ROBUST RECEIVER DESIGN FOR ROAD-TO-VEHICLE COMMUNICATION SYSTEM USING LED ARRAY AND HIGH-SPEED CAMERA

**Yasutake Shiraki[†], Toru Nagura[†], Takaya Yamazato[†], Shintaro Arai[††]
Tomohiro Yendo[†], Toshiaki Fujii[†††] and Hiraku Okada[†]**

**[†]Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603, JAPAN
{shiraki, nagura}@katayama.nuee.nagoya-u.ac.jp,**

**{yamazato, yendo, okada}@nuee.nagoya-u.ac.jp
[††]Aichi University of Technology, 50-2 Manori, Nishihasama-cho, Gamagori, Aichi, 443-0037, JAPAN
arai-its@aut.ac.jp**

**[†††]Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro-ku, Tokyo, 152-8550, JAPAN
fujii@it.ss.titech.ac.jp**

ABSTRACT

In this paper, we focus attention on the visible light communication systems using an LED array as a transmitter and a high-speed camera as a receiver for road-to-vehicle communications in intelligent transport systems. Previously, we have proposed the hierarchical coding scheme which enables reception of high-priority data even if the receiver is far from the transmitter and have confirmed the effectiveness of the hierarchical coding scheme from results of primitive implementation experiments. However, there are many important works to develop the real-time communication system for an actual driving situation. In this paper, we discuss a robust receiver design in an actual driving situation. We introduce a series of image processing operations and demonstrate their effectiveness by field trials. As the results of the field trials, we have achieved 16kbps transmission and error-free communication up to communication distance of 70m using 16x16 LED array (transmitter) and high-speed camera (receiver) with the frame rate of 1000.

Key words: LED, ITS, Road-to-Vehicle Communication, Visible Light Communication, Hierarchical Coding

INTRODUCTION

Light emitting diodes (LEDs) are expected as lighting sources for the next generation. In fact, LED devices, such as an LED lamp and an LED display, have become popular in the past several years since LEDs are superior to conventional incandescent lights in their low power consumption, long life, good visibility and low heat generation.

Along with the popularization of LED devices, visible light communications (VLC) using LED have attracted a great deal of attention as novel communication systems. Especially, VLC applications using LED traffic lights are one of interesting topics in the field of intelligent transport systems (ITS) (1) (2). Since LEDs are semiconductor devices, we can control LED's intensity (i.e. luminance) electrically at fast rate. Thus, it is possible to transmit data with an LED devices while it is illuminating and/or displaying image. In the case of using LED traffic lights as a transmitter, vehicles and/or pedestrians can receive latest traffic information from LED traffic lights. Moreover, the traffic lights can simultaneously play the primary role (i.e. traffic control) by blinking LED luminance with a lighting speed. For the above reasons, this paper focuses on a VLC using an LED traffic light (Transmitter) and an in-vehicle high-speed camera (Receiver) (3), namely, road-to-vehicle visible light communication (R2V-VLC). As advantages using a high-speed camera, the recognition of the LED traffic light and the estimation of its position can be realized easily. Further, the parallel data transmissions are possible by modulating LED luminance individually. In other words, we can send the data as two-dimensional (2D) LED pattern.

The one of important points for VLC using a high-speed camera is that channel characteristics of this system are different from conventional wireless communication systems. If the camera is far from the LED traffic light, the captured 2D LED pattern degrades due to reduction of pixel size and defocusing. Thus, it is hard to distinguish individual LED, which causes loss of high spatial-frequency components of data patterns in the captured images. However, low spatial-frequency components can be retrieved from the images. In other words, the camera can capture 2D LED pattern which contains low spatial-frequency components even if the camera is far from the LED traffic light.

To take advantage of these channel characteristics, we have proposed the hierarchical coding scheme in our previous research, which can transmit two kinds of data, high-priority data and low-priority data, simultaneously (4). Figure 1 shows an illustrated figure of the R2V-VLC system. We consider a situation that a vehicle is approaching to an intersection, where the data is transmitted from an LED traffic light installed on the intersection. In our system, we allocate high-priority data to low spatial-frequency components of 2D LED pattern and low-priority data to high spatial-frequency components of 2D LED pattern. Those high-priority and low-priority data are simultaneously transmitted from an LED traffic light, in a form of a specific 2D LED pattern. Since the camera can capture 2D LED pattern which contains low spatial-frequency components from a long distance, it is possible to receive the high-priority data even if the vehicle is far from the LED traffic light (blue area in Fig. 1). As the vehicle approaches the LED traffic light, additional low-priority data can be received (red area in Fig. 1). The hierarchical transmission can be realized easily by introducing 2D orthogonal data modulation. As results of the primitive implementation experiments (5), the effectiveness of the hierarchical coding has been confirmed and the reception of the data while driving has been achieved. However, we have not achieved error-free communication of this system although the receiving performance of the high-priority data has been achieved with the bit error rate (BER) of 10^{-3} in the driving distance between 10m and 60m. Moreover, these achievements have been confirmed with the very low data rate (1kbps) and the off-line data processing (i.e. non-real-time processing). As the next step, we consider that it needs to realize R2V-VLC with the hierarchical coding in an actual driving situation.

