Tracking an LED Array Transmitter for Visible Light Communications in the Driving Situation

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Abstract—In this paper, we discuss on a decoding algorithm for visible light communication systems in the driving situation using an LED array transmitter and a high-speed camera receiver. We propose an LED array detection method using M-sequence and an LED array tracking method using inverted signals. We confirm that we can distinguish LED array candidates correctly with M-sequence. We also confirm that we can suppress the flicker of the LED and improve the data rate as compared with the previous method.

I. INTRODUCTION

Light emitting diodes (LEDs) are expected as next generation lighting sources. LEDs are superior to conventional incandescent lights due to their low power consumption, strong directivity, good visibility, long life, and low heat generation. Also, LEDs are able to control their intensity electrically at a fast rate, since they are semiconductor devices. That is, LEDs can be used not only as illuminating devices, but also as communication devices. Some cases of LED being used as communication devices are: LED traffic lights broadcasting driving assistance data to vehicles, as a road-to-vehicle communications, and LED vehicle brake lights transmitting warning data to vehicles behind, as a vehicle-to-vehicle communications. Because of that, visible light communication systems using LED are well studied [1]–[4].

In this paper, we consider a parallel visible light communication system using an LED array as a transmitter and high-speed camera on a vehicle as a receiver [5]. The advantage of using a camera is that it is able to recognize the position of individual LEDs in the array easily, because of it's wide viewing angle. Therefore, if each LED in the traffic lights and the brake lights were individually modulated, parallel data communication would be possible. However, using a camera also has disadvantages. When the camera is far from the LEDs array, the received images are blurred due to the defocus and reduction of pixel sizes. It then becomes hard to distinguish adjacent LEDs. In other words, high spatial frequency components of images are lost. Then, in such a condition, received images mainly contain low spatial frequency components.

To take advantage of these channel characteristics, we have proposed a hierarchical coding scheme in our previous research [6]. If we allocate high-priority data to low spatial
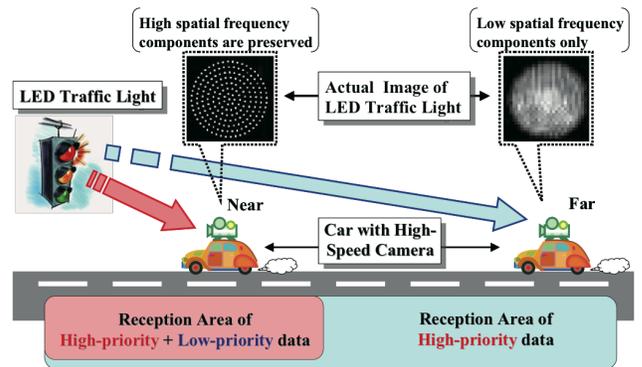

Fig. 1. Visible light communication system using an LED traffic light and a high-speed camera.

frequency components and low-priority data to high spatial frequency components, the reception of high-priority data can be guaranteed even when the camera is far from LEDs array. As the camera attached to a vehicle gets closer to the LED transmitter, additional low-priority data also can be received.

In our previous research, we have discussed on the static situation in which the vehicle does not move. However, we need to discuss on the visible light communication system in an actual environment: the driving situation. Then, we consider a decoding algorithm for the driving situation. To be more precise, we propose detection and tracking methods of an LED array and evaluate on a driving trial. As results, we confirm that we can distinguish LED array candidates correctly and recognize multiple LED arrays with M-sequence. We can also suppress the flicker of LEDs and improve the data rate as compared to the previous method.

II. SYSTEM OVERVIEW

Figure 2 shows the block diagram of the system model.

