Intensity Estimation of LEDs from Spatially and Temporally Mixed Images in Image Sensor Communication

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***Abstract*— We focus on the road-to-vehicle visible light communication that system is composed of LED matrix as transmitter and high-speed camera as receiver. In proposed method, there are two problems. First problem is in case of long distance. It is difficult to receive data correctly because neighboring LEDs on the received image are merged due to less number of pixels and/or blurring by defocus. In this paper, we propose estimation method of LED intensity from merged image. We evaluated the method by measuring Bit Error Rate and confirmed effectiveness of the method. We also performed real time communication and succeeded to extend communication distance from the previous work by applying the method. Second problem is that, the transmitting rate has been reduced to half of the frame rate of the camera, to avoid intersymbol interference because of exposure time of camera frame. We propose a method to improve the communication rate. The transmitting rate is set same to receiver's frame rate, and the sent data is estimated from pattern mixed image. Using 8b/10b encoding instead of conventional reversal pattern to reduce the flickering of transmitter's lighting is also proposed.**

Keyword—Intelligent Transport System; Visible Light Communication; High-speed camera; LED traffic light

I. INTRODUCTION

Visible light communication is an optical wireless communication technology that uses visible light for human. LED is used as a transmitter. LED illumination and signal lights are rapidly spreading because of advantages of longer operating life, lower power consumption. LED can blink as rapidly as undetectable by human eye. The function of transmitting data can be added to LED lights by exploiting this feature. For receiver Photo Diode and Image sensor are used.
In optical communication area, PD is generally used as receiving device. PD device has fast responsiveness. However simple PD has large field of view and is easily affected by ambient light. On the other hand, using image sensor as a receiver has some advantages. Image sensor can separate LED light from ambient light because lights from different directions are focused different position in the image plane. Moreover image sensor can separate light from multiple LEDs individually. It means multiple light source can be utilized for improving communication rate.

One of the area of VLC application is Intelligent Transport System(ITS)[1]. This paper focuses a road-to-vehicle Visible Light Communication (VLC) system using an on-vehicle camera as a receiver and a LED traffic light as a transmitter for assisting drivers as shown in Fig.1.

The traffic light is composed of multiple LEDs on two dimensional plain. Data is sent as two dimensional intensity patterns by controlling each LED of the traffic light individually, and they are received as images by the image sensor. There is a research which propose VLC system using on-vehicle high-speed camera and LED matrix. Kasai have achieved real-time VLC between PCs and LED square matrix [2]. There are two major problems in previous research and we propose improving method of these in this paper.

First problem, the receiver cannot recognize intensity of each LED if the receiver is distant from the transmitter. One of reasons is that neighboring LEDs on the received image are merged due to less number of pixels, and/or due to blurring by defocus of the image sensor. Hierarchical encoding system of road-to-vehicle communication is proposed as a way to solve this problem [3] [4]. This problem is translated that high-frequency component of image is lost at a long distance. Thus, encoding which allocate preferential data to low-frequency components is hierarchical encoding. On the other hand, Arai have proposed an estimation method applying Point Spread Function (PSF) to LED intensity [5]. However, the method considers only if the number matches the pixels and the LEDs. Ito have proposed a method to estimate intensity of the LED from received image in a case of the number of the pixels is different from the number of the LEDs [6]. First, we propose a communication system using the method to estimate intensity of the LED from received image in a case of the number of the pixels is different from the number of the LEDs. In this system, intensity of LED is estimated by using Pseudo-Inverse matrix of coefficient matrix, which expresses relation between intensity of LEDs and pixel values. In this paper, we assume the coefficient matrix is known.

Second problem is about transmitter's updating rate. Using high-speed camera as receiver, the communication rate is essentially decided by the frame rate of high-speed camera because the response speed of LED is much higher than camera frame rate. However, the transmitter's updating rate has been set to half of the frame rate of the camera in previous researches. One of the reasons is that it is difficult to synchronize transmitter and receiver. If the intensity pattern of the transmitter changes in exposure time of a camera frame, the receiver may receive pattern mixed image. To receive unmixed image of each pattern, the transmitter's updating rate has been set to half of the frame rate of the camera. To improve the communication rate, we propose a method to recognize a lighting pattern from pattern mixed image and to reduce flickers on LEDs by using 8b/10b coding.

The remainder of this paper is organized as follows. In Section 2, we describe system model for this study. In Section 3, we describe communication system using the method to estimate intensity of the LED from received image in a case of the number of the pixels is different from the number of the LEDs. In Section 4, we describe a method to recognize a lighting pattern from pattern mixed image and to reduce flickers on LEDs by using 8b/10b coding. In Section 5, we describe conclusions.

