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Proposal of Two-Dimensional Self-Matching Receiver Using Chaotic Spatial Synchronization for Free Space Optics Communication System and Its Application to Image Transmission and Code Division Multiplexing

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SUMMARY This paper proposes a two-dimensional self-matching receiver for Free Space Optics (FSO) communication system using chaotic spatial synchronization. This system is able to obtain the information of two-dimensional code from received pattern. This paper considers that proposed system is applied to two applications. The first application is image transmission. This paper shows that applying proposed system to image transmission enables to restore the desired image, which doesn't require strict alignment of receiver, and evaluates transmission optical power. The second application is Code Division Multiplexing (CDM). This paper shows that applying proposed system to CDM system enables to demodulate desired digital signals regardless of the uncertainty of received position. Moreover, the required transmission optical power and bit error rate performance are obtained by computer simulation.

key words: *image transmission, intensity pattern, self-matching receiver, chaotic spatial synchronization, projection system*

1. Introduction

FSO communication has been attracting increasing attention in recent years as a solution to the so-called last-mile problem [1], [2]. FSO communication links are free from electromagnetic interference, and enable to utilize wireless communication in such as the medical centers, research facilities and the other places where is difficult to use electromagnetic wave owing to effect to electric instruments. Moreover, optical spectrum is not regulated, and thus, capacity values are only limited by technological constraints. Therefore, FSO communication has prospects of high speed and high capacity communication.

FSO links can employ various designs. Among them nondirected-non-LOS FSO link design, which is often referred to as a diffuse link, is thought of as the most appropriate design for mobile communication, because this design doesn't require strict aiming between transmitter and receiver and has a tolerance against shielding of links due to obstacles [3]. Projection FSO system illustrated in the center of Fig. 1 is one of the candidates of nondirected-non-LOS link design. HIEI Projector (Harmonious Invisible Extended Information Projector) [4] has been proposed as one of these FSO systems. HIEI Projector projects visible and infrared light in parallel. Additional information of visible information could be transmitted by projecting infrared light to mobile terminals using optical on-off keying scheme.

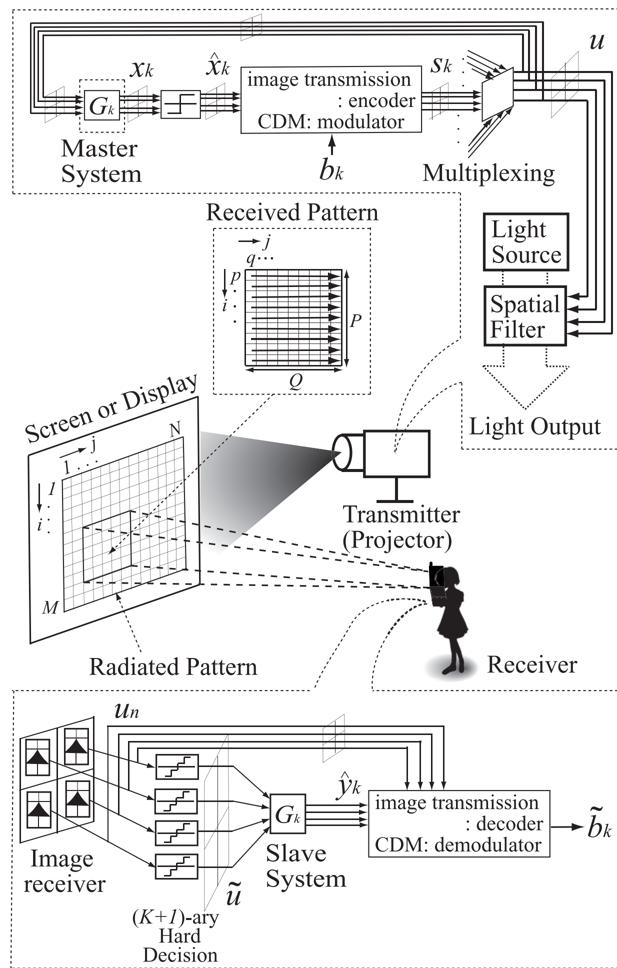

Fig. 1 System model.

Spatial coded diffuse FSO system which can be applied to image transmission or multiplexing system is considered in this paper as an extended system. For image transmission system, access control and protecting confidential are very important. For multiplexing communication system,

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two-dimensional code enables to transmit chips in parallel, thus high-speed parallel or high-capacity multiuser CDM systems can be realized.

