The 23rd International Technical Conference on Circuits/Systems,
Computers and Communications (ITC-CSCC 2008)

Experimental Evaluation of Optical ZCZ-CDMA System

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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.

This paper gives and evaluates an optical ZCZ-CDMA wireless communication 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.

1. 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]. An optical CDMA system using the optical ZCZ code, which is a set of pairs of binary and bi-phase sequences with zero correlation zone [4], [5] can remove co-channel interference. This optical CDMA system using the optical ZCZ code is called optical ZCZ-CDMA system. We proposed the compact construction of a code generators [6], [7] and a bank of matched filters [8], [9] for this system.

In this paper, we give and evaluate an optical ZCZ-CDMA wireless communication system[10], 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.

2. Optical ZCZ Codes

Let a_N^j be a bi-phase sequence of length N whose elements take 1 or -1, written as

$$\begin{aligned} a_N^j &= (a_{N,0}^j, a_{N,1}^j, \cdots, a_{N,i}^j, \cdots, a_{N,N-1}^j), \\ & \quad a_{N,i}^j \in \{1,-1\}. \end{aligned} \tag{1}$$

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

$$\begin{aligned} \hat{a}_N^{j,d} &= (\hat{a}_{N,0}^{j,d}, \hat{a}_{N,1}^{j,d}, \cdots, \hat{a}_{N,i}^{j,d}, \cdots, \hat{a}_{N,N-1}^{j,d}), \\ & \quad \hat{a}_{N,i}^{j,d} \in \{1,0\}, d \in \{1,0\}, \end{aligned} \tag{2}$$

where i denotes $i \bmod N$. 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

$$\begin{aligned} A &= \{(a_N^1, \hat{a}_N^{1,d}), (a_N^2, \hat{a}_N^{2,d}), \cdots, (a_N^j, \hat{a}_N^{j,d}), \\ & \quad \cdots, (a_N^M, \hat{a}_N^{M,d})\}. \end{aligned} \tag{3}$$

A periodic correlation function between sequences a_N^j and $\hat{a}_N^{j',d}$ at shift i' is defined by

$$\rho_{a_N^j, \hat{a}_N^{j',d}, i'} = \sum_{i=0}^{N-1} a_{N,i}^j \hat{a}_{N,(i+i') \bmod N}^{j',d}. \tag{4}$$

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[4], [5], if the periodic auto- and cross-correlation functions satisfy

$$\rho_{a_N^j, \hat{a}_N^{j',d}, i'} = \begin{cases} w & ; i' = 0, j = j', d = 0, \\ -w & ; i' = 0, j = j', d = 1, \\ 0 & ; i' = 0, j \neq j', \\ 0 & ; 1 \leq |i'| \leq Zcz, \end{cases} \tag{5}$$

with $w = \sum_{i=0}^{N-1} \hat{a}_{N,i}^{j,d} < N$ and Zcz is zero correlation zone. The optical ZCZ codes are bounded by $M \leq N/(Zcz+1)$, where M is the number of sequences in a sequence family and is called family size.

3. Optical ZCZ-CDMA system

In the optical CDMA system using optical ZCZ codes, $\hat{a}_N^{j,d}$'s, the correlator of 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.

$$\begin{aligned} b_L^{j,d} &= \left(b_{L,0}^{j,d}, b_{L,1}^{j,d}, \cdots, b_{L,i}^{j,d}, \cdots, b_{L,L-1}^{j,d}\right) \\ &= \Big(\underbrace{\hat{a}_{N,N-Zcz}^{j,d}, \cdots, \hat{a}_{N,N-1}^{j,d}}_{Zcz}, \underbrace{\hat{a}_{N,0}^{j,d}, \cdots, \hat{a}_{N,N-1}^{j,d}}_{N}, \\ & \quad \underbrace{\hat{a}_{N,0}^{j,d}, \cdots, \hat{a}_{N,Zcz-1}^{j,d}}_{Zcz}\Big) \\ & \quad b_{L,i}^{j,d} \in \{1,0\}, \end{aligned} \tag{6}$$

where $L = N + 2Zcz$. Figure 1 shows an optical ZCZ-CDMA system using an optical ZCZ code. A transmitter sends binary sequences, $\hat{a}_N^{j,d_j}$'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.