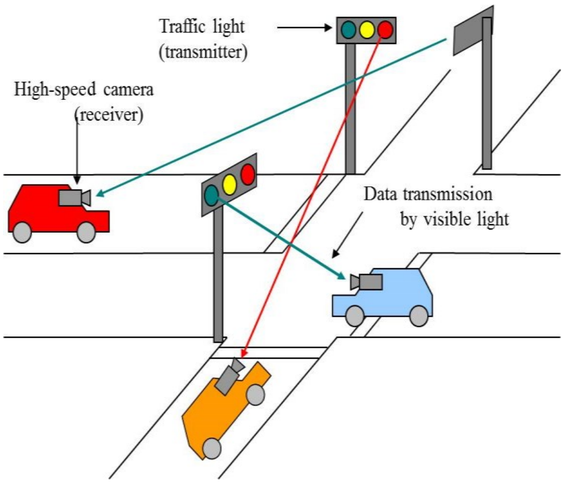


Fig.1 Image of VLC system

II. SYSTEM MODEL

This section describes the system model using transmitter and receiver. Fig.2 shows image of system.

A. Transmitter

Transmitter is composed of multiple LEDs arranged in a two-dimensional plain. In this system, data is sent in the form of two dimensional brightness pattern by controlling each LED individually, and it is received as image by image sensor. Alignment of LEDs is assumed IxI square matrix. On-Off-Keying (OOK) is adopted as modulation scheme. Hence, intensity of LEDs is directly modulated by transmit data bits. Hereafter, intensity of the LED in the i-th horizontal and j-th vertical is expressed as $l(i,j)$ $(i = 0,1,..,I-1;\ j = 0,1,\dots,I-1)$.

B. Receiver

Receiver is composed of image sensor and image processing section. Alignment of pixels on the imaging device is assumed MxM square matrix. Hereafter, intensity of pixels in the m-th horizontal and n-th vertical is expressed as $P(m,n)$ $(m = 0,1,..,M-1;\ n = 0,1,\dots,M-1)$.

III. INTENSITY ESTIMATION METHOD OF LED MATRIX

This section describes the proposed estimation method of LED intensity and the experiments.

A. Relationship between value of pixels and intensity of LEDs

As shown in Fig.3, LED image has a certain dimension due to blurring in imaging optics as well as the dimension of LED itself. Light from one LED is received by one or more pixels. Contrariwise, one pixel may receive light from multiple LEDs because pixels also have a certain dimension. Therefore, image of adjacent LEDs are mixed mutually in the received image. In this time, we consider intensity of a certain pixel which is influenced by LEDs. The intensity is represented as sum of the light from LEDs with considering degree of the influence. The degree of the influence from each LED is represented as coefficient $a_{ij,mn}$ which depends on the positional relationship between the pixel and the LED. For illustrative purposes, as shown in Fig.4, we deal with the situation that the number of LEDs is 2x2 and number of pixels is 5x5. Here, we consider $(2,2)$: the intensity of the pixel which is located at the center in Fig. 4. $p(2,2)$ is represented by Eq. (1).

$$p(2,2) = a_{00,22} \cdot l(0,1) + a_{01,22} \cdot l(0,1) + a_{10,22} \cdot l(1,0) + a_{11,22} \cdot l(1,1) \quad (1)$$

Here, general expression for $p(m,n)$ is defined as Eq. (2).

$$p(m,n) = \sum_{i=0}^{I-1} \sum_{j=0}^{J-1} a_{ij,mn} \cdot l(i,j) \quad (2)$$

When we consider all the pixels on the imaging device, MxM numbers of equations of Eq. (2) can be written. The intensity of each LED is estimated by solving these equations as s simultaneous equation.

Here, the intensity of LEDs estimated in the i-th horizontal and j-th vertical is expressed as $\tilde{l}(i,j)$.

Simultaneous equation is expressed as Eq. (3).

$$p = A \cdot l \quad (3)$$

Where p is the vector of value of pixels, l is the vector of intensity of LEDs and A is the coefficient matrix of $a_{ij,mn}$. Intensity of LEDs is estimated by Eq. (4), when the vector which expresses estimated intensity of LEDs is defined as $\tilde{l}$.

$$\tilde{l} = A^{+} \cdot p \quad (4)$$

A^{+} is the Moore-Penrose Pseudo-Inverse matrix of A. The following is the reason of using the Moore-Penrose Pseudo-Inverse Matrix. l is IxI dimension, p is MxM dimension, and A has MxM lines and IxI columns. Solution of $\tilde{l}$ become indeterminate or impossibility when I≠M. Thus, we employ a Moore-Penrose Pseudo-Inverse Matrix of A in order to calculate the solution in the case of I≠M.

Finally, transmitted data is estimated by performing a threshold processing for $\tilde{l}$ because the transmitted data is binary. The threshold value is determined by using discriminant analysis one of ways to determine threshold value.

