \neq j'$ are called auto- and cross- correlation function, respectively. The set is called an optical ZCZ code[5], [6],

Therefore, a set of bi-phase sequences, a_N^j 's, and binary sequences, $\hat{a}_N^{j,d}$'s, is an optical ZCZ code with $Zcz = 1$ and $M = N/2 - 2 = N/(Zcz + 1) - 2$.

III. OPTICAL CDMA SYSTEM USING OPTICAL ZCZ CODES

In the optical CDMA system using optical ZCZ codes, $\hat{a}_N^{j,d}$'s, the correlator on a receiver outputs not only the even-correlation function, but also the odd-correlation function by the data modulation. Therefore, the optical ZCZ codes, $\hat{a}_N^{j,d}$'s, are enhanced as follows, to remove co-channel interference.

$$\begin{aligned} b_L^{j,d} &= (b_{L,0}^{j,d}, b_{L,1}^{j,d}, \dots, b_{L,i}^{j,d}, \dots, b_{L,L-1}^{j,d}) \\ &= (\underbrace{\hat{a}_{N,N-Zcz}^{j,d}, \dots, \hat{a}_{N,N-1}^{j,d}}_{Zcz}, \underbrace{\hat{a}_{N,0}^{j,d}, \dots, \hat{a}_{N,N-1}^{j,d}}_N, \\ &\quad \underbrace{\hat{a}_{N,0}^{j,d}, \dots, \hat{a}_{N,Zcz-1}^{j,d}}_{Zcz}) \\ b_{L,i}^{j,d} &\in \{1, 0\}, \end{aligned} \quad (13)$$

where $L = N + 2Zcz$. Figure 1 shows the optical CDMA system using an optical ZCZ code. A transmitter sends binary sequences, $b_L^{j,d}$'s corresponding to $\hat{a}_N^{j,d}$'s in according to input data $d_j \in \{1, 0\}$ as optical signal, which is converted by the electrical to optical (E/O) converter. The received optical signal is converted from optical signal to electrical signal by the optical to electrical (O/E) converter. The electrical signal is passed through a filter matched to the bi-phase sequence, a_N^j , which is called the matched filter (MF), and is recovered to the bit data in the detector.

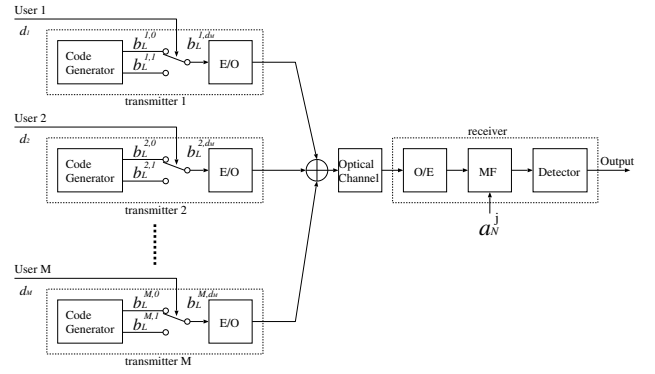


Fig. 1. Optical CDMA system using an optical ZCZ code.

IV. INDOOR EXPERIMENT OF FREE-SPACE OPTICAL ZCZ-CDMA SYSTEM

Table I shows the specifications of optical components used by the free-space optical multiplex data transmission experiment using optical ZCZ-CDMA system. From Table I, the direct-current (DC) components of receiving signal are cut off by the APD module with alternating-current (AC) amplifier. Similarly, a lot of APD modules of other companies cut off the DC components. But interference by the removed

TABLE I
SPECIFICATIONS OF OPTICAL COMPONENTS USED BY THE FREE-SPACE OPTICAL MULTIPLEX DATA TRANSMISSION EXPERIMENT SYSTEM OF OPTICAL CDMA SYSTEM USING OPTICAL ZCZ CODES.

Near infrared LED	L7558-01, L7558 (Hamamatsu Photonics)
Peak emission wavelength λ_p	850nm
Cut-off frequency f_c	50MHz
Spectral half width $\Delta\lambda$	50nm
Radiant flux ϕ_e	7mW, 14mW
APD module	C5331-03 (Hamamatsu Photonics)
Active area	dia. 1.0mm
Peak sensitivity wavelength λ_p	800nm
Spectral response range λ	400nm to 1000nm
Frequency bandwidth	4kHz to 100MHz
Minimum detection limit	3nWrms

direct-current components can be removed by using bi-phase sequences, a_N^j 's, which are balanced sequences[11].