In this paper, we discuss a robust receiver design in an actual driving situation. We introduce a series of image processing operations and demonstrate their effectiveness by field trials. Especially, we focus on four tasks of the image processing unit of the receiver; Detection of LED traffic light, Tracking of LED traffic light, LED position estimation and Luminance normalization. The details of the image processing unit are described in Sec. 3.

In Sec. 3.1, we explain the simple detection using frame difference method for real-time communication. As the high-speed camera captures every image in 1ms, most of background image other than LED array can be eliminated.

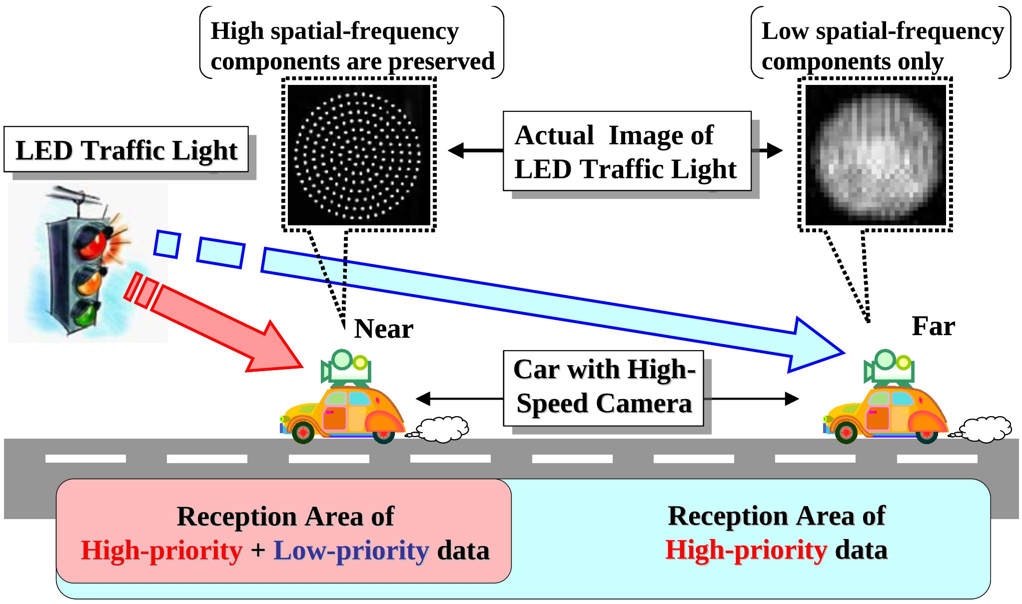


Figure 1. Proposed road-to-vehicle visible light communication (R2V-VLC).

In Sec. 3.2, we introduce a new LED traffic light tracking method without unmodulated pattern. A well-known template matching for the tracking needs unmodulated pattern used only for LED traffic light detection and tracking. Therefore, a reduction of data rate can not be avoided by the template matching. As all LEDs are used to transmit the data, we can improve the data rate by our new method. Further, the method is simple enough to operate in real time.

In Sec. 3.3, an LED position estimation method is discussed. In our R2V-VLC system, each of LED luminance conveys the data. To extract the LED luminance from the captured images correctly, it is necessary to determine a position of each LED accurately. However, the position of each LED shifts by some pixels in every frame since the vehicle vibrates depending on the driving environment.

Once the position of each LED is decided, LED luminance can be retrieved. However, LED luminance in the received images varies depending on the camera parameter and/or ambient light. In Sec. 3.4, we explain LED luminance value normalization method to recognize data correctly.

We conduct an implementation experiment using the above methods and observe the performance of our archiving methods in Sec. 4. Finally, we conclude this paper in Sec. 5.

SYSTEM OVERVIEW

In this section, we introduce our proposed R2V-VLC system using an LED array transmitter, assumed to be an LED traffic light, and an in-vehicle receiver equipped with a high-speed camera. Figure 2 shows the block diagram of our system.