A. Transmitter

The transmitter consists of 256 LEDs in the form of a 16×16 square matrix (LED array), a hierarchical encoder, and an error correcting encoder. In this paper, we use a turbo code as the error correcting scheme. The transmitter LEDs generate
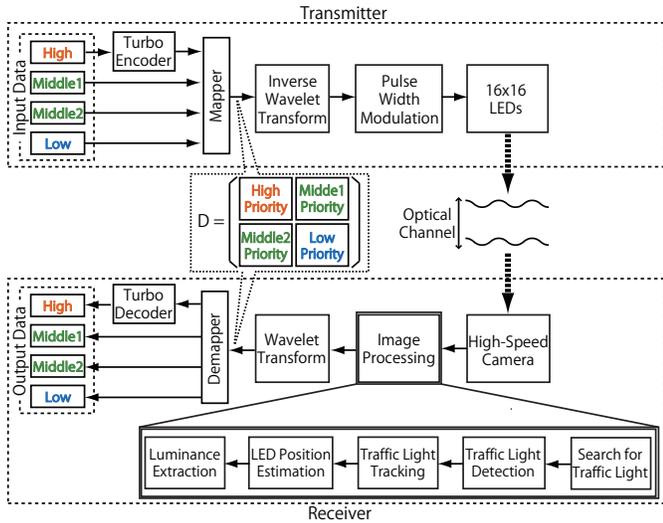
Fig. 2. System model.

a nonnegative pulse with a width of T_b, where T_b is the bit duration. By changing the width of T_b, LEDs can express the luminance. Let the data rate be $R_b(=1/T_b)$, then the bit rate of the transmitter becomes $256R_b$ since each LED transmits a different bit. The transmit power emitted by an LED with row u and column v at time t is

$$x_{u,v}(t) = \sum_k x_{u,v,k} \cdot A \cdot g(t - (k-1)T_b), \qquad (1)$$

where $k = 1, 2, \ldots$ is an index of an LED pattern, $x_{u,v,k}$ is the coefficient that determines the intensity of an LED, and A is the peak optical power of the transmitter. The range of $x_{u,v,k}$ is $0 \le x_{u,v,k} \le 1$. If we use On-Off Keying(OOK) in modulation, $x_{u,v,k} = \{0, 1\}$. A pulse function $g(t)$ is defined as follows,

$$g(t) = \begin{cases} 1 & (0 \le t < T_b) \\ 0 & (\text{otherwise}) \end{cases} \qquad (2)$$

B. Receiver

The receiver consists of a high-speed camera, an image processing unit, an error correcting decoder, and a hierarchical decoder. The transmitted signal arrives at the receiver high-speed camera through the optical channel. The receiver has the CMOS image sensors and each pixel outputs a photo-current corresponding to the received light intensity. The signal at the u, vth LED is

$$y_{u,v}(t) = h_{u,v} \cdot x_{u,v}(t) + n_{u,v}(t), \qquad (3)$$

where $h_{u,v}$ is the optical channel gain and $n_{u,v}(t)$ is the shot noise from ambient light. When ambient light has high-intensity, shot noise from ambient light can be modeled as a white Gaussian noise. We assume $n_{u,v}(t)$ as a white Gaussian noise process with a double-sided power spectral density $N_0/2$.

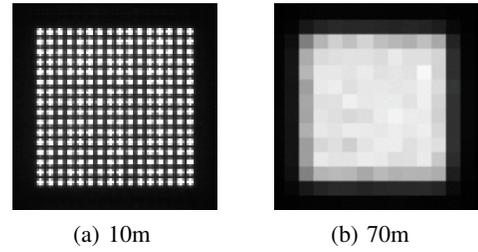Let us assume that the receiver camera is exactly synchronized with the transmitter LED. We let the image sampling

(a) 10m   (b) 70m

Fig. 3. Received image.

period be T_b and the image light exposure time be τ, where $\tau \le T_b$. The image light exposure can then be represented as

$$f(t) = \sum_i g_{sh}(t - (i-1)T_b), \qquad (4)$$

where $i = 1, 2, \ldots$ is an index of image exposure intervals. A shutter pulse $g_{sh}(t)$ is

$$g_{sh}(t) = \begin{cases} 1 & (0 \le t < T_b) \\ 0 & (\text{otherwise}) \end{cases} \qquad (5)$$

The sample output of the pixel corresponding to u, vth LED in the ith exposure intervals is

$$r_{u,v,i} = c \int_{(i-1)T_b}^{iT_b} y_{u,v}(t) \cdot f(t) dt, \qquad (6)$$

where c is a constant coefficient that represents light-to-current transfer efficiency.

