2019 International Workshop on Smart Info-Media Systems in Asia (SISA 2019), Sep. 4-6, 2019

Research on Optical CDMA System Using Two-Dimensional Optical ZCZ Sequence Set

Ryosuke Shimizu*, Koki Nomura*, Takahiro Matsumoto*, Hideyuki Torii†, Yuta Ida*
and Shinya Matsufuji*
*Yamaguchi University, Japan
†Kanagawa Institute of Technology, Japan

***Abstract*—In this paper, we propose an optical ZCZ-CDMA system using a two-dimensional(2D) optical zero-correlation zone(ZCZ) sequence set that is orthogonal in a 2D zone around shift 0. In order to show the effectiveness of the proposed method, we evaluated the BER characteristics of the optical code-division multiple access(OCDMA) system using a 2D Hadamard sequence or a 2D ZCZ sequence set by computer simulation. As a result, it has been confirmed that the method using the 2D ZCZ sequence set has better BER characteristics than the 2D Hadamard sequences and that the BER is improved by increasing the zero-correlation zone.**

I. Introduction

In optical wireless communication, an optical code-division multiple access (OCDMA) system using a spreading sequence has been proposed as one of the communication systems that enables multiplex transmission without controlling time or wavelength. A spreading sequence for optical wireless communication is used to spread transmission information and consists of N chips, where N is called sequence length or period. Its elements basically take 1 and 0, and its smallest step is called a chip. So far, it has already been clarified that interference between other stations can be suppressed by using a spreading sequence such as an extended prime sequence or an optical zero-correlation zone (ZCZ) sequence set. The transmission time needs T_c to transmit 1bit information if the spread sequence is not used, however, it needs NT_c to that if the spread sequence is used since information is spread on the frequency domain. This means that the transmission rate is reduced to 1 / N by using the spread sequence.

In this paper, we propose an optical ZCZ-CDMA system using a two-dimensional (2D) optical ZCZ sequence set which is orthogonal in the 2D zone around a shift 0. In this method, it is possible to transmit 1bit in 1chip by spreading information to spatial frequency domain, so that information transmission can be performed without reducing the transmission speed. Moreover, although the interference by a light-emitting element which adjoins becomes a problem, it can be solved by using a 2D optical ZCZ sequence set orthogonal in a 2D zone around shift 0. In order to show the effectiveness of the proposed method, we evaluated the BER characteristics of the OCDMA system using a 2D Hadamard sequence or a 2D ZCZ sequence set by computer simulation.

II. Optical ZCZ Sequence Set

A. Definition of Optical ZCZ Sequence Set

An optical ZCZ sequence set is a code that has a zero-correlation zone(ZCZ) and has ideal correlation characteristics in zero-correlation zone [1]–[6]. A bi-phase sequence a_N^j of length N consisting of 1 and -1 is expressed as

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

where, i is an ordinal variable and $0 \le i < N$, and j is a sequence number and $0 \le j < M$. Similarly, a binary sequence $\hat{a}_N^{j,d^j}$ consisting of 1 and 0 is expressed as

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

The Set of pairs of these sequences is expressed as

$$\begin{aligned} A &= \{(a_N^0, \hat{a}_N^{0,d^0}), (a_N^1, \hat{a}_N^{1,d^1}), \cdots, (a_N^j, \hat{a}_N^{j,d^j}), \\ & \quad \cdots, (a_N^{M-1}, \hat{a}_N^{M-1,d^{M-1}})\}. \end{aligned} \tag{3}$$

The periodic correlation function of a bi-phase sequence a_N^j and a binary sequence $\hat{a}_N^{j,d^j}$ is defined as

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

The set of bi-phase sequence a_N^j and binary sequence $\hat{a}_N^{j,d^j}$ of (3) is called an optical ZCZ sequence set [2], [4] having a zero-correlation zone when a periodic correlation function is expressed as

$$\rho_{a_N^j, \hat{a}_N^{j',d^{j'}}, i'} = \begin{cases} (-1)^{d^{j'}} \omega & ; i' = 0,\ j = j', \\ 0 & ; i' = 0,\ j \ne j', \\ 0 & ; 1 \le |i'| \le Zcz. \end{cases} \tag{5}$$

In this paper, for convenience, when the periodic correlation function of (5) is $j = j'$ is called the auto-correlation function, and $j \ne j'$ is called the cross-correlation function.