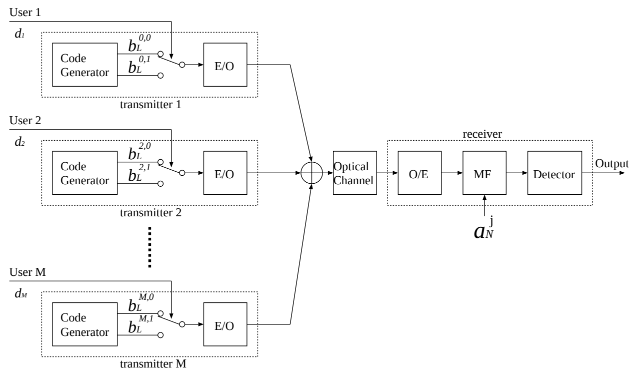

Figure 1. Optical ZCZ-CDMA communication system using an optical ZCZ code.

4. Optical ZCZ Codes for Transmission Channel with Direct Current Interruption Properties

4.1 Problem of free-space optical data transmission using the APD module

Table 1 shows the specifications of optical components used by the free-space optical multiplex data transmission experiment using optical ZCZ-CDMA system. From Table 1, 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. Therefore, the correlator output of zero correlation zone is as follows.

$$\begin{aligned} r_{i'} &= \sum_{i=0}^{N-1} \Big\{ \big(\sum_{j=1}^{M} b_{L,Zcz+i+i'}^{j,d_j}\big) - \bar{b} \Big\} a_{N,i}^{j'} \\ &= \sum_{j=1}^{M} \sum_{i=0}^{N-1} \hat{a}_{N,i+i'}^{j,d_j} a_{N,i}^{j'} - \bar{b} \sum_{i=0}^{N-1} a_{N,i}^{j'} \\ &= \sum_{j=1}^{M} \rho_{a_N^{j'}, \hat{a}_N^{j,d_j}, i'} - \bar{b} \sum_{i=0}^{N-1} a_{N,i}^{j'}, \end{aligned} \quad (7)$$

where $|i'| \leq Zcz$ and $\bar{b}$ is the mean value of multiple received signal $\sum_{j=1}^{M} b_{L,i}^{j,d_j}$. The first and second term in the right side of an equation are ideal and interference component of correlator output, respectively . Therefore, interference can be removed by using bi-phase sequencesa_N^j, which are balanced sequences.

Table 1. Specifications of optical components used by the free-space optical multiplex data transmission experiment system.

Near infrared LED	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	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

4.2 Construction of 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

$$\mathbf{H}_{N_1} = [h_{N_1}^0, h_{N_1}^1, \cdots, h_{N_1}^j, \cdots, h_{N_1}^{N_1-1}]^T, \quad (8)$$

$$h_{N_1}^j = (h_{N_1,0}^j, h_{N_1,1}^j, \cdots, h_{N_1,i}^j, \cdots, h_{N_1,N_1-1}^j), \quad (9)$$
$$h_{N_1,i}^j \in \{1, -1\},$$

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

$$\mathbf{H}_{N_1} = \mathbf{H}_{\frac{N_1}{2}} \otimes \mathbf{H}_2 \quad (10)$$

$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \quad (11)$$

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 $N = 2N_1$ is given by

$$a_{N,i}^j = \alpha_{N,i} \cdot h_{N_1, i \bmod N_1}^j \quad (12)$$

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

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

$$\sum_{i=0}^{N-1} a_{N,i}^j = \sum_{i=0}^{N_1-1} h_{N_1,i}^0 h_{N_1,i}^j - \sum_{i=0}^{N_1-1} h_{N_1,i}^1 h_{N_1,i}^j = 0, \quad (13)$$

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

A binary sequence $\hat{a}_N^{j,d}$ is given by

$$\hat{a}_{N,i}^{j,d} = \frac{1 + (-1)^d a_{N,i}^j}{2} \quad (14)$$

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

$$\rho_{a_N^j, \hat{a}_N^{j',d}, i'} = \begin{cases} \frac{N}{2} & ; i' = 0, j = j', d = 0 \\ -\frac{N}{2} & ; i' = 0, j = j', d = 1 \\ 0 & ; i' = 0, j \neq j' \\ 0 & ; i' = \pm 1 \end{cases} . \quad (15)$$

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 $M = N/2 - 2 = N/(Zcz + 1) - 2$.