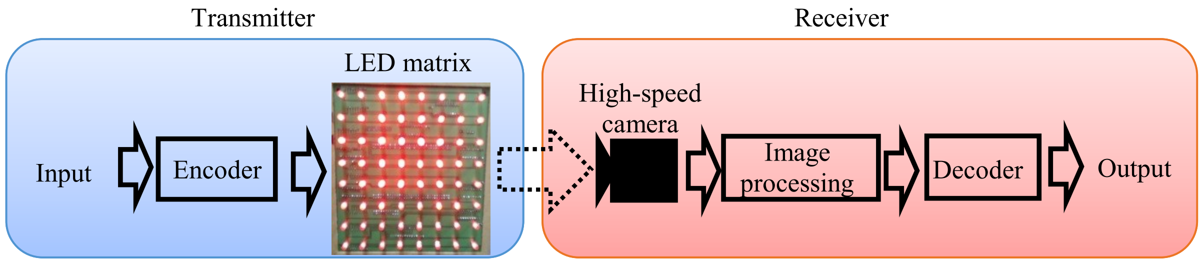


Fig.2 The image of system

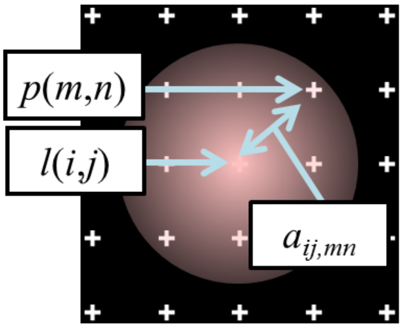


Fig.3 Appearance of lighted LED

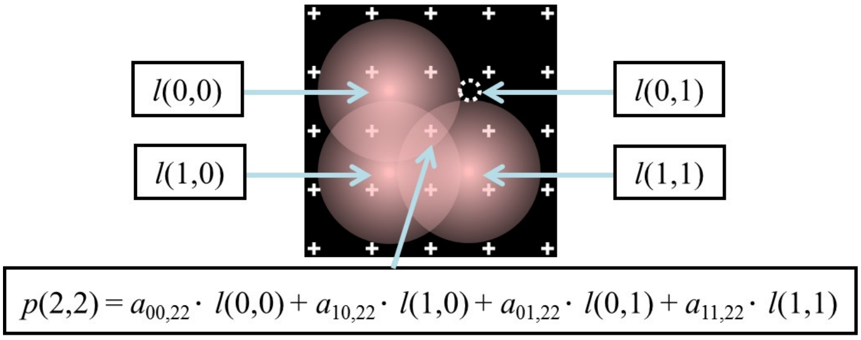


Fig.4 Relation between pixels and LEDs on the imaging device

B. *Experimental system*

The LED matrix which is 8x8 square matrix is used as the transmitter. The high-speed camera whose maximum frame rate is 2000 fps is used as the receiver. We don't consider influence of illumination light in this experiment because image sensor can separate LED light from ambient light. Fig.5 shows pictures of the LED matrix and the high-speed camera.

TABLE I, II show specification of the LED matrix and the high-speed camera. OOK was adopted as modulation scheme. Hence, intensity of LEDs is directly modulated by transmit data.

This part explain about specification of the communication system. 8bit monaural music data is transmitted by using the LED matrix. Frame rate of the high-speed camera is set in 2000 fps. Refresh frequency of the LED matrix is 1 kHz. Hence, bitrate of each LED is 1 kbps. 2 columns of both end of the LED matrix are used for synchronizing. Thus, data is sent by 48 (6x8) LEDs. The transmitter's bitrate is 48 (LEDs) x 1 (kHz) = 48 kbps. Distance between the LED matrix and the high-speed camera is set in 20 m. In this time, we determined the distance so that the ratio of the number of pixels and the number of LEDs is 1:1. Fig.6 shows picture of scenery of the communication experiment.

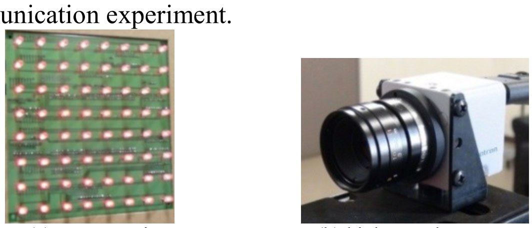

(a) LED matrix (b) high-speed camera
Fig.5 Experimental system

TABLE I. Specification of LED matrix

Number of LED	64 (8x8)
LED Pitch	20 [mm]

TABLE II. Specification of high-speed camera and lens

Model Number	Photron IDP-Express R2000
Resolution	512x512 [pixel]
Max Frame Rate	2000 [fps]
Image Gradation	8 [bit]
Focus Length	8 [mm]