As a two-dimensional code, for example, Optical Orthogonal Signature Pattern (OOSP) [5], [6] has been proposed. In [5], [6], image and parallel transmission system using multicore fiber have been proposed by using OOSP as a signature code. As an other example, M-array which is arranged M-sequence into two-dimensional array is proposed and applied to two-dimensional positioning and image transmission [7], [8].

In Fig. 1, spatial coded diffuse FSO system have a problem that receiver needs position information of its own in imaged elements in order to achieve code synchronization. In addition, generally the receiver cannot receive whole incident radiation pattern and there is an uncertainty of received position. Therefore, two-dimensional code synchronization cannot be achieved and correlation characteristics will be deteriorated. The purpose of this paper is to overcome these problems in spatial coded diffuse FSO system. Whereat, self-matching receiver using chaotic spatial synchronization [9], [10] is proposed. This is the system that enables to synchronize variant two-dimensional chaotic codes and regenerate two-dimensional code in the receiver without complicated code synchronization processes.

In Sect. 2, principles of chaotic spatial synchronization are shown. In Sect. 3, applying proposed system to image transmission system is introduced and it is shown that restoring the desired image is enabled in spite of uncertainty of received position by computer simulation. In Sect. 4, applying CDM method is introduced and it is shown that this system enables to demodulate the desired digital signals under the condition that there are uncertainties of received position. Finally, the conclusions are presented in Sect. 5.

2. Chaotic Spatial Synchronization

In this section, the principles of chaotic spatial synchronization and advantage of proposed system are indicated. Figure 1 shows configuration of proposed system. To expanding chaotic synchronization [11], [12] to two-dimension, two-dimensional state variables are introduced. In a master system, two-dimensional state variables $x_k(i, j)$, $k = 1, 2, \cdots, K$, where K is the maximum number of multiplexing are generated by the corresponding chaotic maps, G_k which are inherent for each system. The recurrence equation of $x_k(i, j)$, which has an arbitrary initial value, $x_k(i, 1)$, is expressed by

$$x_k(i, j+1) = a \cdot x_k(i, j) + G_k(u(i.j)) \tag{1}$$

where $|a| < 1$ is the constant, and (i, j), $i = 1, 2, \cdots, M$, $j = 1, 2, \cdots, N$ denote the positions of pixels. State variables $x_k(i, j)$ are quantized to binary code $\hat{x}_k(i, j)$ by the use of A/D converter. Encoded signal $s_k(i, j)$ is obtained by inputting $\hat{x}_k(i, j)$ and information bit $b_k(i, j)$. The two-dimensional Globally Coupled Maps, $u(i, j)$ is defined as

$$u(i, j) = \sum_{k=1}^{K} s_k(i, j) \tag{2}$$

k-th spatial filter, who have $M \times N$ [pixels] generates two-dimensional chaos pattern according to Eq. (2), externally modulates the spatial light intensity. Spatially modulated optical signal is radiated on the screen by projector. A part of projected intensity pattern on the screen is imaged by the receiver ($P \times Q$ [pixels]). Since the element of imaged pattern can be considered as the $(K + 1)$-ary Pulse Intensity Modulation format, detected photocurrent is compared with a set of K thresholds. Obtained $\tilde{u}(i, j)$ is input to the slave system. In the slave system, G_k is identical to the master system's one. Correspondingly, state variable is regenerated by the recurrence equation with its initial value of $y_k(i, q)$,

$$y_k(i, j+1) = a \cdot y_k(i, j) + G_k(\tilde{u}(i.j)) \tag{3}$$

where $i = p, p+1, \cdots, p+P-1$, $j = q, q+1, \cdots, q+Q-1$ and (i, j) represents the position of the element of imaged intensity at the receiver. Inputting $y_k(i, j)$ into A/D converter, $\hat{y}_k(i, j)$ in binary format is produced. Chaotic synchronization with $\hat{x}_k(i, j)$ is caused when $u(i, j) = \tilde{u}(i, j)$. Therefore, $\hat{y}_k(i, j)$ can be utilized as the reference signal that is a replica pattern of $\hat{x}_k(i, j)$. In decoder, decoded signal $\tilde{b}_k$ is generated by utilizing $\hat{y}_k(i, j)$ and received signal $u_n(i, j)$. $u_n(i, j)$ is a received pattern added noise in the image receiver.