As an example, we generate an optical ZCZ code of $N = 2N_1 = 2 \times 4 = 8$, $Zcz = 1$ and $M = N/2 - 2 = 2$. Let

$$\mathbf{H}_4 = \begin{bmatrix} h_4^0 \\ h_4^1 \\ h_4^2 \\ h_4^3 \end{bmatrix} = \begin{bmatrix} + & + & + & + \\ + & - & + & - \\ + & + & - & - \\ + & - & - & + \end{bmatrix},$$

where $+$ and $-$ denote $+1$ and -1, respectively. From Equation (12), we can generate bi-phase sequences, a_8^j's, as follows, respectively.

$$\begin{aligned} a_8^2 &= (+,+,-,-,-,+,+,-), \\ a_8^3 &= (+,-,-,+,-,-,+,+). \end{aligned}$$

From Equation (14), we can generate binary sequences, $\hat{a}_8^{j,d}$'s, as follows, respectively.

$$\begin{aligned} \hat{a}_8^{2,0} &= (+,+,0,0,0,+,+,0), \\ \hat{a}_8^{2,1} &= (0,0,+,+,+,0,0,+), \\ \hat{a}_8^{3,0} &= (+,0,0,+,0,0,+,+), \\ \hat{a}_8^{3,1} &= (0,+,+,0,+,+,0,0). \end{aligned}$$

A set of bi-phase sequences, a_8^j's, and binary sequences, $\hat{a}_8^{j,d}$'s, is an optical ZCZ code with $Zcz = 1$ and $M = 2$.

Its auto-correlation functions are given by

$$\begin{aligned} \rho_{a_8^2, \hat{a}_8^{2,0}, i'} &= (4,0,-2,0,0,0,-2,0), \\ \rho_{a_8^2, \hat{a}_8^{2,1}, i'} &= (-4,0,2,0,0,0,2,0), \\ \rho_{a_8^3, \hat{a}_8^{3,0}, i'} &= (4,0,-2,0,0,0,-2,0), \\ \rho_{a_8^3, \hat{a}_8^{3,1}, i'} &= (-4,0,2,0,0,0,2,0) \end{aligned}$$

and its cross-correlation functions

$$\begin{aligned} \rho_{a_8^2, \hat{a}_8^{3,0}, i'} &= (0,0,2,0,-4,0,2,0), \\ \rho_{a_8^3, \hat{a}_8^{2,0}, i'} &= (0,0,2,0,-4,0,2,0), \\ \rho_{a_8^2, \hat{a}_8^{3,1}, i'} &= (0,0,-2,0,4,0,-2,0), \\ \rho_{a_8^3, \hat{a}_8^{2,1}, i'} &= (0,0,-2,0,4,0,-2,0). \end{aligned}$$

5. Experiment of Free-Space Optical Multiplex Data Transmission of Optical ZCZ-CDMA System

Figure 2 and Table 2 show the block diagram and specifications of free-space optical multiplex data transmission experiment system of 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, respectively. Code generators for M-sequence of period 1023 and optical ZCZ codes of length $N = 32$ and $Zcz = 1$, an 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 up table (LUT), a register, and additional logic.

Table 2. Specifications of free-space optical multiplex data transmission experiment system using optical ZCZ-CDMA system.