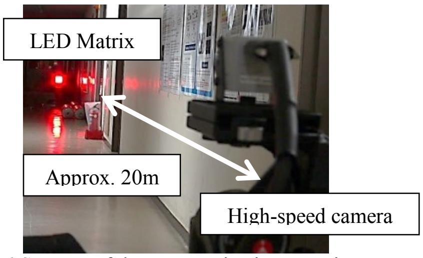


Fig.6 Scenery of the communication experiment

C. *Method to determine coefficient matrix 'A'*

To estimate intensity of LEDs it is necessary to determine the coefficient matrix in Eq. (3). Received image gives the coefficients corresponding to a LED when the LED itself lights alone. We determined the coefficient matrix *A* from single LED lit image for all LEDs of the LED matrix. 10 frames of single LED lit image are captured and averaged because influence of noise of received image is reduced.

D. *Method of communication experiment*

The coefficient matrix is determined subsequently, we experiment on the communication. Intensity of LEDs is estimated from received image and music data is played. The LED matrix and the high-speed camera are fixed.

E. *Result of communication experiment*

In the result of communication experiment, we achieved transmitting music data in real time. We compared the transmitted sound of the proposed method to a conventional method that the value of pixel corresponding to a LED is directly picked up as the intensity of LED in the communication experiment. In the conventional method, we confirmed that the sound is noisy. However, we confirmed that the proposed method was obtained better sound than the conventional method.

F. Condition of measuring BER

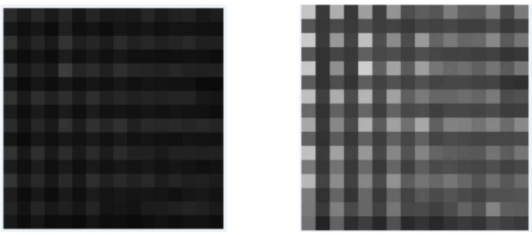
We explain about condition of measuring BER. Number of trials is 10,000 times. 64 LEDs are used. Thus, 640 kbits pseudo random number data is sent.

We measured BER with varying the distance between the LED matrix and the high-speed camera and Signal-to-Noise Ratio (SNR). We set the distance so that the ratios of the number of pixels and LEDs are approximately 2:1 and 1:1. SNR was set under conditions of multiple. SNR is varied by adjusting aperture of the camera. Value of SNR is estimated from observed images. SNR is defined as Eq. (5).

$$\mathrm{SNR} = 20 \cdot \log_{10} S/N \tag{5}$$

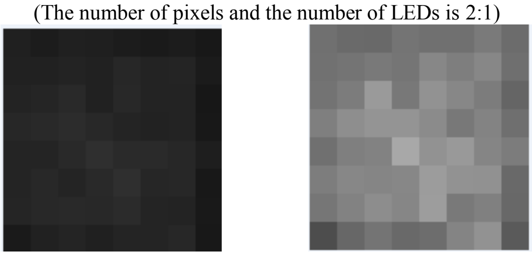
Then, S is difference between pixel value when LED light is on and pixel value when LED light off. N is variance of pixel value of the image when LED light is on.

Fig.7, 8 show images when the ratios of the number of pixels and LEDs are 2:1 and 1:1 and SNR is different.



(a) Low SNR (b) High SNR

Fig.7 All LED lit image
(The number of pixels and the number of LEDs is 2:1)



(a) Low SNR (b) High SNR

Fig.8 All LED lit image
(The number of pixels and the number of LEDs is 1:1)

G. Result of measuring BER

We compared BER of the proposed method to the conventional method. When the ratios of the number of pixels and LEDs are 2:1 and 1:1, measured BER are shown in TABLE III, IV. In the result, proposed method was better than conventional method.

Fig.9 shows BER–SNR characteristic obtained from simulation [7] when the ratios of the number of pixels and LEDs are 2:1 and 1:1, and spread of LED light was fixed. We explain about definition of spread of LED light. In the simulation, coefficient matrix is modeled as Gaussian function. Definition of spread of LED light is shown as variance of Gaussian function. In Fig.9, variance of Gaussian function is set to be $g\left(\frac{w}{\sqrt{2}}, \frac{w}{\sqrt{2}}\right) = 0.5$. Here, w is the pixel pitch.