This system enables to regenerate two-dimensional code $\hat{x}_k(i, j)$ from received signal $\tilde{u}(i, j)$, thus it is enabled to decode information signal without pilot signals or calculation about receiver position, which requires complicate and time-consuming processes. In following section, we elaborate two effective applications in proposed system, image transmission and CDM systems.

3. Image Transmission System

3.1 System Configuration

In this section, it is considered that proposed system is applied to image transmission system. Spatiotemporal chaotic code $\hat{x}_k(i, j)$ is generated according to the Eq. (1). The chaotic map used in generation is presented as

$$G_k(u(i, j)) = \mathrm{mod}((u(i, j) + d_k)^2) \tag{4}$$

where mod (X) denotes fractional part of X. Figure 2(a) shows configuration of encoder. Output signal of encoder $s_k(i, j)$ is expressed by

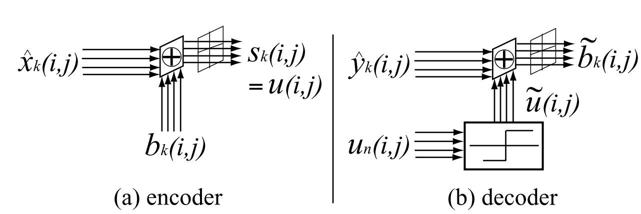


Fig. 2 Configuration of the encoder and decoder.

$$s_k(i, j) = b_k(i, j) \oplus \hat{x}_k(i, j) \tag{5}$$

where $\oplus$ means exclusive OR operation, $b_k(i, j)$ denotes an image source data with binary-bit format. Transmitting pattern is expressed by $u(i, j) = s_k(i, j)$. As an image receiver, PD array is employed. Figure 2(b) shows configuration of decoder. Output signal of decoder is acquired by

$$\tilde{b}_k(i, j) = \tilde{u}(i, j) \oplus \hat{y}_k(i, j) \tag{6}$$

3.2 Simulation of Image Transmission

It is shown that spatiotemporal chaotic code doesn't require strict alignment of receiver position and imaged elements by comparing to M-array. M-array is obtained by arranging M-sequence $a(l)$ generated with m columns shift register in two-dimensional array $W_i \times W_j$ [pixels]. The method of arranging in two-dimensional array is expressed by $i = l(\mathrm{mod}\ W_i)$ and $j = l(\mathrm{mod}\ W_j)$. The two-dimensional autocorrelation characteristic of M-array has a shape peak value at the origin.

It is assumed that optical source power is enough large to occur no error of transmitted pattern in the FSO link. In addition, it is assumed that the desired image for user k-th is a part of source image $b_k(i, j)$, which is presented the area in dashed line as shown in Fig. 3. Figure 4 shows simulation results of restored image in the case of no misalignment of receiver when user points a receiver at a desired part of transmitted image. Figure 5 shows ones in the case that there is one pixels misalignment of receiver i-axially. In Fig. 4, M-array system can restore image accurately due to the complete reconstruction of local M-array (Fig. 4(a)). On the other hand, proposed system generates errors in parts of chaotic spatial chaos synchronization proceeding, but it can be said that a desired part of image is restored (Fig. 4(b)). Correspondingly, in Fig. 5, M-array system can't restore image at all due to uncertainty of two-dimensional code corresponding each pixels of received pattern, and proposed system can restore most of desired image because two-dimensional code is regenerated from received pattern. These results shows that proposed system is able to restore desired image except for parts of spatial chaotic synchronization proceeding in spite of the misalignment of receiver.

3.3 Required Optical Source Power

In this section, the required transmission optical power of proposed system is evaluated by computer simulation. Figure 6 illustrates the typical gist of the FSO link model of diffuse optical channel [13], [14]. It is assumed that the screen is an ideal Lambertian reflector and the gain of an optical fil-

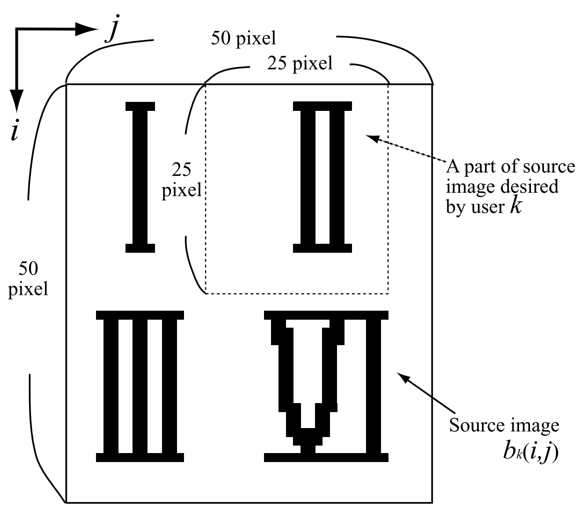


Fig. 3 Source image used in the simulation.