Figure 2 and Table II show the block diagram and specifications of free-space optical transmission experiment system of optical CDMA system using optical ZCZ codes, consisting of a infrared light emitting diode(LED), an avalanche photo diode(APD) module and field programmable gate array(FPGA) boards, respectively. Code generators for optical ZCZ codes of length $L = 34(N = 32)$, sequence number $j = 2, 3, 4$ and 5, and $Zcz = 1$, a matched filter (MF) for an optical ZCZ code and detector have been implemented on a field programmable gate array (FPGA) corresponding to 400,000 logic gates. This FPGA has 488 pins which the user can freely use and 16,640 logic elements (LEs) which the basic building blocks of a FPGA, containing a 4-input look

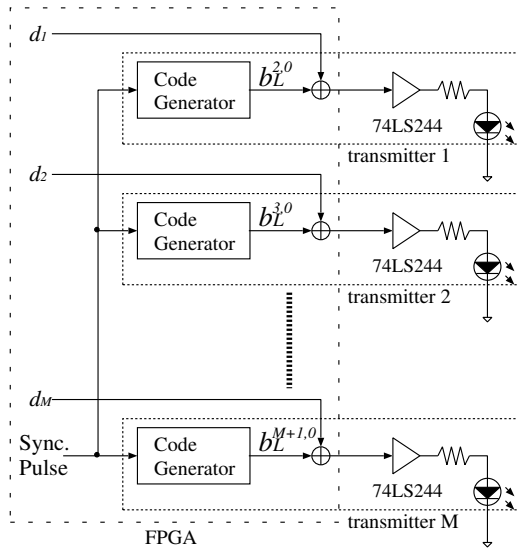


Fig. 2. Free-space optical multiplex data transmission experiment system of optical CDMA system using optical ZCZ codes.

TABLE II
SPECIFICATIONS OF FREE-SPACE OPTICAL MULTIPLEX DATA TRANSMISSION EXPERIMENT SYSTEM OF OPTICAL CDMA SYSTEM USING OPTICAL ZCZ CODES.

Transmitter signal	M-sequence
Sequence period	32,767
Primitive polynomial	$x^{15} + x^1 + x^0$
Number of trials	1,000,000
Spreading sequence	optical ZCZ code
Sequence length $L(N)$	34(32)
Zero correlation zone Z_{cz}	1
Number of multiple M	1, 2, 3, 4
Sequence number j	2, 3, 4, 5
Sampling frequency f_s	60Msps
Chip rate r_c	30Mcps
Bit rate r_b	882.4kbps
Transmission bandwidth B	4kHz to 50MHz
LED Interval h	1cm

up table (LUT), a register, and additional logic. The transmitter 1, 2, ..., M have synchronized by the synchronization pulse.

The influence on the BER performance by an increase in the number of users was verified by the experiment. Figures 3 and 4 show a model and BER performance of free-space multiplex data transmission experiment on optical CDMA system using optical ZCZ codes, whose shifting of optical axis is 0 degree, respectively. The BER performance of optical ZCZ-CDMA system with number of multiple $M = 2, 3$ and 4 goes down a little compared with BER performance with $M = 1$. Therefore, this optical CDMA system can suppress co-channel interference, but can't remove completely co-channel interference.

Next, the influence on the BER performance by shifting of optical axis was verified by the experiment. Figure 5 shows a model of shifting of optical axis. The distance between LED and APD changes if an optical axis shifts. Therefore the optical receiver with short distance of LED and APD is received

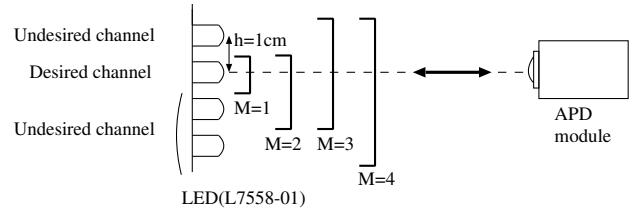
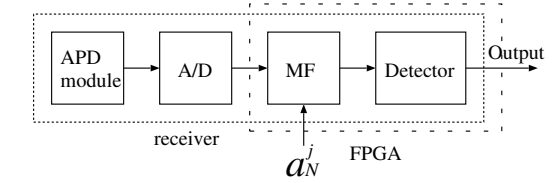


Fig. 3. Model of free-space multiplex data transmission experiment of optical CDMA system using optical ZCZ codes.