B. Construction of Optical ZCZ Sequence Set

For the optical ZCZ sequence set, two kinds of construction methods have been proposed for ZCZ:$Zcz = 1$ and $Zcz = 4n_1 - 2$,$n_1 = 1, 2, \cdots$. In addition, ZCZ can be extended by interleaving these optical ZCZ sequence set [2]–[4]. In this paper, we use $Zcz = 2^{n_I}$ generated by interleaving the optical ZCZ sequence set of $Zcz = 1$ and the optical ZCZ sequence set of $Zcz = 4n_1 - 2$. Where n_I is the number of interleavings and $n_I > 0$.

First, we will describe how to construct the optical ZCZ sequence set of $Zcz = 1$. An optical ZCZ sequence of $Zcz = 1$ and length N is generated from a Sylvester-type Hadamard matrix h_N^j of length $N_1 = N/2 = 2^{n_2}$,$n_2 = 2, 3, \cdots$. Let a_N^j be a bi-phase sequence of length N ,which can be expressed as

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

$$\gamma_{N,i} = \begin{cases} h_{N_1,i}^0 & = 1 \quad ; 0 \le i < \frac{N}{2}, \\ -h_{N_1, i \bmod N_1}^1 & = (-1)^{i+1} \quad ; \frac{N}{2} \le i < N, \end{cases}$$

where the Hadamard sequence $h_{N_1}^j$ is a sequence of the j-th line of the $N_1 \times N_1$ Hadamard code $\mathbf{H}_{N_1}$. It is shown below.

$$\mathbf{H}_{N_1} = \left[h_{N_1}^0, h_{N_1}^1, \cdots, h_{N_1}^j, \cdots, h_{N_1}^{N_1-1}\right]^T, \quad (7)$$

$$h_{N_1}^j = \left(h_{N_1,0}^j, h_{N_1,1}^j, \cdots, h_{N_1,i}^j, \cdots, h_{N_1,N_1-1}^j\right), \quad (8)$$

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

where T means transpose. Also, a Hadamard code $\mathbf{H}_N$ is defined as

$$\mathbf{H}_{N_1} = \mathbf{H}_{\frac{N_1}{2}} \otimes \mathbf{H}_2, \quad (9)$$

$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \quad (10)$$

where $\otimes$ is the Kronecker product, $+$ and $-$ are $+1$ and -1. Hadamard sequences have the property that the inner products of different sequences are orthogonal. Therefore, the average value of the bi-phase sequence is 0 except unbalanced sequence numbers $j = 0, 1$. A binary sequence $\hat{a}_{N,i}^{j.d^j}$ corresponding to this bi-phase sequence $a_{N,i}^j$ is expressed as

$$\hat{a}_{N,i}^{j,d^j} = \frac{1 + (-1)^{d^j} a_{N,i}^j}{2}. \quad (11)$$

At this time, the periodic correlation function of the bi-phase sequence $a_{N,i}^j$ and the binary sequence $\hat{a}_{N,i}^{j.d^j}$ which excluding the sequence of sequence numbers $j = 0, 1$ is expressed as

$$\rho_{a_N^j, \hat{a}_N^{j',d^{j'}}, i'} = \begin{cases} (-1)^{d^{j'}} \frac{N}{2} & ; i' = 0, j = j', \\ 0 & ; i' = 0, j \ne j', \\ 0 & ; |i'| = 1, j \ne j'. \end{cases} \quad (12)$$

The set $\{(a_N^2, \hat{a}_N^{2,d^2}), (a_N^3, \hat{a}_N^{3,d^3}), \cdots, (a_N^{N/2-1}, \hat{a}_N^{N/2-1,d^{N/2-1}})\}$ of a pair of bi-phase sequence and binary sequence is a optical ZCZ sequence set [4].

Next, we describe the construction method of $Zcz = 2^{n_I}$ generated by interleaving the optical ZCZ sequence set of the zero-correlation zone $Zcz = 1$. Let $a_{N_2,i}^j$, $N_2 = 2^{n_2} \cdot 2^{n_I - 1} = 2^{n_2 + n_I - 1}$ be the bi-phase sequence of the optical ZCZ sequence set used for interleaving. where, in the interleaving, $j = 0, 1$ lines which are unbalanced sequences are used. A binary sequence α_N^j generated by interleaving is expressed as

$$\begin{aligned} \alpha_N^j = & \Big(a_{N_2,0}^{j-(j \bmod 2)}, (-1)^j a_{N_2,0}^{j+1-(j \bmod 2)}, \\ & a_{N_2,1}^{j-(j \bmod 2)}, (-1)^j a_{N_2,1}^{j+1-(j \bmod 2)}, \\ & \cdots, a_{N_2,N_2-1}^{j-(j \bmod 2)}, (-1)^j a_{N_2,N_2-1}^{j+1-(j \bmod 2)}\Big). \quad (13) \end{aligned}$$