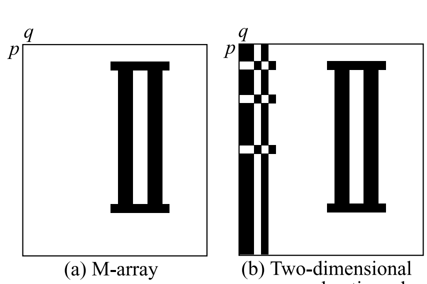


Fig. 4 Restored pattern when there is no misalignment of receiver.

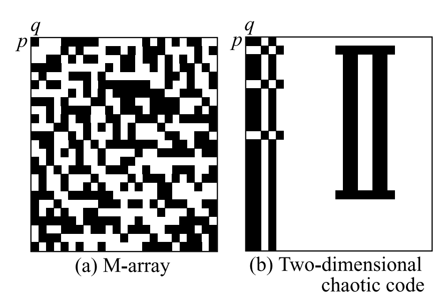


Fig. 5 Restored pattern when there is a i-axial 1 pixel misalignment.

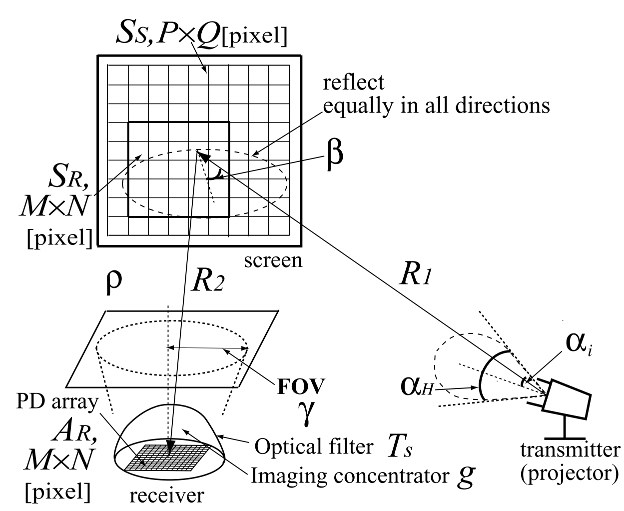


Fig. 6 Analysis model of FSO link.

Table 1 Parameter used for simulation.

α_i	0°	α_H	60°
β	0°	γ	14.2°
R_1	43.3 [cm]	ρ	0.9
T_s	1.0	g	1.0
m	12	a	0.3
d_k	1.9937	$P\times Q$	25^2 [pixels]
Distance between screen and receiver, R_2			1.0 [m]
Quantum efficiency of PD, η			0.95 [A/W]
Signal Wavelength, λ			1550 [nm]
Load resistance, R_L			50 [Ω]
Bandwidth, B			10 [kbps]
Absolute temperature, T			300 [K]
Background light noise, P_b			1.0 [A/m^2]
The number of transmitted pixels, $M\times N$			50^2 [pixels]
The number of pixels of M-array, $W_i\times W_j$			63×65 [pixels]
Transmitted area on screen, S_s			50^2 [cm^2]
Received area on screen, S_R			25^2 [cm^2]
Physical area of detector in a PD, A_R			1.6^2 [mm^2]

ter T_s and the gain of imaging concentrator g is constant relative to the angle of incidence. The received optical power per a pixel P_R is expressed by

$$P_R = \frac{1}{2\pi R_1^2}\left(1-\frac{\ln 2}{\ln(\cos\alpha_H)}\right)P_s\rho A_1 T_s g \cos^n\alpha_i \cos\beta \sin^2\gamma \tag{7}$$

where P_s is the transmission optical power radiated from projector, α_i is the beam directivity, α_H is the beam divergence angle, β is the angle of incidence on the screen, $0° < \gamma \leq 90°$ is the field of view (FOV) of receiver, R_1 is the distance between the projector and the screen, ρ is the reflection coefficient and A_1 is the photosensitive area of a pixel. Furthermore, shot noise, background light and thermal noise are considered as noise source. It is considered that each pixels in PD-array is the binary Intensity Modulation/Direct Detection (IM/DD) receiver. Furthermore, it is assumed that the threshold level D is optimized and expressed by