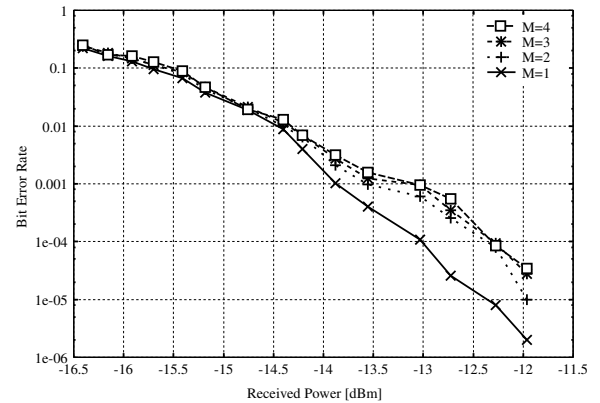


Fig. 4. BER performance of free-space optical CDMA system using optical ZCZ codes, whose shifting optical axis is 0 degree and numbers of multiple are 1, 2, 3 and 4.

early compared with the optical receiver with long distance by shifting of optical axis. In fact, near-far problem happens by shifting of optical axis. Additionally, this problem is influenced also by the transmission directional characteristics of a LED, which is L7558 from Hamamatsu photonics. Figure 6 shows the transmission directional characteristics of a LED, which

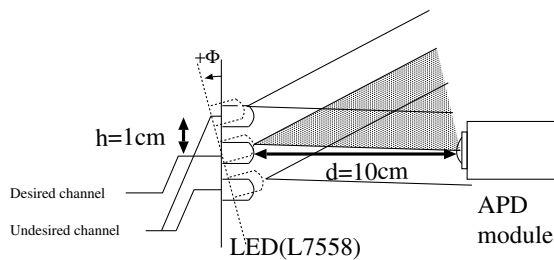


Fig. 5. Model of shifting of optical axis.

is used the data multiplex transmission experiment. Figures 7

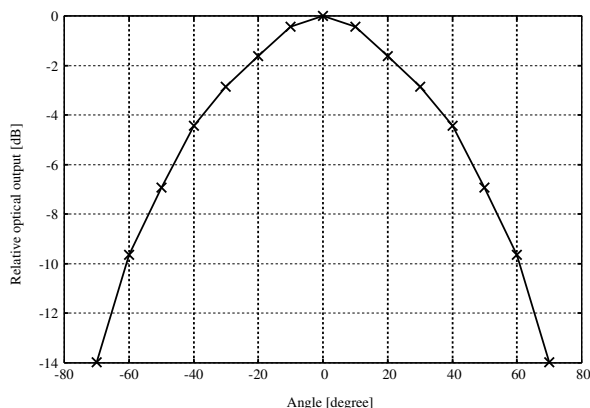


Fig. 6. Transmission directional characteristics of LED, which is L7558 from Hamamatsu Photonics.

shows BER performance of free-space multiplex data transmission experiment of optical CDMA system using optical ZCZ codes, whose shifting optical axis is shifted, distance d between LED and APD is 10cm and number of multiple is 3. As a result of data transmission experiment, interference

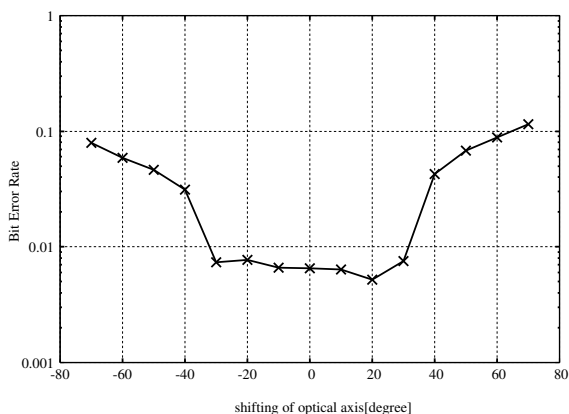


Fig. 7. BER performance of free-space optical CDMA system using optical ZCZ codes, whose optical axis is shifted, distance d between LED and APD is 10cm and number of multiple is 3.

by shifting of optical axis is suppressed from about -30 to 30 degrees.

V. CONCLUSIONS

In this paper, we clarified that the influence of interference by increase in a multiple number and shifting of optical axis on the BER performance by the experiment of data transmission using optical ZCZ-CDMA system, consisting of a infrared light emitting diode(LED), an avalanche photo diode(APD) module and field programmable gate array(FPGA) boards corresponding to 400,000 logic gates.

As a result of data transmission experiment, optical ZCZ-CDMA system can suppress co-channel interference, but can't remove completely co-channel interference, and interference by shifting of optical axis is suppressed from about -30 to 30 degrees.

In the future, it is important to compare other optical wireless systems with the BER performance by computer simulation.

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