We compared measured BER by the experiment to BER by the simulation. In both case of 1:1 and 2:1, BER by the experiment was worse than the simulation but it showed similar tendency. Fig. 10 shows result of BER-spread of LEDs obtained from simulation [7] when the ratio of number of pixels and LEDs is 2:1 and spread of LED light was varied. According to this characteristic, BER depends on the spread of LED light. We estimated $g\left(\frac{w}{\sqrt{2}}, \frac{w}{\sqrt{2}}\right)$ from single LED lit image. In case of 2:1, $g\left(\frac{w}{\sqrt{2}}, \frac{w}{\sqrt{2}}\right)$ was estimated approx. 0.5. In case of 1:1, $g\left(\frac{w}{\sqrt{2}}, \frac{w}{\sqrt{2}}\right)$ was estimated approx. 0.7. In Fig.9, $g\left(\frac{w}{\sqrt{2}}, \frac{w}{\sqrt{2}}\right)$ is 0.5. On the one hand, in the experiment, $g\left(\frac{w}{\sqrt{2}}, \frac{w}{\sqrt{2}}\right)$ is 0.7. In Fig.10, BER when $g\left(\frac{w}{\sqrt{2}}, \frac{w}{\sqrt{2}}\right)$ is 0.7 was better than 0.5. This is considered as one of the reason why BER by the experiment was better than the simulation.

TABLE III Result of BER (pixels : LEDs = 2:1)

Ratio of pixels and LEDs		2:1		
BER	Proposed method	3.53×10^{-3}	4.50×10^{-5}	0
	Conventional method	2.33×10^{-2}	2.39×10^{-3}	0
SNR		16.03	22.14	30.83

TABLE IV Result of BER (pixels : LEDs = 1:1)

Ratio of pixels and LEDs		1:1		
BER	Proposed method	3.71×10^{-2}	1.95×10^{-4}	0
	Conventional method	2.01×10^{-1}	3.57×10^{-2}	1.57×10^{-2}
SNR		20.69	25.97	32.72

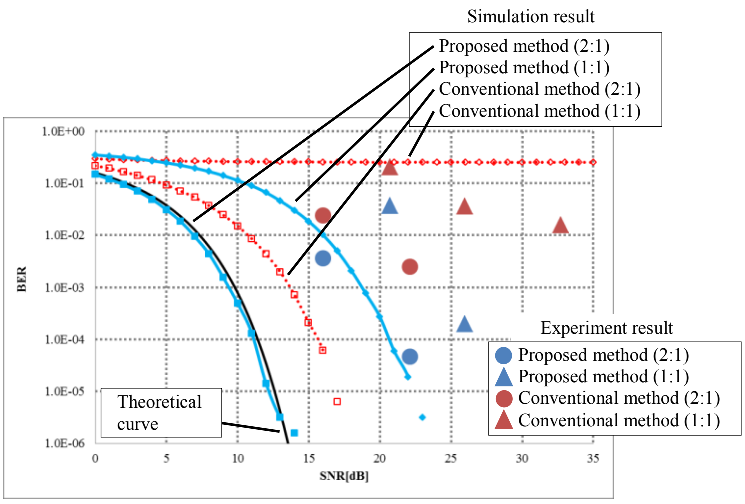


Fig.9 BER-SNR characteristic
(Spread of LED light: 0.5, ratio of number of pixels and LEDs: varied)

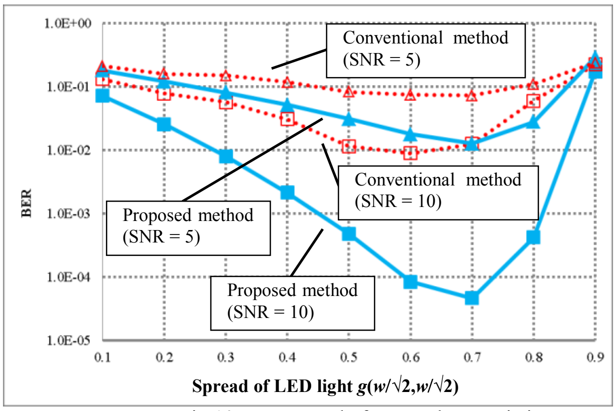


Fig.10 BER-spread of LEDs characteristic
(Spread of LED light: varied, ratio of number of pixels and LEDs: 2:1)

IV. METHOD TO IMPROVE THE COMMUNICATION RATE

This section describes three proposal methods to improve the communication rate of system.

A. *Data estimation using phase difference*

This system captures mixed image of two consecutive patterns in a constant ratio for every frames, if receiver's frame rate and transmitter's updating rate are same. In this case, the ratio is determined by temporal difference of receiver's shutter timing and transmitter's updating timing (Fig.11)[2]. Hereinafter, this temporal difference is referred to as phase difference P. Here, we assume time of one frame and exposure time are same.