Figure 3 (a) and (b) shows experimental instruments; LED array transmitter, the in-vehicle high-speed camera connected to a PC. As the high-speed camera, we use Photron FASTCAM-1024PCI 100K. Table 1 (a) and (b) summarize the parameters of experimental instruments. Parameters of the LED array are almost the same as the actual LED traffic lights in Japan.

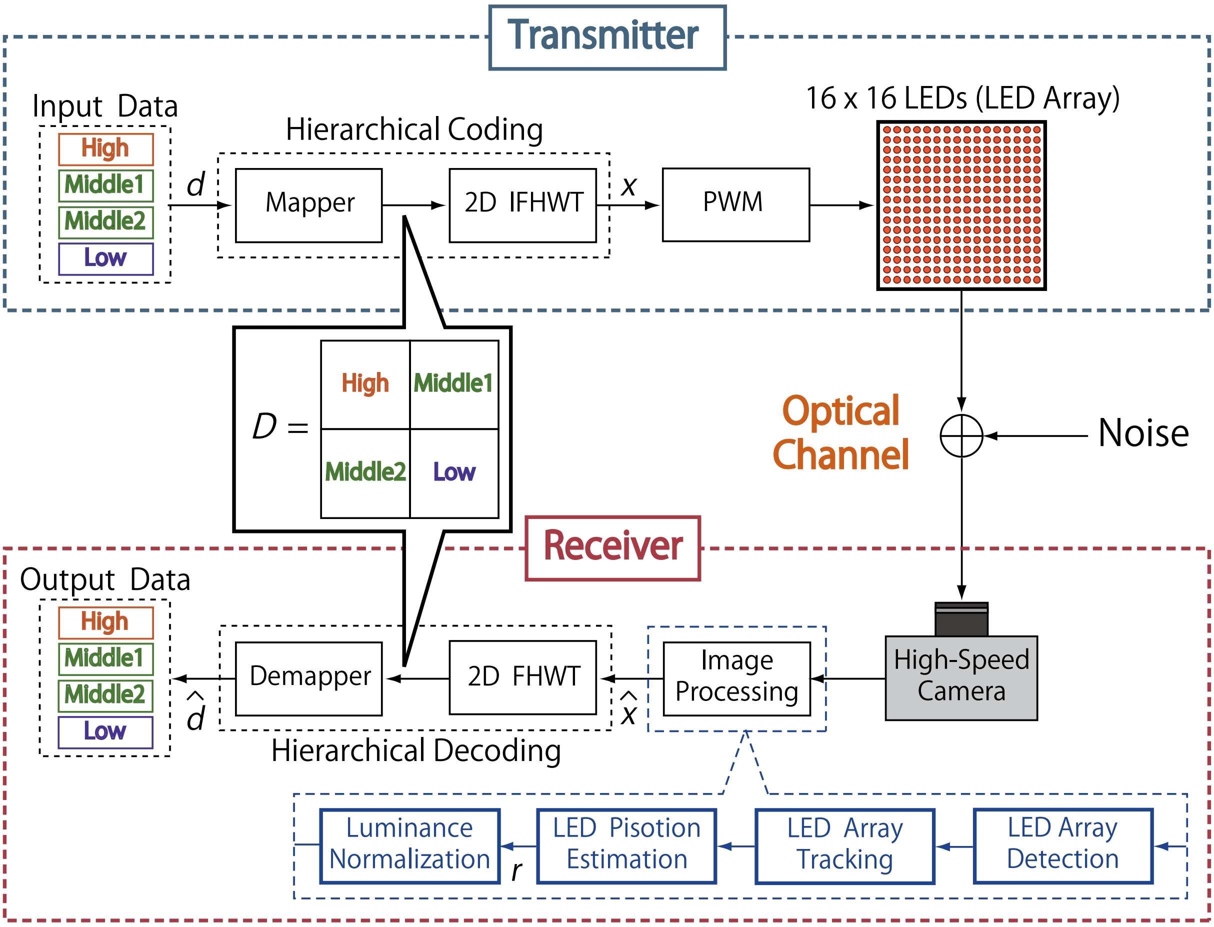


Figure 2. System model.

(a) LED array transmitter.

(b) High-speed camera.

Figure 3. Experimental instruments.