By further interleaving the generated bi-phase sequence α_N^j, it becomes $Zcz = 4, 8, 16, 32, \cdots, 2^{N_I}, \cdots$, and ZCZ is expanded. In the generated bi-phase sequence α_N^j, when the number of interleaving times is $n_I \bmod 2 = 1$, the row of sequence number $j = 1$ is balanced. On the other hand, in the case of $n_I \bmod 2 = 0$, it becomes unbalanced. Also, the lines with sequence number $j = 1$ are always unbalanced regardless of n_I, but all lines after $j = 2$ are balanced. The binary sequence $\hat{\alpha}_N^{j,d^{j'}}$ can be obtained by using the bi-phase sequence $\alpha_{N_2,i}^j$ and (11). The periodic correlation function of a bi-phase sequence $\alpha_{N_2,i}^j$ and a binary sequence $\hat{\alpha}_N^{j,d^{j'}}$ is expressed as

$$\rho_{\alpha_N^j, \hat{\alpha}_N^{j',d^{j'}}, i'} = \begin{cases} (-1)^{d^{j'}} \frac{N}{2} & ; i' = 0, j = j', \\ 0 & ; i' = 0, j \ne j', \\ 0 & ; 1 \le |i'| \le 2^{n_I}. \end{cases} \quad (14)$$

these set of a,b pairs is expressed as a sequence length $N = 2^{n_2 + 2_I}$, zero-correlation zone$Zcz = 2_I^N$,and the number of sequences $M = \frac{N}{2^{n_I+1}} - 2 + (n_I mod 2)$ and becomes a optical ZCZ sequence set [8].

III. 2D Sequence Set

A. Construction of 2D Hadamard Sequence Set

The 2D Hadamard sequence is a matrix representation of a sequence obtained by multiplying the same Hadamard sequence and is orthogonal at shift 0 as in the Hadamard sequence. By preparing the bi-phase sequence $h_{N_1}^k$ obtained from (8) and multiplying the sequence of the same sequence number, a 2D bi-phase sequence $g_{N_1}^j$ consisting of 1 and -1 can be obtained with a length $N_1 \times N_1$. A 2D bi-phase sequence $g_{N_1}^j$ is expressed as

$$g_{N_1}^j = \begin{bmatrix} g_{N_1,0,0}^j & g_{N_1,0,1}^j & \cdots & g_{N_1,0,N_1-1}^j \\ g_{N_1,1,0}^j & g_{N_1,1,1}^j & \cdots & g_{N_1,1,N_1-1}^j \\ \vdots & \vdots & \ddots & \vdots \\ g_{N_1,N_1-1,0}^j & g_{N_1,N_1-1,1}^j & \cdots & g_{N_1,N_1-1,N_1-1}^j \end{bmatrix}, \quad (15)$$

$$g_{N_1,i,k}^j \in \{1, -1\}.$$

Also, a 2D binary sequence $\hat{g}_{N_1}^{j,d^j}$ consisting of 1 and 0 is expressed as

$$\hat{g}_{N_1}^{j,d^j} = \begin{bmatrix} \hat{g}_{N_1,0,0}^{j,d^j} & \hat{g}_{N_1,0,1}^{j,d^j} & \cdots & \hat{g}_{N_1,0,N_1-1}^{j,d^j} \\ \hat{g}_{N_1,1,0}^{j,d^j} & \hat{g}_{N_1,1,1}^{j,d^j} & \cdots & \hat{g}_{N_1,1,N_1-1}^{j,d^j} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{g}_{N_1,N_1-1,0}^{j,d^j} & \hat{g}_{N_1,N_1-1,1}^{j,d^j} & \cdots & \hat{g}_{N_1,N_1-1,N_1-1}^{j,d^j} \end{bmatrix}, \quad (16)$$

$$\hat{g}_{N_1,i,k}^{j,d^j} \in \{1,0\}.$$

At this time, the periodic correlation function of the bi-phase sequence $g_{N_1}^{j}$ and the binary sequence $\hat{g}_{N_1}^{j,d}$ is expressed as

$$\rho_{g_{N_1}^{j},\hat{g}_{N_1}^{j',d^{j'}},i'} = \sum_{k=0}^{N_1-1}\sum_{i=0}^{N_1-1} g_{N_1,i,k}^{j}\hat{g}_{N_1,(i+i') \bmod N_1,N_1,(k+k') \bmod N_1}^{j',d^{j'}} \quad (17)$$