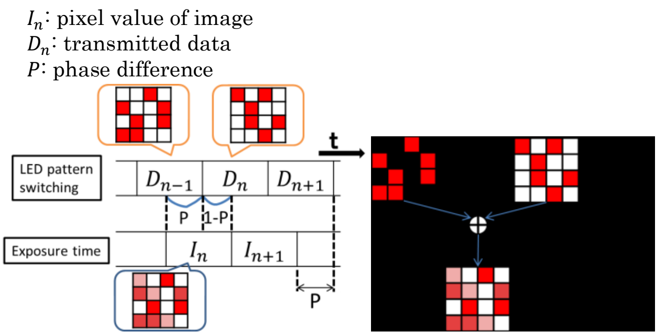


Fig.11 Relation of phase difference and pixel value of image

Here, we think about pixel value of corresponding pixel to a LED i_n and transmitted data $d_{n-1}$and d_n.

The pixel value of pattern mixed image i_n is expressed by (6) using phase difference P, transmitted data d_{n-1} and d_n.

$$i_n = (1 - P) \times d_{n-1} + P \times d_n, \quad 0 \le P < 1 \tag{6}$$

And we can derive (7) by deformation of (6).According to (7), we can calculate transmitted data d_n sequentially if pixel value i_n, phase difference P and previous transmitted data d_{n-1} are known.

$$\tilde{d}_n = \frac{i_n - P \times d_{n-1}}{1 - P} \tag{7}$$

However practically, pixel value of real image $\hat{\imath}_n$ has noise N and it is expressed in (8).

$$\hat{\imath}_n = (1 - P) \times d_{n-1} + P \times d_n + N \tag{8}$$

And (9) is derived by substituting pixel value $\hat{\imath}_n$ into (7). (9) means that the noise N is emphasized if phase difference P is close to 1.

$$\tilde{d}_n = d_n + \frac{N}{1 - P} \tag{9}$$

B. *Data estimation using two mixed image*

When the phase difference P is close to 1, the ratio of data d_n composing the pixel value i_n is small. So, the noise N affects the pixel value strongly in our proposal method mentioned in section 4.A. On the other hands, the pixel value of next image $i_{n+1}$is composing data d_n at high rate. So we think that it is able to improve the estimation accuracy by using two pixel values i_n and i_{n+1}.

The pixel value of images i_n and i_{n+1} are decided by phase difference P and combination of consecutive three data d_{n-1}, d_n and d_{n+1}. We use two levels of data (0,1) here. So, i_n and i_{n+1} are calculated by (8) and the results of all sequence are shown TABLE V. And Fig.12 shows plotted data of Table V in i_n-i_{n+1} plane. The horizontal axis shows pixel value of image i_n and the vertical axis shows pixel value of next image i_{n+1}. And Fig.12 (a), (b) and (c) shows in the case of phase difference *P=0.2*, *0.5* and *0.8* respectively. The label of each point shows the data sequence (d_{n-1}, d_n, d_{n+1}), and black points show in the case of $d_{n-1} = 0$, white points show in the case of $d_{n-1} = 1$.

In this time, we estimate data d_n by using maximum likelihood estimators. Practically, pixel value of real image has noise as shown (9), so pixel values are not always plotted on ideal point as shown Table V. Assuming the noise is AWGN(additive white Gaussian noise), the likelihood of each sequence of data is a monotonically decreasing function of Euclidean distance between ideal position of the sequence of data and point of pixel values in i_n-i_{n+1} plane. Thus, choosing the nearest sequence is same to maximum likelihood estimators

C. *8b/10b coding*

We thought that a reason of flickers on a LED is low frequency component of LED switching pattern. In precious research, conventional reversal pattern [8] reduces the low frequency component. But, this method uses two images to receive a pattern of LEDs. So communication rate becomes half to use this method. In contrast, we propose to use 8b/10b coding to reduce flickers on a LED and to improve communication rate. 8b/10b coding is a code system that used at high-speed serial interface for example USB 3.0 and PCI Express2.0. The coded 10 bits data are reduced low frequency component.

TABLE V. The pixel values of images for each data sequence (d_{n-1}, d_n, d_{n+1})

d_{n-1}	d_n	d_{n+1}	i_n	i_{n+1}
0	0	0	0	0
0	0	1	0	1-P
0	1	0	1-P	P
0	1	1	1-P	1
1	0	0	P	0
1	0	1	P	1-P
1	1	0	1	P
1	1	1	1	1