III. HIERARCHICAL CODING

Figures 3(a) and (b) show the received image for the communication distance of 10m and 70m respectively. We can distinguish each LED in Fig. 3(a). But, in Fig. 3(b), we cannot distinguish them because the LEDs are lumped in with neighboring ones. In other words, as communication distance grows, high spatial frequency components of images experience severe degradation.

To take advantage of these channel characteristics, we employed the hierarchical coding scheme using a two-dimensional fast Haar wavelet transform (2D FHWT) in our previous research [6]. 2D FHWT is used to allocate high-priority data to low spatial frequency components and low-priority data to high spatial frequency components. Hence, we can decode the primary data from afar and obtain the additional data when closer.

In this paper, we use 256 LEDs in the form of a 16×16 square matrix as the transmitter. The input binary data is

$$\boldsymbol{D} = \left\{ \begin{matrix} \boldsymbol{D}_{11} & \boldsymbol{D}_{12} \\ \boldsymbol{D}_{21} & \boldsymbol{D}_{22} \end{matrix} \right\} = \left\{ \begin{matrix} d_{1,1} & d_{1,2} & \cdots & d_{1,16} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,16} \\ \vdots & \vdots & \ddots & \vdots \\ d_{16,1} & d_{16,2} & \cdots & d_{16,16} \end{matrix} \right\}, \qquad (7)$$

where $\boldsymbol{D}_{11}, \boldsymbol{D}_{12}, \boldsymbol{D}_{21}$ and $\boldsymbol{D}_{22}$ are 8×8 matrices, $d_{m,n} = \{-1, 1\}$, and $d_{m,n}$ is assumed to be independent and identically distributed (i.i.d.). When using 2D FHWT, input data is divided into 3 blocks depending on priority. The matrix
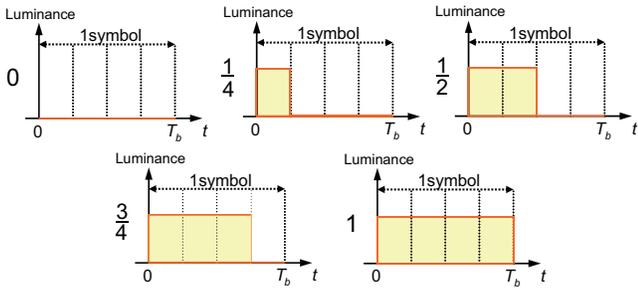
Fig. 4. Pulse Width Modulation.

Fig. 5. Packet format.

$\boldsymbol{D}_{11}$ corresponds to the highest priority block with a data rate of $64R_b$. The matrices $\boldsymbol{D}_{12}, \boldsymbol{D}_{21}$ correspond to the middle priority block with a data rate of $128R_b$. The matrix $\boldsymbol{D}_{22}$ is the lowest priority block with a data rate of $64R_b$.

A. Encoding

The input data matrix $\boldsymbol{D}$ is transformed into matrix $\boldsymbol{x'}$ by applying a 2D inverse fast Haar wavelet transform (2D IFHWT) with the hierarchical encoder. The element of $\boldsymbol{x'}$ with row u and column v is

$$x'_{u,v} = \frac{1}{2} \sum_{m=1}^{16} \sum_{n=1}^{16} d_{m,n} H_{n,v}^{16} H_{m,u}^{16}, \qquad (8)$$

where $H_{m,n}^{16}$ is an element of matrix $\boldsymbol{H^{16}}$ with row m and column n, is given as follows,

$$\boldsymbol{H^{16}} = \begin{Bmatrix} 1 & 1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & -1 \end{Bmatrix}. \qquad (9)$$

As a result of this processing, the range of $x'_{u,v}$ becomes five patterns $\{0, \frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1\}$. It is difficult to express the five patterns by modulating voltage amplitude because of the individual difference of the LEDs and the pixel gaps in the images. Thus, we express the luminance of the five patterns by changing the lighting cycle of each LED, i.e., pulse width modulation (PWM) as shown in Fig. 4. Note that T_b on Fig. 4 means the maximum lighting cycle per 1 symbol. Arbitrary luminance is shown based on T_b. As the example, to express the luminance "$\frac{1}{2}$", the LED lights half of T_b.