Table1. Parameters of experimental instruments

(a) LED array

Number of LEDs	16×16 (256)
Spacing of LEDs	2cm
Lighting frequency	4kHz
Half-value angle	26°

(b) High-speed camera

Frame rate	1000fps
Focus of lens	35mm
Lens diaphragm	11
Focus of a lens	Infinity

Transmitter

The transmitter consists of 256 LEDs arranged in 16×16 square matrix and an encoder. Here, we define a LED in the u-th row and v-th column as LED(u,v). We use two-dimensional inverse fast Haar wavelet transform (2D IFHWT) for performing the hierarchical coding. We divide input data according to priorities and allocate those data to some spatial-frequencies. The whole data are orthogonally transformed to determine the coefficient $x_{u,v}$ that represents LED luminance. The input binary data matrix is

$$D = \begin{Bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{Bmatrix} = \begin{Bmatrix} d_{1,1} & d_{1,2} & \cdots & d_{1,16} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,16} \\ \vdots & \vdots & \ddots & \vdots \\ d_{16,1} & d_{16,2} & \cdots & d_{16,16} \end{Bmatrix}, \quad (1)$$

where D_{11}, D_{12}, D_{21} and D_{22} are 8 × 8 matrix, and $d_{m,n} = \{-1, 1\}$. The input binary data $d_{m,n}$ is assumed to be independent and identically distributed (i.i.d.). When we apply 2D IFHWT, the input data is divided into 3 blocks depending on their assigned priorities; high, middle and low. The matrix D_{11} corresponds to the high-priority data. Let bit rate per one LED be R_b and then bit rate of D_{11} is $64R_b$. In the same way, the matrices D_{12} and D_{21} correspond to the middle-priority data and their bit rates are $128R_b$. The matrix D_{22} corresponds to the low-priority data and its bit rate is $64R_b$.

The input binary data matrix D is transformed into matrix x' by 2D IFHWT. The element of x' in the u-th row and v-th column is

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

where $H^{16}_{m,n}$ is a element of matrix H^{16} in the u-th row and v-th column, given as follows,

$$H^{16} = \begin{Bmatrix} 1 & 1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & -1 \end{Bmatrix}. \quad (3)$$

The range of $x'_{u,v}$ varies from −2 to 2. We bias and normalize $x'_{u,v}$ to set the range from 0 to 1 as

$$x_{u,v} = \frac{(x'_{u,v} + 2)}{4}. \quad (4)$$

The element $x_{u,v}$ have five-valued patterns of $\{0,1/4,1/2,3/4,1\}$. According to $x_{u,v}$, the transmitter generates nonnegative pulse. The transmitter expresses the luminance by pulse width modulation (PWM).

<u>Receiver</u>

The receiver consists of a high-speed camera, an image processing unit and a decoder. The transmitted 2D LED pattern passes through the optical channel and is captured by the high-speed camera. The image processing unit determines the position of each LED and extracts the LED luminance. We describe the detail of the image processing unit for the driving environment in Sec. 3; detection and tracking of traffic light, LED position estimation, luminance extraction and luminance normalization.

After the image processing, we get received luminance $\widehat{x}'_{u,v}$ corresponding to LED(u,v) extracted from captured images. 2D FHWT (i.e. decoding of the hierarchical coding) is performed to the matrix that consists of $\widehat{x}'_{u,v}$. After the transformation, the element of output matrix in the m-th row and n-th column is

$$\widehat{d}'_{m,n} = \frac{1}{2}\sum_{u=1}^{16}\sum_{v=1}^{16}\widehat{x}'_{u,v}H^{16}_{n,v}H^{16}_{m,u}. \qquad (5)$$

By performing this operation, the matrix which consists of the received luminance is changed into spatial-frequency components again. Finally, threshold detection is performed to recover the input binary data. If $\hat{d}_{m,n}$ is positive (or negative) then received data is determined as 1 (or −1).

IMAGE PROCESSING FOR DRIVING SITUATION

In this section, we will describe the image processing unit shown in Fig. 2. The image processing unit consists of four units necessary for the data detection in a driving situation; LED array detection, LED array tracking, LED position estimation and luminance normalization. Before we explain the units in detail, let us begin with the packet format as shown in Fig. 4.

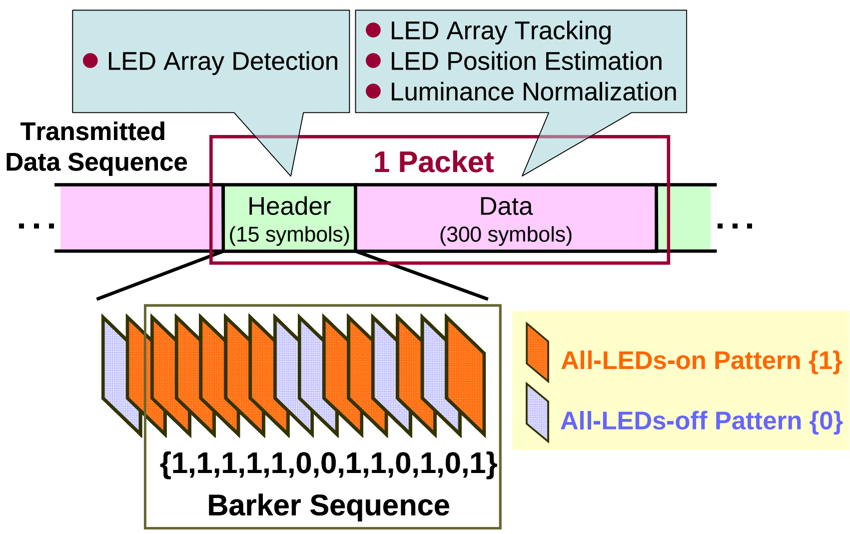


Figure 4. Packet format.