Therefore, The set of bi-phase sequence $g_{N_1}^{j}$ and binary sequence $\hat{g}_{N_1}^{j,d}$ in (15) and (16) is called a 2D Hadamard sequence when the periodic correlation function is expressed as

$$\rho_{g_{N_1}^{j},\hat{g}_{N_1}^{j',d^{j'}},i'} = \begin{cases} (-1)^{d^{j'}}\omega' & ; i'=0, k'=0,\ j=j', \\ 0 & ; i'=0, k'=0,\ j\neq j'. \end{cases} \quad (18)$$

B. Construction of 2D Optical ZCZ Sequence Set

The 2D optical ZCZ sequence set is a matrix representation of a sequence obtained by multiplying the optical ZCZ sequence set and has the property of being orthogonal in a 2D zone around a shift 0. In this paper, we use two sets of optical ZCZ sequence of the same sequence length so that ZCZ has the same size in both axes. By preparing the bi-phase sequence a_N^j obtained from (1) and multiplying the sequence of the same sequence number, a 2D bi-phase sequences b_N^j consisting of 1 and -1 of length $N \times N$. 2D bi-phase sequences b_N^j can be expressed as

$$b_N^j = \begin{bmatrix} b_{N,0,0}^{j} & b_{N,0,1}^{j} & \cdots & b_{N,0,N-1}^{j} \\ b_{N,1,0}^{j} & b_{N,1,1}^{j} & \cdots & b_{N,1,N-1}^{j} \\ \vdots & \vdots & \ddots & \vdots \\ b_{N,N-1,0}^{j} & b_{N,N-1,1}^{j} & \cdots & b_{N,N-1,N-1}^{j} \end{bmatrix}, \quad (19)$$

$$b_{N,i,k}^{j} \in \{1,-1\}.$$

Similarly, a 2D binary sequence $\hat{b}_N^{j,d^j}$ consisting of 1 and 0 is expressed as

$$\hat{b}_N^{j,d^j} = \begin{bmatrix} \hat{b}_{N,0,0}^{j,d^j} & \hat{b}_{N,0,1}^{j,d^j} & \cdots & \hat{b}_{N,0,N-1}^{j,d^j} \\ \hat{b}_{N,1,0}^{j,d^j} & \hat{b}_{N,1,1}^{j,d^j} & \cdots & \hat{b}_{N,1,N-1}^{j,d^j} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{b}_{N,N-1,0}^{j,d^j} & \hat{b}_{N,N-1,1}^{j,d^j} & \cdots & \hat{b}_{N,N-1,N-1}^{j,d^j} \end{bmatrix}, \quad (20)$$

$$\hat{b}_{N,i,k}^{j,d^j} \in \{1,0\}.$$

At this time, the periodic correlation function of the bi-phase sequence b_N^j and the binary sequence $\hat{b}_N^{j,d^j}$ is defined as

$$\rho_{b_N^j,\hat{b}_N^{j',d^{j'}},i'} = \sum_{k=0}^{N-1}\sum_{i=0}^{N-1} b_{N,i,k}^{j}\hat{b}_{N,(i+i') \bmod N,N,(k+k') \bmod N}^{j',d^{j'}}. \quad (21)$$

Therefore, the set of bi-phase sequence b_N^j and binary sequence $\hat{b}_N^{j,d^j}$ in (21) is referred to as a 2D optical ZCZ sequence set when the periodic correlation function is expressed as

$$\rho_{b_N^j,\hat{b}_N^{j',d^{j'}},i'} = \begin{cases} (-1)^{d^{j'}}\omega' & ; i'=0, k'=0,\ j=j', \\ 0 & ; i'=0, k'=0,\ j\neq j', \\ 0 & ; 1 \le |i'|, |k'| \le Zcz. \end{cases} \quad (22)$$

IV. Transmission Model

This section describes the transmission model used in this simulation. The transmission model of this simulation is shown in Figure 1, and the model when the light receiving surface is viewed from the front is shown in Figure 2. In this

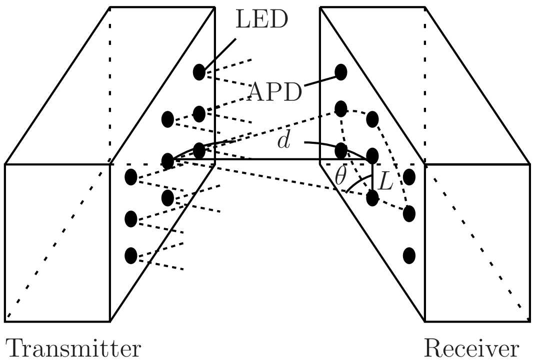

Fig. 1. Transmission model.