$$D = \frac{\sigma_0}{\sigma_0+\sigma_1}\cdot i(1) \tag{8}$$

where σ_κ is the noise power generated in receiver when information bit of a pixel, $b_k(i,j) = \kappa$ is transmitted. $i(1)$ is the peak level of photocurrent when mark ($b_k(i,j) = 1$) is received. It is assumed that $b_k(i,j) = 0$ and $b_k(i,j) = 1$ are transmitted identically. Thus, the probability of error in a pixel of the image receiver is expressed by

$$p(E) = \frac{1}{2}\mathrm{erfc}\left[\frac{i(1)}{\sqrt{2}(\sigma_0+\sigma_1)}\right] \tag{9}$$

The parameters used for simulation are shown in Table 1. Figure 7 shows simulation result indicating the transmission optical power versus pixel error rate of image in the cases of no misalignment and 1 pixel misalignment in i-axis. In the case of M-array pixel error rate is improved by enhancing transmission optical power under the condition of no misalignment of receiver. However, under the condition that there is a misalignment of receiver pixel error rate doesn't improve even if transmission optical power is enhanced. In contrast, pixel error rate of proposed system is improved by enhancing transmission optical power to about 0.11 under the condition both of there is a misalignment and no misalignment. As shown in previous simulation in Figs. 4 and 5, if pixel error rate less than 0.2 is achieved, the error is ignorable for the discrimination of restored image. It is considered that because pixel error is generated in a part of chaotic spatial synchronization necessarily, pixel error rate doesn't decrease less than about 0.11. It is evaluated that proposed image transmission system requires transmission optical power of −8 [dBm] from this simulation.

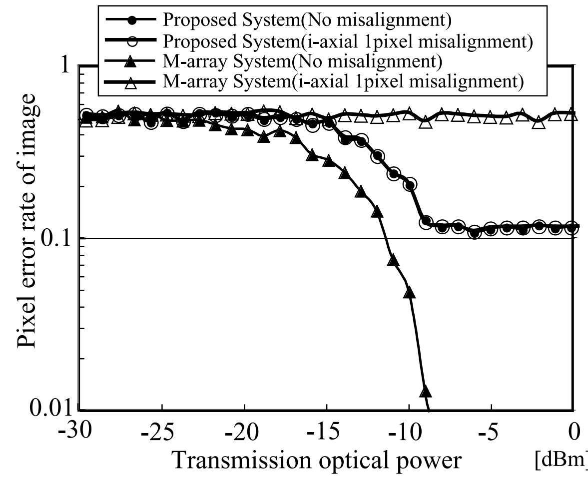


Fig. 7 Transmission optical power versus pixel error rate of image.

4. Code Division Multiplexing System

4.1 System Configuration

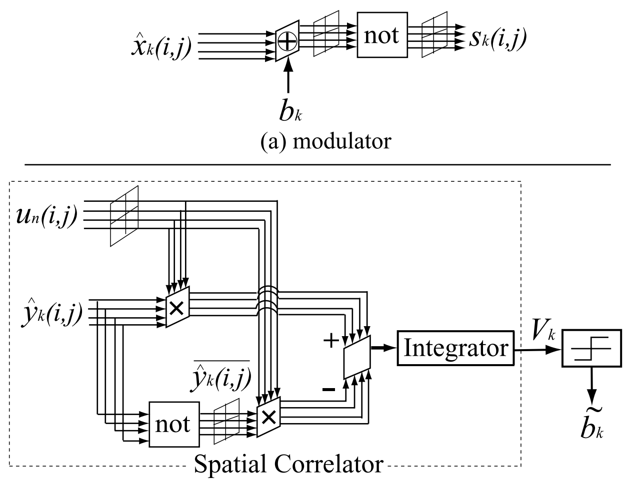
In this section, it is considered that proposed system is applied to CDM system. Two-dimensional code of proposed multiplexing communication system $\hat{x}_k(i,j)$ for user k-th is generated by chaotic map given by

$$G_k(u(i,j)) = \mathrm{mod}((u(i,j)+d_k)^2 - x_k^2(i,j)) \tag{10}$$

Sequence Inverse Keying(SIK) [15] is employed as a spread modulation method of proposed system. SIK enables the bipolar detection in spite of the unipolar nature of optical channel. Figure 8(a) shows configuration of modulator. When digital signal $b_k = 1$ is transmitted, two-dimensional spread code $\hat{x}_k(i,j)$ isn't changed. When digital signal $b_k = 0$ is transmitted, the complementary pattern, i.e. $\overline{\hat{x}_k(i,j)}$ is transmitted. Output signal of modulator $s_k(i,j)$ is expressed by