The packet consists of a header part and a data part. The header part consists of all-LEDs-on pattern and all-LEDs-off pattern and is used mainly for LED array detection. The data are conveyed in the data part. We track the LED array using the data in the data part. The LED position estimation and the luminance normalization are also performed during the date part.

LED Array Detection

Using the header part of the packet, the receiver searches the LED array from the captured images. As we notice from the header part, the LED array turns on and off. Figure 5 shows an example of captured two successive images. By a frame difference method, we can easily find the LED array. The resulted image contains the LED array and some noise as shown in Fig. 5. Since the high-speed camera captures images at high rate (1000fps), most of the background can be eliminated. Further, we employ Barker sequence {1, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 0, 1} for robust LED array detection. Barker sequence is well-known for its good autocorrelation characteristic in time domain. Note that we represent the Barker sequence by all-LEDs-on pattern {1} and all-LEDs-off pattern {0} as shown in Fig. 4. By experimental result, we detect LED array correctly without miss detection, which will be described later. After the LED detection, we track the LED array.

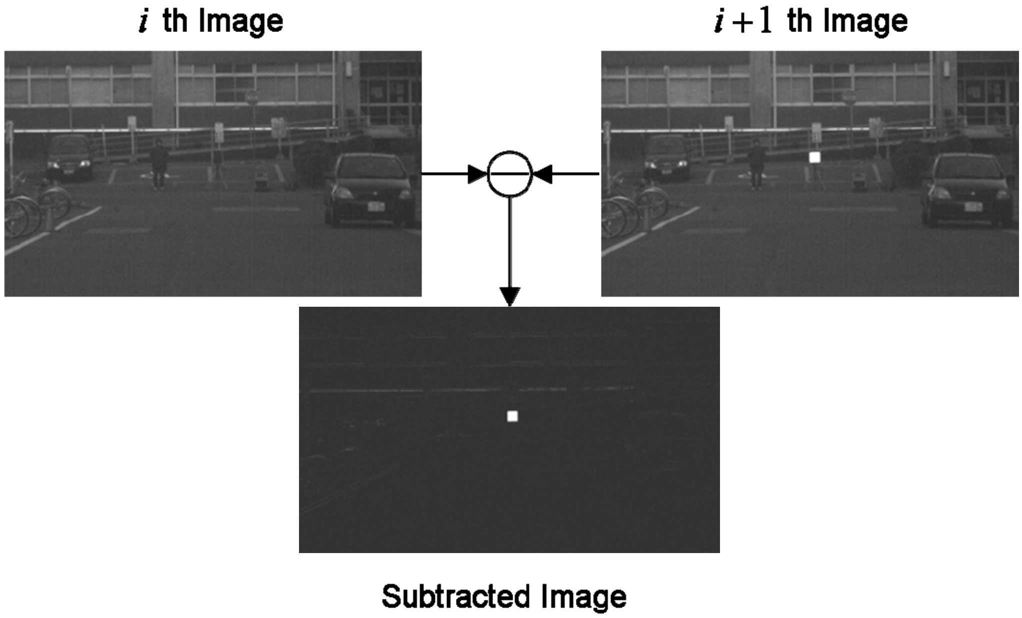


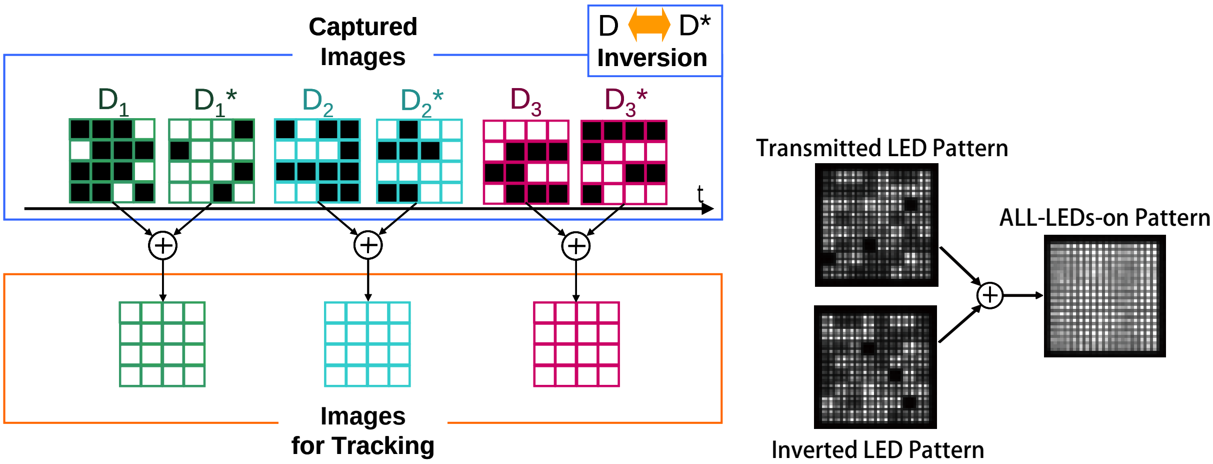
Figure 5. Resulted image by subtracting two successive images.

LED Array Tracking

We track the LED array in the data part. The most common method for the tracking may be a template matching. Unfortunately, because each LED blinks independently, an LED array tracking method for the data part using the template matching is difficult. For this reason, in our previous research, we keep the LEDs, in a fringe of the LED array, on for the template matching. However, since the contour of the LED array is used only for the template matching, this method sacrifices the data rate. Here, we employ an LED array tracking method using inverted LED patterns (6).

At the transmitter, we make the inverted pattern of each transmitted LED pattern and transmit them alternatively. Figure 6 (a) shows examples of the transmitted LED pattern (D) and its inverted LED pattern (D*).

At the receiver, those two patterns are added together to generate all-LEDs-on pattern. In Fig. 6 (b), we show examples of the actual captured images and the generated all-LEDs-on pattern. In this way, the robust LED array tracking can be performed using the generated all-LEDs-on pattern.