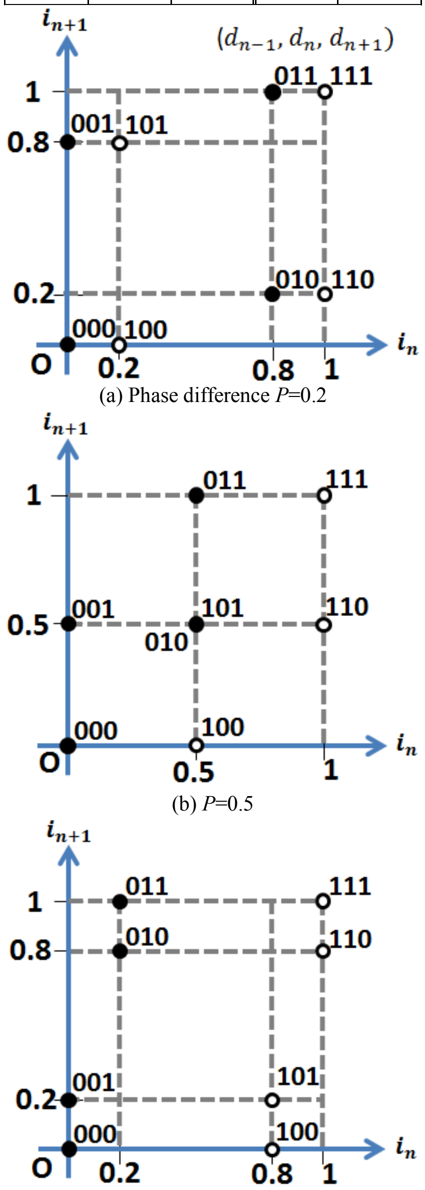


Fig.12 The graph of 2 pixel values for each data sequence

D. Experimentation

We experimented with this proposal methods and we measured BER while changing phase difference using the LED matrix and the high-speed camera. We also simulated the experiment. Receiver received luminance of LED as pixel value. Thus in order to prevent overlapping of LED lights in image, we determined distance between transmitter and receiver 2m and fixed these positions. We used pseudorandom numbers as send data, and initial data d_{-1} was determined. Receiver was synchronized with transmitter by using trigger signal. And by controlling the trigger signal, we determined phase difference. In this time, we experimented them under 2 conditions of aperture of camera for varying brightness. We call the 2 conditions bright condition and dark condition for all phase differences. To use (2), we had to normalize pixel value. In here, histogram of pixel values of LED has 2 groups (high value and low value) and we fit them into Gaussian distribution. We use the average values of 2 groups to normalize results. Fig.13 shows the experimental results of each method. The horizontal axis shows phase difference P and the vertical axis shows BER. Result of method B was error-free under bright condition for all differences. In experimentation, the average of pixel values of low and high group was 23.17 and 96.58 under bright condition. And these values were 23.17 and 51.05 under dark condition.

In simulation, we measure BER while changing the standard deviation σ of AWGN added to images. Fig.14 shows the simulation results of each method. The result of method B when the standard deviation was 0.01 was error-free. In the simulation, the minimum pixel value and maximum pixel value were 0 and 1.

According to Fig.13, BER of method A was big when phase difference was big. But BER of method B became small when phase difference became over 0.6. And the BER of method B was smaller than method A regardless of phase difference.

According to Fig.14, BER of method A was big when phase difference was big that was same to experimental results. And BER of method B became small when phase difference became over 0.6. The BER of method B is smaller than method regardless of phase difference.

When experimental condition was corresponded with simulation condition, the standard deviation were 0.0264 under bright condition, and 0.0883 under dark condition. According to Fig.13 and 14, the both result of experiment and simulation were not so different under bright condition. But the simulation result was worse than result of experiment under dark condition. One of the reasons is thought that we didn't consider the change of standard deviations by changing pixel value in simulation. About method B, BER is maximum when phase difference is 0.6 in the results of experiment and simulation. And, the distance between points of 001 and 010 on i_n-i_{n+1} plane (Fig.12) when $d_{n-1} = 0$ or, points of 101 and 110 when $d_{n-1} = 1$ becomes the smallest. In this case, estimating method becomes most sensitive to noise. That is the one of reasons. On the other hands, we confirmed reducing flickers on a LED by using the 8b/10b coding.

V. CONCLUSIONS

In this paper, we propose two methods on communication using the LED matrix and the high-speed camera.

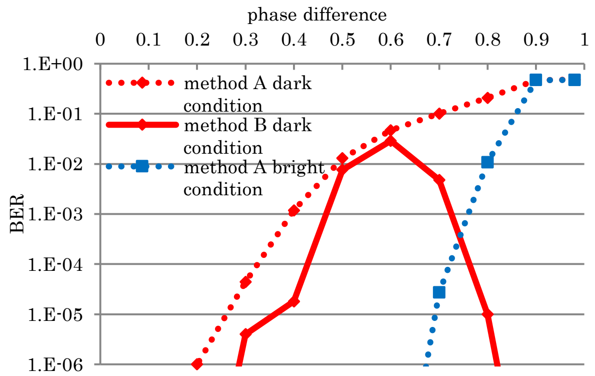


Fig.13 The experimental results of each method
(Result of method B was error-free under bright condition.)