$$s_k(i,j) = \overline{b_k \oplus \hat{x}_k(i,j)} \tag{11}$$

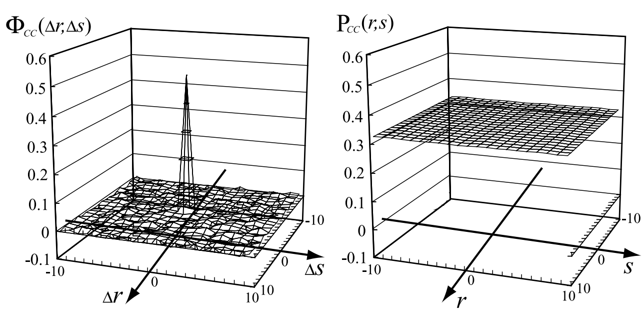
which means exclusive-NOR operation between b_k and $\hat{x}_k(i,j)$. Avalanche Photo Diode (APD) array is employed



(a) modulator

(b) demodulator

Fig. 8 Configuration of the modulator and demodulator.



(a) M-array (b) Proposed system (Chaos)

Fig. 9 Partial autocorrelation function of M-array and power component distribution of proposed system.

as an image receiver. Figure 8(b) shows configuration of demodulator, which includes spatial correlator. Output signal of spatial correlator V_k is expressed by

$$V_k = \sum_{i=p}^{p+P-1} \sum_{j=q}^{q+Q-1} \left[\{\hat{y}_k(i, j) - \overline{\hat{y}_k(i, j)}\} \cdot u_n(i, j) \right] \quad (12)$$

Demodulated digital signal $\tilde{b}_k$ is obtained by judging V_k with the threshold $V_k = 0$.

4.2 Autocorrelation Function of M-Array and Power Distribution of Proposed System

Considering that receiver can receive only a part of projected pattern, it is concerned that enough autocorrelation value can't be obtained and system performance deteriorates generally. Figure 9(a) shows the partial autocorrelation function $\Phi_{cc}(\Delta r, \Delta s)$ of M-array, which is expressed as

$$\Phi_{cc}(\Delta r, \Delta s) = \frac{1}{P \times Q} \sum_i \sum_j [C(i, j) \times \{C(i+\Delta r, j+\Delta s) - \overline{C(i+\Delta r, j+\Delta s)}\}] \quad (13)$$

where $C(i, j)$ denotes M-array. The parameters used in this calculation are shown in Table 2. A peak value of autocorrelation at the origin is observed of 0.5 and drastically degraded at the others. From this result, the CDM system applying M-array as a two-dimensional code is considered that accurate demodulation cannot be performed when the receiver is spatially misaligned imaged elements. On the other hand, because proposed system can regenerate two-dimensional code from received signal, an accurate demodulation is expected. However, if the power distribution of the proposed chaotic code had depended on position, proposed system would have weakness to the uncertainty of receiver position. Next the power distribution of the proposed chaotic code and the tolerance to uncertainty of receiver position is derived. The power components of desired signal normalized by the number of received pixels is defined by

$$P_{cc}(r, s) = \frac{1}{P \times Q} \sum_i \sum_j [C_t(i+r, j+s) \cdot C_r(i+r, j+s)] \quad (14)$$

where $C_t(i, j)$ and $C_r(i, j)$ denote two-dimensional chaos codes in the transmitter and receiver respectively. The parameters used for this calculation are shown in Table 2 and Fig. 9(b) shows this calculation result. Proposed chaotic code keeps nearly constant values at all position. Thus it can be said that proposed system has a tolerance to the uncertainty of received position.

When applying proposed system to CDM system, cross-correlation is also the very important factor for system performance. Chaotic sequences have been paid increase attention to be applied to CDMA as spreading sequences [16]. It is reported that chaos codes have approximate equivalent cross-correlation and interference suppression characteristics with M-sequence and Gold sequence. Thus, chaos codes have potentials for spatial coded multiplex communication. However, the discussion about it has missed remains a future study.

Table 2 Parameter used for calculation.