(a) Examples of patterns. (b) Actual images.

Figure 6. Tracking method using inverted LED patterns.

LED Position Estimation

We need to estimate the position of each LED which transmits the modulated data independently. By the LED array tracking method explained above, the position and the size of the LED array can be easily estimated from the generated all-LEDs-on patterns. The position of each LED can be easily estimated. However, the communication distance is limited by the number of pixels between two neighboring LEDs in the captured image.

Figure 7 shows the relation of the communication distance and the number of pixels between two neighboring LEDs. We need 2 pixels between neighboring LEDs in order to demodulate each LED independently. As shown in Fig. 7, in the case of our experimental instruments, the LED array and the high-speed camera, the number of pixels between two neighboring LEDs in the captured image is about 2 pixels at the communication distance of 20m. At the communication distance of 40m, two neighboring LEDs can not be distinguished as the number of pixels between two neighboring LEDs is one. Therefore, the maximum communication distance is 40m for our experimental instruments.

To lengthen the communication distance, we represent one data bit by 4 LEDs (2x2 LEDs) as shown in Fig. 8. As shown in Fig. 7, if we represent one data bit by 4LEDs (2x2 LEDs), the communication distance is lengthened to 40m. Applying the hierarchical coding, we can receive the data from further distance as to high-priority data.

In driving situation, the position of each LED shifts in every frame since the vehicle vibrates. From our experimental results, the vehicle vibration can not be ignored even though we capture the images at 1000 fps. Figure 9 (a) and (b) show the extent of the vertical and horizontal camera vibration in the captured images respectively in driving situation with the vehicle speed of 30km/h at the distance of 50m. From the figures, we confirm that we must take at least 2 pixels camera vibration into account.

As we will show in Sec. 4, the representation of one data bit by 4 LEDs (2x2 LEDs) is also effective for the camera vibration.

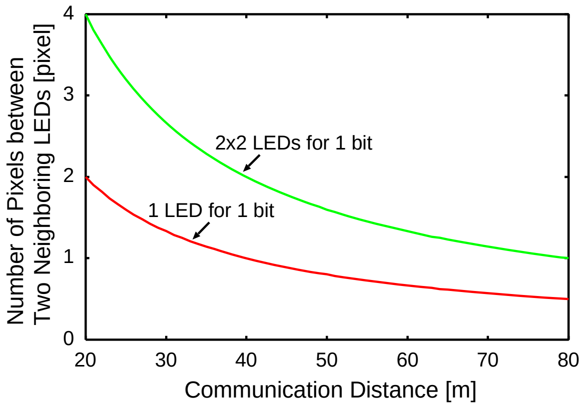


Figure 7. Relation of the communication distance and the number of pixels between two neighboring LEDs