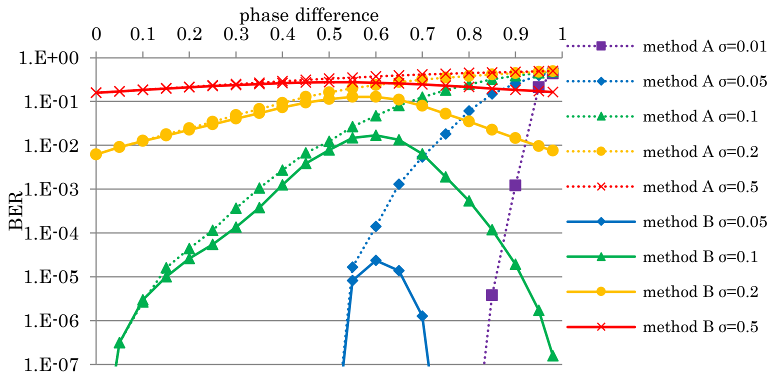


Fig.14 The simulation results of each method
(Result of method B when the standard deviation was 0.01 was error-free.)

First, we propose method to communication system using the estimation method applying PSF to LED intensity. In this result, effectiveness of the proposed method was evaluated by BER with varying the distance between the LED matrix and the high-speed camera and SNR. We set the distance so that the ratios of the number of pixels and LEDs are 2:1 and 1:1. We varied SNR by adjusting aperture of the camera and we estimated value of SNR from observed images. In the result, proposed method was better than conventional method. In this proposed method, coefficient matrix needs to be known. In this experimentation, we determine the coefficient matrix beforehand by measuring single LED lit image for all LEDs of the LED matrix. However, the coefficient matrix changes every moment because it is determined by positional relation between the receiver and the LED traffic light in VLC system. Therefore, to determine the coefficient matrix from the single lit images is not realistic. To get the coefficient matrix from images while communicating is future issue.

Second, we propose the 2 data estimation methods that use the temporal difference of receiver's shutter timing and transmitter's updating timing. One uses 1 frame(IV Method A), another uses 2 frames(IV method B). BER of IV method A becomes bigger when phase difference is close to 1. But IV method B can use even if phase difference is close to 1. BER of IV method B is maximum when phase difference is 0.6. BER of estimation IV method B is smaller than IV method A in all phase differences. In addition, we confirmed reducing flickers on a LED by using the 8b/10b coding. In the future, we will consider estimation using 3 and more frames and using 3 and more luminance levels.

REFERENCES

[1] T. Yamazato, M. Kinoshita, S. Arai, E. Souke, T. Yendo, T. Fujii, K. Kamakura, and H. Okada , "Vehicle Motion and Pixel Illumination Modeling for Image Sensor Based Visible Light Communication", Selected Areas in Communications, IEEE Journal on, pp.1-1 (2015): doi: 10.1109/JSAC.2015.2432511

[2] M. Kasai, T. Yendo, S. Arai, T. Yamazato, H. Okada, and T. Fujii, "Visible Light Communication System Using Real-time Processing of High-speed Camera Image", Proceedings of The2014 International Workshop on Advanced Image Technology, pp.258-263, 2014 (Jan. 2014)

[3] S. Arai, S. Mase, T. Yamazato, T. Endo, T. Fujii, M. Tanimoto, K. Kidono, Y. Kimura, and Y. Ninomiya, "Experiment on hierarchical transmission scheme for visible light communication using LED traffic light and high-speed camera," Proc. Of 1st IEEE International Symposium on Wireless Vehicular Communications, (Sep. 2007)

[4] S. Nishimoto, T. Nagura, T. Yamazato, T. Yendo, T. Fujii, H. Okada, and S. Arai, "Overlay Coding for Road-to-Vehicle Visible Light Communication using LED Array and High-Speed Camera", International IEEE Conference on Intelligent Transportation Systems, pp.1704-1709, (Oct. 2011)

[5] S. Arai, and S. Ozawa, "Signal Detection from Blurred Camera Image in Visible Light Communication Using LED, " IEICE Technical Report, vol.110, no.421, pp. 107-111, (Feb. 2011) (in Japanese)

[6] T. Ito, T. Yendo, S. Arai, T. Yamazato, H. Okada, and T. Fujii, "Intensity estimation method of LED array for visible light communication" Proc. SPIE 8663 , Video Surveillance and Transportation Imaging Applications, 86630V (March 19, 2013); doi:10.1117/12.2005738

[7] T. Nagura, T. Yamazato, M. Katayama, T. Yendo, T. Fujii, and H. Okada, "Improved Decoding Methods of Visible Light Communication System for ITS using LED array and High-Speed Camera", Proc. Of IEEE Vehicular Technology Conf. (VTC 2010-Spring), pp.1-5 (2010)