Transmitter signal	M-sequence
Sequence period	1023
Primitive polynomial	$x^{10} + x^7 + x^0$
Spreading sequence	optical ZCZ code
Sequence length N	32
Zero correlation zone Zcz	1
Number of multiple	2
Sequence number j	2, 3
Sampling frequency f_s	20Msps
Chip rate r_c	4Mcps
Bit rate r_b	117.7kbps
Transmission bandwidth B	4kHz to 50MHz

Figure 3 shows the experimental result of auto- and cross-correlation outputs of free-space optical multiplex data transmission system using optical ZCZ-CDMA system. As a re-

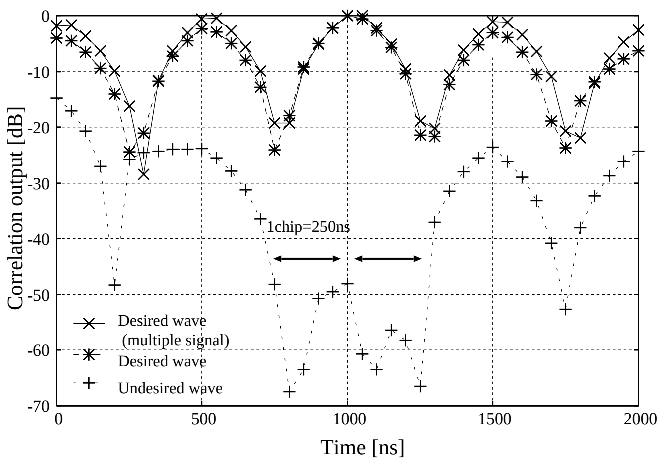

Figure 3. Experimental result of auto- and cross-correlation outputs.

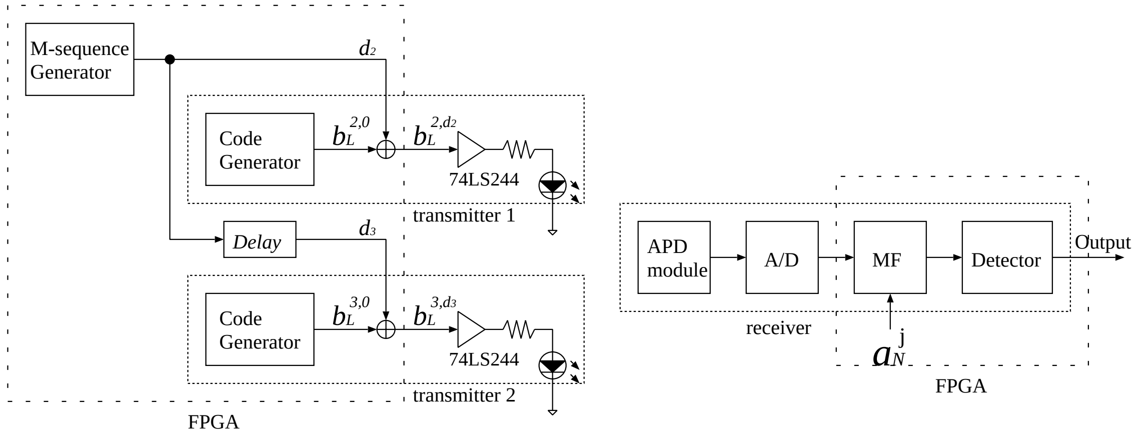

Figure 2. Free-space optical multiplex data transmission experiment system using optical ZCZ-CDMA system.

sult of data transmission experiment, co-channel interference is suppressed in the range of zero correlation zone, which is from 750 to 1,250ns. Desired to undesired signal ratio (DU ratio) in correlation output is improved about 48.0dB .

6. Conclusions

In this paper, we gave and evaluated an optical ZCZ-CDMA wireless communication system, consisting of a infrared light emitting diode(LED), an avalanche photo diode(APD) module and field programmable gate array(FPGA) board. As a result of experiment on the optical multiplex data transmission, it was shown that this system can suppress co-channel interference in the range of zero correlation zone (ZCZ).

Acknowledgements

This work is supported by the Research for Promoting Technological Seeds of the Japan Science and Technology Agency, and VLSI Design and Education Center(VDEC), the University of Tokyo in collaboration with Mentor Graphics, Inc..

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