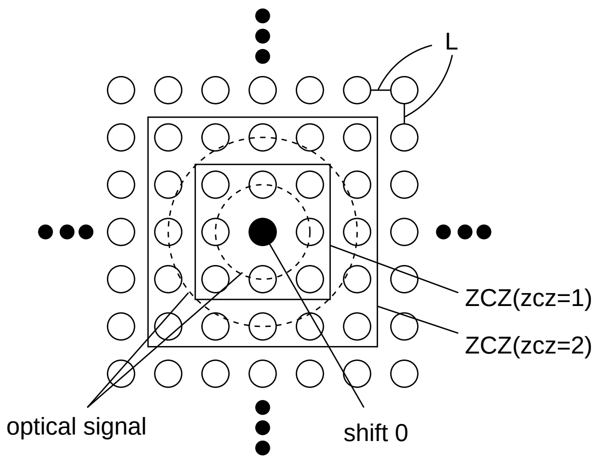

Fig. 2. Light receiving surface.

simulation, a LED(light-emitting diode) is used as a light emitting element, and an APD(avalanche photodiode) is used as a light receiving element. The LEDs and APDs are equally spaced so that both have a square shape, and it is assumed that they are directly opposite each other. Then, the created 2D ZCZ sequence set is assigned to each of the light emitting elements and transmitted. That is, the size of the 2D optical ZCZ sequence set is equal to the number of light emitting elements and the light receiving elements. In this section, since a 2D optical ZCZ sequence set with a sequence length, $N \times N = 32 \times 32$ is used, the number of LEDs and APDs is 32×32 respectively. The spread of light is closely related to the distance d [m] between the transmitter and the receiver, the directivity of the LED and the directivity of the APD. The portion surrounded by the dotted line in Figure 2 is the spread of light. As the light spreads, the number of APDs that cause interference increases, and the degree of interference that occurs in adjacent APDs also increases. Therefore, when a 2D ZCZ sequence set is used, interference can be prevented with respect to the portion enclosed by a square of Figure 2 according to the size of the zero-correlation zone. So, it is thought that it leads to the improvement of communication quality.

V. Evaluation by Computer Simulation

A. Experimental Specifications

This section describes evaluation by computer simulation. First, in the case of one user, the difference between the 2D Hadamard sequence and the 2D optical ZCZ sequence set, the difference in the size of the zero-correlation zone, and the difference in distance between transceivers are evaluated by the BER characteristics using computer simulation. Next, in the case of two users, the same evaluation as above is performed. The simulation specifications are shown in Tab. I.

TABLE I
Experimental specifications.

Diffusion sequence	2D Hadamard sequence, 2D optical ZCZ sequence set
Sequence length $N \times N$	32×32
Zero-correlation zone Zcz	1,2,4
Number of trials	10^5
Light wavelength λ	830[nm]
APD quantum efficiency η	0.6
APD gain G	100.0
APD ionization coefficient K_{eff}	0.02
Bulk leakage current I_b	0.1[nA]
Surface leakage current I_s	10[nA]
Modulation loss ratio M_e	100.0
Receiver noise temperature T_r	1100.0[K]
Receiver load resistance R_L	1030.0[Ω]
Background noise P_b	-45.0[dBm]
Distance between LED and APD L	1.0[m]
Distance between each LED (APD) d	$0 \sim 1.20$[m]
Number of APDs affected No	$0 \sim 48$
Chip rate r_c	3744[Mcps]

B. Comparison of 2D Hadamard Sequence, 2D Optical ZCZ Sequence Set and Comparison of Zero-correlation zone, Difference in Distance between Transceivers in the Case of One User

First, we compare the BER characteristics when using a 2D Hadamard sequence and when using a 2D optical ZCZ sequence set, and compare the BER characteristics when changing the zero-correlation zone. Figures 3, 4, 5, and 6 show BER characteristics when using a 2D Hadamard sequence and a 2D optical ZCZ sequence set at $Zcz = 1, 2, 4$. In the above figure, the distance d between the transmitter and the receiver is extended, and the BER characteristics are shown when another APDs exceeds a certain value when receiving interference. Therefore, interference is gradually received from the APD close to the APD where the shift is 0, and the number No increases as $No = 0$, 4, 8, 12, 20, 24, 28, 36, 44, 48. Although the BER characteristics deteriorate as the number of interfering APDs increases in all cases, it can be seen that the 2D ZCZ sequence set has better BER characteristics than the 2D Hadamard sequence. In addition, as the zero-correlation zone increases, the range in which the interference can be suppressed increases, so it can be seen that the BER characteristics are better. Next, in order to compare each BER characteristic, the transmission power