The number of transmitted pixels, $W_i \times W_j$	149×151 [pixels]
The number of received pixels, $P \times Q$	100^2 [pixels]
Chotic map parameters, a d_k	0.3 1.9937
The number of shift resister columns, m	15

4.3 Transmission Optical Power Evaluation

In this section, required transmission optical power is evaluated. In addition, it is shown that proposed system can demodulate desired digital signal under the condition that receiver position is uncertain comparing with M-array system. The FSO link model considered in this simulation is shown in Fig. 6 and received transmission optical power is expressed by Eq. (7). When the number of multiplexing is K, the signal pattern having $(K + 1)$ level. Thus, each pixel in the APD-array considered as multilevel IM/DD receiver.

Let the peak level of photocurrent $i(K)$, and the received photocurrent of the κ-th level signal is given by

$$i(\kappa) = \frac{\kappa}{K} i(K) \tag{15}$$

Additionally, assuming that the Probability Density Functions (PDF) of noise generated in receiver is gaussian, the threshold level between $i(\kappa)$ and $i(\kappa-1)$ is given by

$$D_\kappa = \frac{\sigma_{\kappa-1} i(\kappa) - \sigma_\kappa i(\kappa-1)}{\sigma_{\kappa-1} + \sigma_\kappa} \tag{16}$$

where σ_κ^2 is the noise power generated in the receiver when the κ-th level signal is transmitted. It is assumed that dominant noise is composed of thermal and shot noise sources of the amplifier.

For this evaluation, ϵ, the input component to decision normalized by expected components, is introduced and expressed by

$$\epsilon = \frac{\left| \sum_{i=p}^{p+P-1} \sum_{j=q}^{q+Q-1} \left[\{\hat{y}_k(i,j) - \overline{\hat{y}_k(i,j)} \cdot u_n(i,j) \right] \right|}{\left\langle \left| \sum_{i=p}^{p+P-1} \sum_{j=q}^{q+Q-1} \left[\{\hat{x}_k(i,j) - \overline{\hat{x}_k(i,j)}\} \cdot u(i,j) \right] \right| \right\rangle} \tag{17}$$

If ϵ takes close to 1, it is considered that the effect of pixel error is suppressed sufficiently and the system operates ideally. On the other hand, if ϵ takes close to 0, it is said that pixel error occurs frequently and the system is scarcely able to operate successfully. Parameters used for this simulation is shown in Table 3. Transmission optical power versus the average of normalized input component to decision $\langle\epsilon\rangle$, is shown in Fig. 10. $\langle\epsilon\rangle$ of M-array system comes 1 by enhancing transmission optical power in the case of no misalignment of receiver. However, in the condition that there is a misalignment of receiver $\langle\epsilon\rangle$ keeps about 0 even if transmission optical power enhances. In contrast, $\langle\epsilon\rangle$ of proposed system comes close to 0.7 if transmission optical power enhances in the case of both no misalignment and existing misalignment of receiver. Because pixel errors are generated in parts of chaos synchronization, $\langle\epsilon\rangle$ doesn't take close to 1. This simulation result indicates that if transmission optical power is provided sufficiently, proposed system is able to demodulate the desired digital signals in spite of uncertainty of received position. Required transmission optical power is founded of -13 [dBm], which the value of $\langle\epsilon\rangle$ is saturated.

4.4 Robustness against Uncertainty of Receiver

In this section, proposed system is compared with M-array system in terms of BER P_e. The distribution of misalignment of receiver is assumed as gaussian and P_e is obtained by varying the variance of misalignment of receiver. As shown in Fig. 11, it is assumed that i-axial and j-axial variances of misalignment of receiver take equally σ_l^2. Parameters using for this simulation are shown in Table 3. The multiple number is assumed K=2. The transmission optical

Table 3 Parameter used for evaluation.

α_i	0°	α_H	60°
β	0°	γ	30°
T_s	1.0	g	1.0
R_1	26.0 [cm]	ρ	0.9
R_2	46.7 [cm]	η	0.5
λ	800 [nm]	R_L	50 [Ω]
T	300 [K]	P_b	1.0 [A/m^2]
$M\times N$	120^2 [pixels]	$P\times Q$	100^2 [pixels]
$W_i\times W_j$	149×151 [pixels]	S_s	30^2 [cm^2]
S_R	25^2 [cm^2]	A_R	1.06^2 [mm^2]
K	2	B	1 [Mbps]
Multiplication factor of APD, M_a			100
Index of excess shot noise, x			0.30
Chaotic parameters, a system 1, d_1 system 2, d_2			0.3 1.3054 3.3054
The number of shift register columns system 1, m_1 system 2, m_2			 15 16