B. Decoding

The demodulation is performed in following manner; first, the position of each LED is estimated from the received images. Second, the received luminance $r_{u,v}$ that forms the 16×16 square matrix is extracted and normalized. Finally, 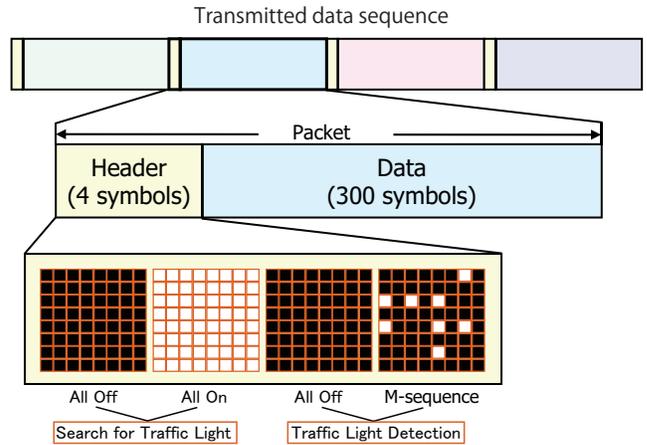the normalized luminance is transformed by 2D FHWT with the hierarchical decoder. After the transformation, the element of output matrix with row m and column n is

$$\hat{d}'_{m,n} = \frac{1}{2} \sum_{u=1}^{16} \sum_{v=1}^{16} \hat{x}'_{u,v} H_{n,v}^{16} H_{m,u}^{16}. \qquad (10)$$

By performing this operation, the procession consisting of the received luminance levels is changed into spatial frequency components again. At last, a threshold detection is performed. If $\hat{d}'_{m,n}$ is positive, then the received data $\hat{d}_{m,n}$ is determined as 1, and if $\hat{d}'_{m,n}$ is negative then the received data $\hat{d}_{m,n}$ is determined as -1.

IV. PROPOSED DECODING ALGORITHM

Figure 5 shows the packet format of the proposed method. The receiver searches and detects an LED array in the header part and clips out the adjacent LED array area. Then, the receiver tracks the LED array in the data part.

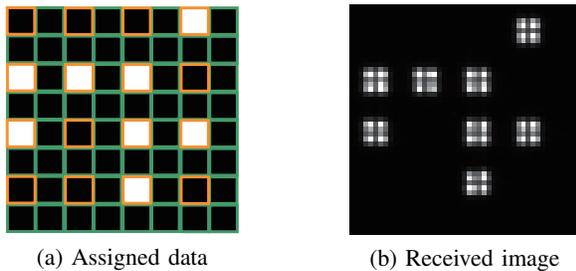*A. Detection method of LED array*

Most of the background light can be eliminated by comparing two successive frames. In the case of the static vehicle, the background can be completely removed from the images, but in the case of the moving vehicle some of the background always remains. The simplest way to detect the LED array is by using an arbitrary pattern such as all LEDs on. In that case, however, there can be a false detection of the LED array area (Fig. 6) because the remaining background light tends to be round or rectangular shaped and this is similar to the shape of the array when all the LEDs are on. False detection of the LED array has a severe influence on the quality of communication, because we will then try to track a false detected LED array area until the next LED array candidate is detected.