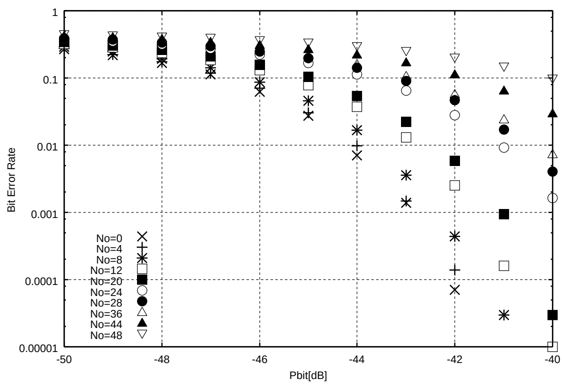

Fig. 3. BER characteristic(2D Hadamard sequence, auto-correlation).

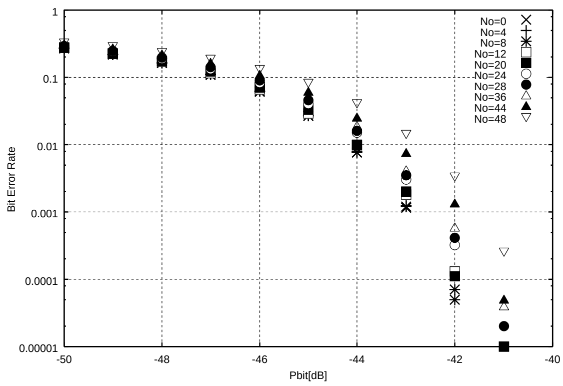

Fig. 4. BER characteristic($Zcz = 1$, auto-correlation).

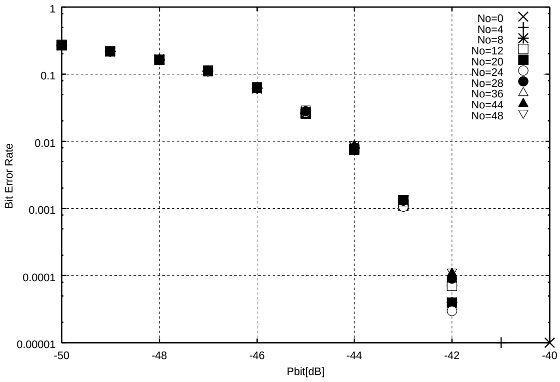

Fig. 5. BER characteristic($Zcz = 2$, auto-correlation).

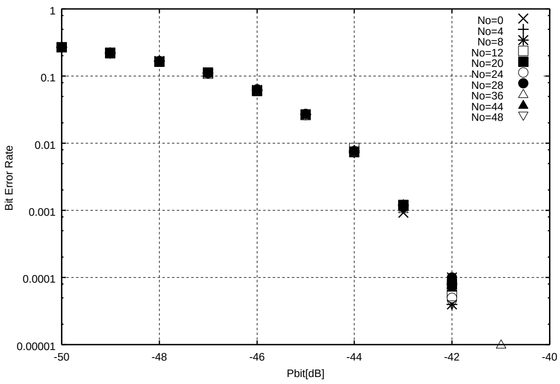

Fig. 6. BER characteristic($Zcz = 4$, auto-correlation).

is fixed at $P_{bit} = -42[dB]$, and each BER characteristic when the horizontal axis is a distance is shown in Figure 7 . Compared with the 2D Hadamard sequence, the BER

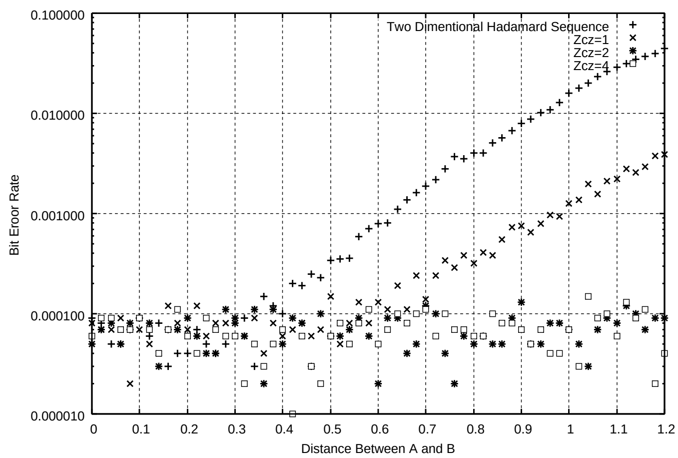

Fig. 7. BER characteristic(Pbit=-42[dB], auto-correlation).

characteristics deteriorate as the distance increases from $d = 0$, but the 2D optical ZCZ sequence set maintains a constant BER up to the range of the zero-correlation zone. In addition, the larger the zero-correlation zone Zcz, the wider the range for maintaining a constant BER. From the above, it can be said that the 2D optical ZCZ sequence set is effective for suppressing the interference of light, and the range that can be suppressed is extended as the zero-correlation zone becomes larger.