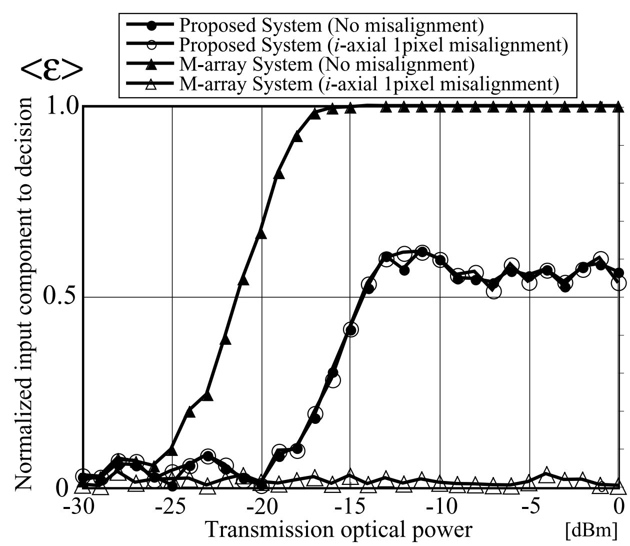


Fig. 10 Transmission optical power versus normalized input component to decision.

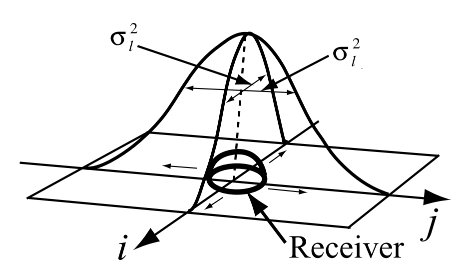


Fig. 11 Simulation model of variance of misalignment of receiver.

powers are set on -16.5 [dBm] for M-array and proposed system, -16.8 [dBm] and -17.0 [dBm] for proposed system. P_e is obtained by transmitting 10^5 bits digital signals.

Figure 12 shows simulation result, the standard deviation of misalignment of receiver σ_l versus BER P_e. P_e of M-array system deteriorates in $\sigma_l^2 > 0$, while proposed sys-

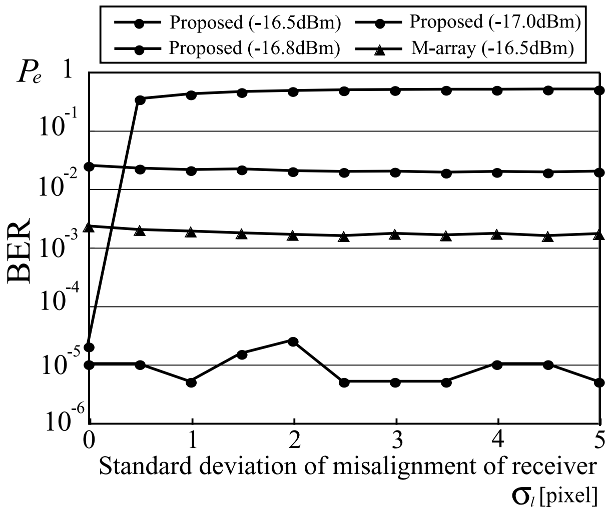


Fig. 12 Standard deviation of misalignment of receiver versus BER.

tems keep virtually constant P_e regardless of σ_l. It is said that the communication performance of proposed system is kept in spite of the condition that received position is uncertain. It is found that the transmission optical power of -16.5 [dBm] is required to achieve $P_e \leq 10^{-4}$.

5. Conclusion

This paper has proposed two-dimensional self-matching receiver using chaotic spatial synchronization in diffuse FSO link without requiring complicated code synchronization processes. In two applications, image transmission and CDM systems, the tolerances against uncertainty of received position are evaluated by computer simulation. It is evaluated that proposed system requires transmission optical power of -8 [dBm] for image transmission to restore transmitted image except for parts of chaotic spatial synchronization in spite of the uncertainty of received position. For CDM system, -16.5 [dBm] is required to achieve $P_e \leq 10^{-4}$.

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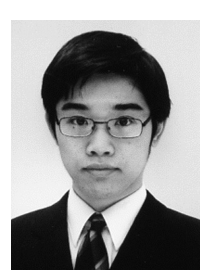

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