Then, we propose an LED array detection method using M-sequence so as to detect an LED array area accurately. M-sequence is a pseudo random sequence and has good autocorrelation characteristics. We use a 15bit M-sequence generated from the polynomial $f(x) = x^4 + x^3 + 1$, and

Fig. 6. False detection of the LED array area.
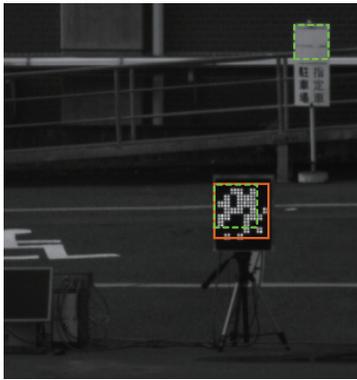
LED array area ☐   False detection ┆ ┆

(a) Assigned data   (b) Received image

Fig. 7. An example of the M-sequence.

Fig. 8. An example of an inverted pattern.
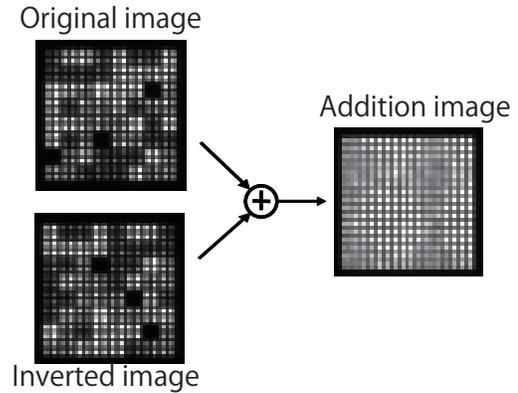
Fig. 9. LED array tracking using inverted signals.

assign the generated data to a two-dimensional image like Fig. 7(a). Figure 7(b) shows the received image of the M-sequence for a communication distance of 25m. We can improve the reliability because this pattern is unique in background light. Also if we allocate some LED arrays to a different M-sequence, we can distinguish these LED arrays.

B. Tracking method of LED array

To achieve robust tracking, it is necessary to correct the position of an LED array in each frame, because of camera vibrations and changes in the size of an LED array during the driving situation. According to previous research, the following methods are supposed to track an LED array.

1) Tracking by the use of partially known tracking patterns
2) Tracking to use motion vector of the background

The first method has the disadvantage that the data rate is not very high, because it is impossible to transmit information by using the area of the array containing the tracking pattern. The second method has the disadvantage that we cannot track an LED array in the case of small lens aperture or at night, because the background light we need for the motion vector is not available in such cases.

In this paper, we propose another tracking method that allows us to solve the problems of previous methods.We use the inverted signals to track an LED array. An inverted signal is the reversed version of an original signal. We make an inverted pattern of each signal and transmit them alternatively. Figure 8 shows a example of an inverted signal pattern. Figure 9
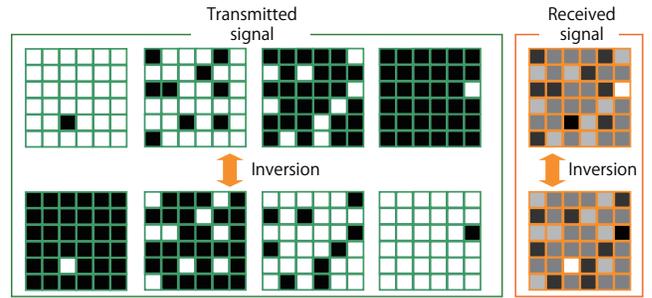
shows that we can easily track an LED array, because we can acquire all LEDs on the pattern by adding signals to inverted signals. When we use the inverted signals, we can suppress the flicker of LED because adding signals has uniform luminance of each LED. Furthermore, the data rate as compared with the previous method was improved because we can use the whole LED array area to transmit information.

V. EXPERIMENTAL RESULTS

The experiments were conducted to confirm the effectiveness of the proposed LED array tracking method.

Figures 10(a) and (b) show field trial instruments; the LED array transmitter and the high-speed camera. The transmitter consists of 256 LEDs allocated in a spacing of 2cm between each LED. This LED spacing is the same as that of the actual traffic light. The half-value angle of each LED is $22.6°$. Table I shows the specifications of the high-speed camera. Table II shows the experiment parameters. The vehicle drives from 80m to 25m at 30km/h and we take images with the high-speed camera set on the dashboard in the vehicle.