C. Comparison of 2D Hadamard Sequence, 2D Optical ZCZ Sequence Set and Comparison of Zero-correlation zone, Difference in Distance between Transceivers in the Case of Two Users

Next, consider the case where cross-correlation considered in the above-mentioned simulation. As in the case of auto-correlation, the BER characteristics when using a 2D Hadamard sequence and a 2D optical ZCZ sequence set at $Zcz = 1, 2, 4$ are shown in Figure 8, 9, 10 and 11. In addition, the BER characteristics when the transmission power is fixed are shown in Figure 12. Although the BER is getting worse

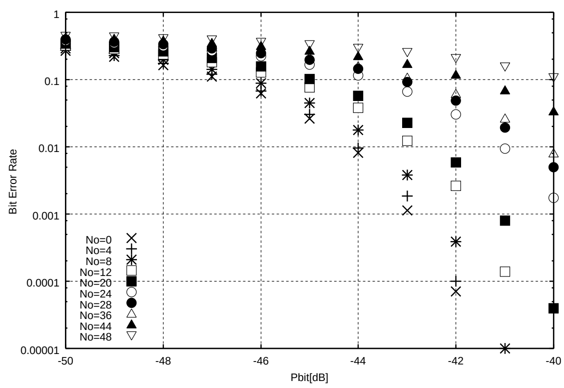

Fig. 8. BER characteristics(2D Hadamard sequence, cross-correlation).

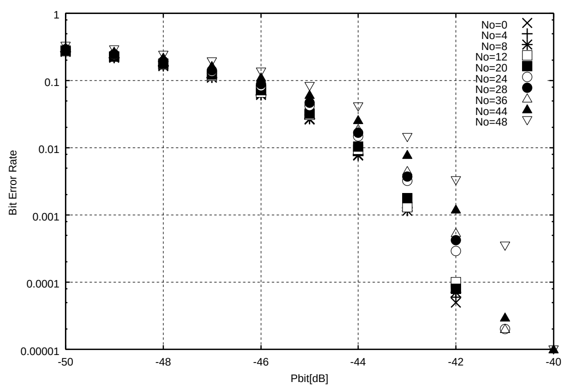

Fig. 9. BER characteristics($Zcz = 1$, cross-correlation).

due to the influence of the cross-correlation, the same tendency as the auto-correlation is obtained. From this, even if there are multiple users, the proposed method is considered to be effective.

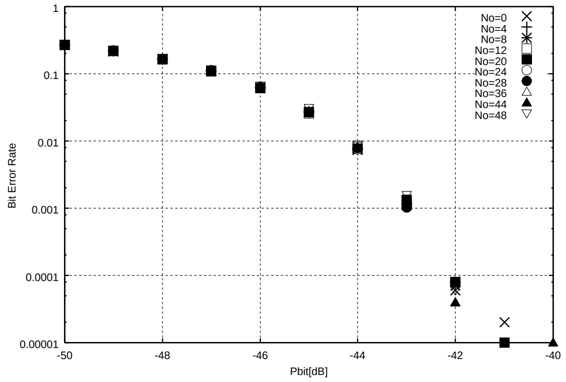

Fig. 10. BER characteristics($Zcz = 2$, cross-correlation).

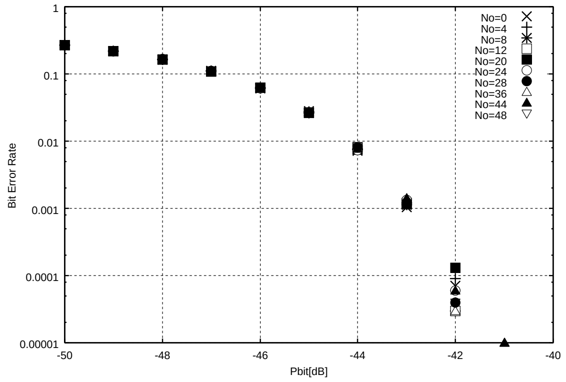

Fig. 11. BER characteristics($Zcz = 4$, cross-correlation).