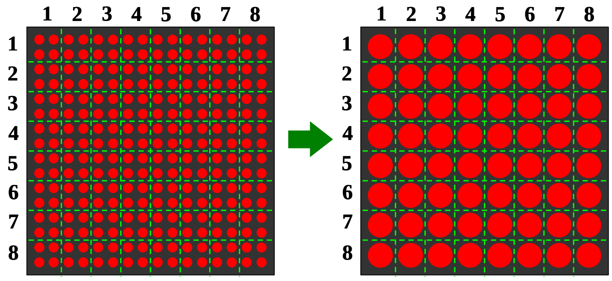
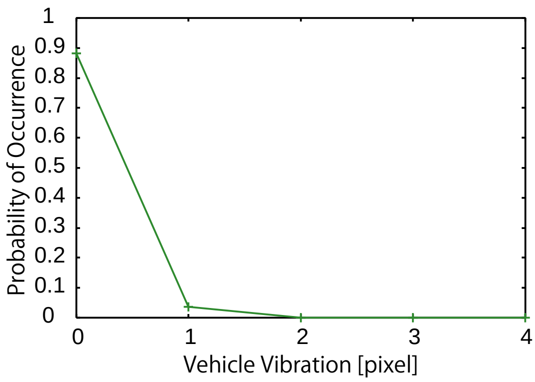
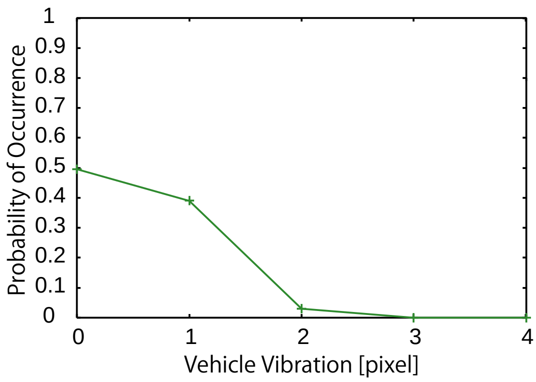


Figure 8. Representation of one data bit by 4 LEDs (2x2 LEDs)



(a) Horizontal vibration.



(b) Vertical vibration.

Figure 9. Vertical and horizontal camera vibration in the captured images in driving situation with the vehicle speed of 30km/h at the distance of 50m.

Luminance Normalization

LED luminance in the captured images varies according to the directivity of each LED, direction of the vehicle, the vibration of the camera and parameters of the camera. To suppress variation in the luminance of LEDs, we must revise the extracted luminance for each LED. Then we introduce normalization of the extracted luminance (7).

After the LED position estimation process, we obtain the luminance $r_{u,v}$ of LED(u,v). We normalize the luminance values by using the mean E and the variance V of the extracted luminance $r_{u,v}$. The normalized value in row u column v is

$$E = \frac{\sum_u \sum_v r_{u,v}}{N}, \tag{6}$$

$$V = \frac{\sum_u \sum_v (r_{u,v} - E)^2}{N}, \tag{7}$$

$$\hat{x}_{u,v} = \frac{r_{u,v} - E}{\sqrt{V}}, \tag{8}$$

where N is the number of bits represented by one lighting pattern (N=64). With the normalization, we can decode data correctly.

When the transmitted data are binary variable, the transmitted luminance distribution of the hierarchical coding corresponds to a Bernoulli distribution (Fig. 10).

Figure 11 (a) and (b) show the received luminance distribution of the hierarchical coding when the communication distance is 30m. From Fig. 11 (a), we can not recognize five transmitted luminance peaks because each LED has different received luminance distribution. On the other hand, as we can see in Fig. 11 (b), we can recognize luminance peaks with the normalization because the received luminance distribution of each LED is revised to be similar distribution. That is, we can decode data more correctly with the normalization.

The normalization is also effective when the LED array and the camera are not directly facing each other. Figure 12 (a) and (b) show the received luminance distributions at communication distance of 30m with and without the normalization respectively when we turn the LED array 30° as shown in Fig. 13. From Fig. 12 (a), we observe that the received luminance distribution is centering upon low luminance value due to the directivity of the LED. From Fig. 12 (b), we can recognize peaks in the received luminance distribution with the normalization. In fact, the distribution we observe almost same as the received luminance distribution as the case when the LED array is facing straight (Fig. 11 (b)).