At first, the experiments were conducted to confirm the robustness of the LED array tracking against camera vibrations and changes in the image size of the LED array during the driving situation. Figure 11 shows the cutout image without the LED array tracking method so that the LED array area moves out of the cutout image due to disturbances such as camera vibrations. On the other hand, Fig. 12 shows the cutout image

(a) LED array   (b) High-speed camera

Fig. 10.   Experimental instruments.

TABLE I
HIGH-SPEED CAMERA SPECIFICATIONS.

Camera model.	FASTCAM-1280PCI made by Photron
Lens model	Ai Nikkor made by Nikon
Sensor type	CMOS
Focus	35mm
Shutter speed	60∼16000fps
Resolution	Max 1280×1024 pixel

TABLE II
EXPERIMENTAL PARAMETER.

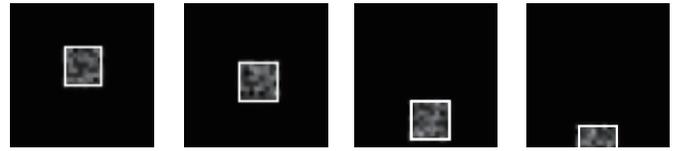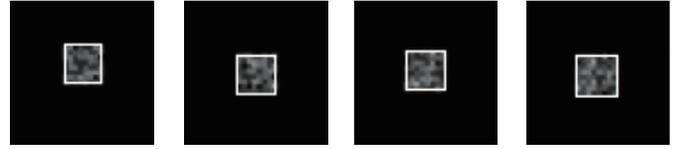|	static	driving
Data Rate R	128kbps	16kbps
Vehicle speed	—	30km/h
Lightning frequency of LED	4kHz	
Shutter speed	1000fps	
Turbo code rate	1/3	
Focal length of a lens	35mm	
Focus of a lens	infinity	
Lens diaphragm	11	
Resolution	1024×512pixel	
Communication distance	25m-80m	

Fig. 11.   Cutout image without an LED array tracking method.

Fig. 12.   Cutout image with an LED array tracking method.

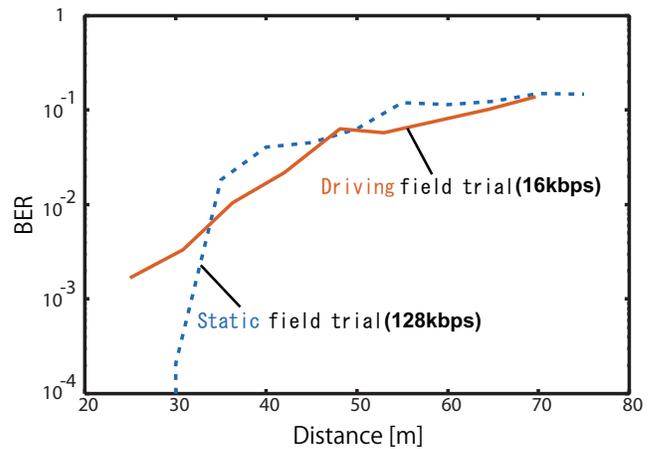Fig. 13.   BER performance in the driving field trial.

with the LED array tracking method. Thus,the LED array area can be reliably captured to the middle of the cutout image.

We evaluate the results of experiments by bit error rate (BER) performance. Figure 13 shows BER performance in the driving situation. We can see that the driving field trial shows tendencies similar to the ones in the static case. This is why, we could confirm robust tracking of an LED array in the driving situation. Also, it was confirmed that if we apply a turbo code with a code rate of one-third, error-free communication between 25m to 80m can be achieved. Furthermore, the flicker was eliminated due to the use of the inverted signals.

VI. CONCLUSION

In this paper, we discussed a decoding algorithm for the driving situation. We have proposed detection and tracking methods for an LED array and have confirmed their effectiveness. Experimental results have shown that the receiver can detect and accurately track and we can achieve error-free communication between 25m to 80m in the driving situation. We plan to extend these detection and tracking methods the case of multiple LED arrays as further step of this work.

ACKNOWLEDGMENT

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