VI. Conclusion

In this paper, we propose an optical ZCZ-CDMA system using a 2D optical ZCZ sequence set. Then, in order to show the effectiveness of the proposed method, the BER characteristics of the OCDMA system using the 2D Hadamard sequence and the 2D optical ZCZ sequence set were evaluated by computer simulation. First, in the case of one user, the BER characteristics were evaluated for differences due to the above sequences, differences due to the size of the zero-correlation zone, and differences when the distance between the light emitting element LED and the light receiving element APD was changed. Furthermore, in the case of two users, the BER characteristics were similarly evaluated.

As a result, it has been confirmed that the OCDMA system using the 2D optical ZCZ sequence set that is orthogonal in around shift 0 has better BER characteristics than the 2D Hadamard sequence that is orthogonal only at shift 0. It was also confirmed that the BER characteristics improved by increasing the zero-correlation zone. Furthermore, even if the distance between the LED and the APD is extended, it is confirmed that the BER characteristics do not deteriorate if the range affected by the interference of the transmission light can be contained in the zero-correlation zone in the proposed method. And it was confirmed that the same tendency as in

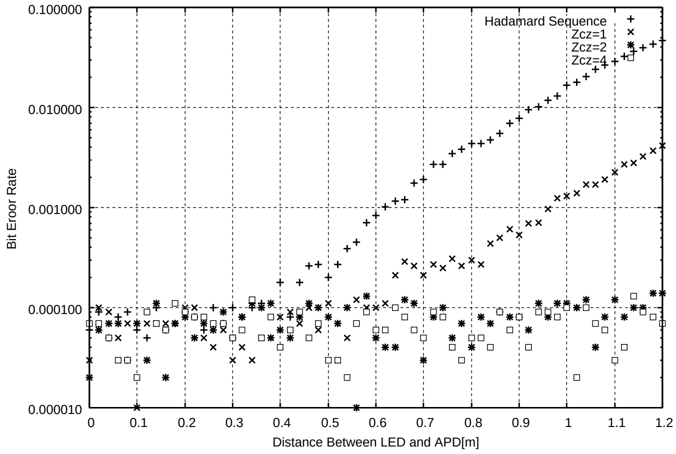

Fig. 12. BER characteristics(Pbit=-42[dB], cross-correlation).

the case of one user can be obtained even in the case of two users.

Acknowledgement

This work is supported by the Japan Society for the Promotion of Science(JSPS), Grant-in-Aid for Scientific Research(C)(18K04145), and the Telecommunication Advancement Foundation (TAF) Grant.

References

[1] T. Takahashi, S. Matsufuji, T. Matsumoto, Y. Tanada, "An optical CDMA system using extended ZCZ sequences," IEICE Technical Report, WBC2003-83, pp. 19-23, 2003.
[2] S. Matsufuji, T. Matsumoto, Y. Tanada, N. Kuroyanagi, "ZCZ codes for ASK-CDMA system,“ IEICE Trans. Fundamentals, vol.E89-A, no.9, pp.2268-2274, 2006.
[3] T. Takahashi, S. Matsufuji, T. Matsumoto, Y. Tanada, "Study on an optical ZCZ code and its applications to optical CDMA communication,", IEICE Technical Report, WBC2004-308, pp. 107-112, 2005.
[4] T. Matsumoto, H. Torii, S. Matsufuji, "Theoretical analysis of BER performance of optical ZCZ-CDMA system,“ International Journal of Computers and Communications., vol.7, issue 1, pp.18-25, 2013.
[5] Y. Suwaki, T. Matsumoto, S. Matsufuji, "Experimental evaluation of optical ZCZ-CDMA system,“ Proc. of the 23rd International Technical Conference on Circuits/Systems, Computers and Communications., pp.1809-1812, 2008.
[6] T. Matsumoto, Y. Ohira, S. Muranaga, H.Torii, Y. Ida, S. Matsufuji, "Trial of free-space parallel transmission system based on optical ZCZ-CDMA system,“ Proc. of the 6th International Workshop on Signal Design and Its Applications in Communications., pp.130-133, 2013.
[7] T. Matsumoto, Y. Ohira, H.Torii, Y. Ida, S. Matsufuji, "Study on BER performance of atmospheric optical ZCZ-CDMA system using equal gain combining,“ Proc. of RISP International Workshop on Nonlinear Circuits, Communications and Signal Processing., pp.521-524, 2014.
[8] T. Hayashida, T. Matsumoto, S. Matsufuji, "Design of ZCZ codes with a sharp aperiodic autocorrelation function," The 32nd Symposium on Information Theory and Its Applications., pp. 588-591, 2009.