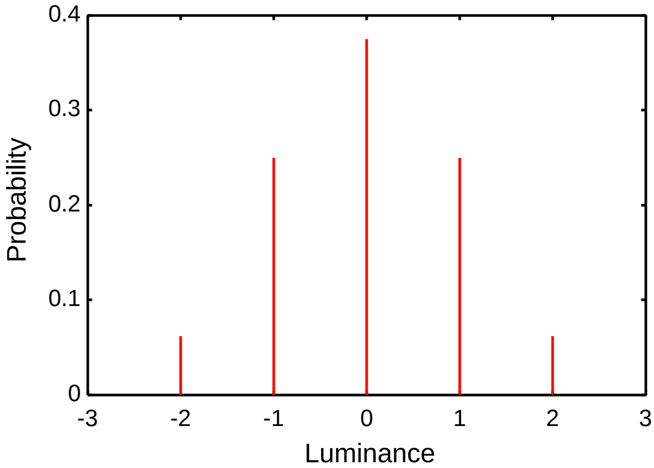
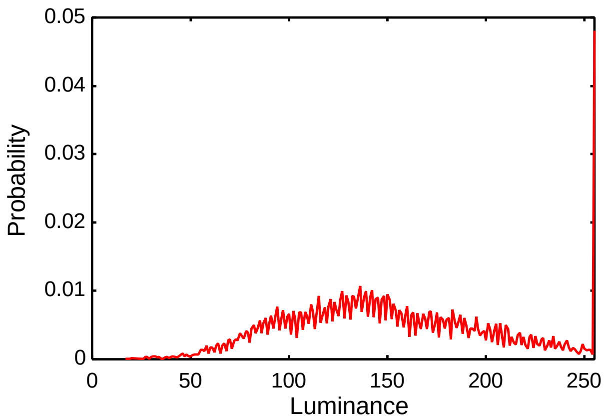
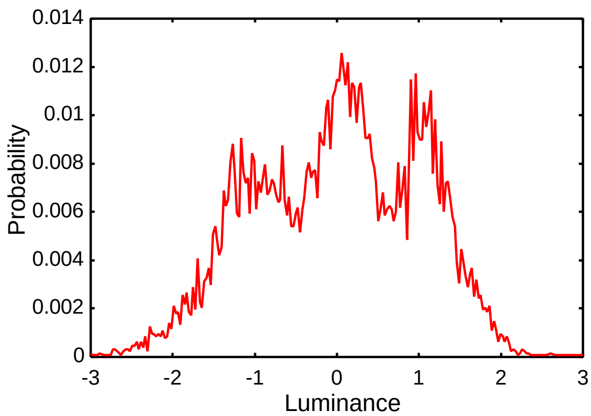


Figure 10. Transmitted luminance ($x'_{u,v}$) distribution of the hierarchical coding.

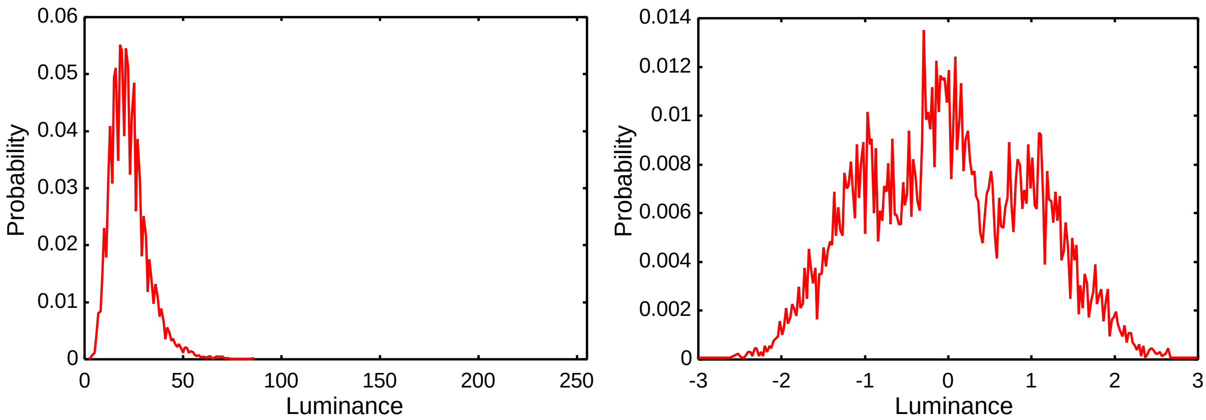


(a) w/o normalization ($r_{u,v}$).



(b) w/ normalization ($\hat{x}_{u,v}$).

Figure 11. Received luminance distribution of the hierarchical coding (30m).



(a) w/o normalization ($r_{u,v}$). (b) w/ normalization ($\hat{x}_{u,v}$).

Figure 12. Received luminance distribution at rotation angle 30° (30m).

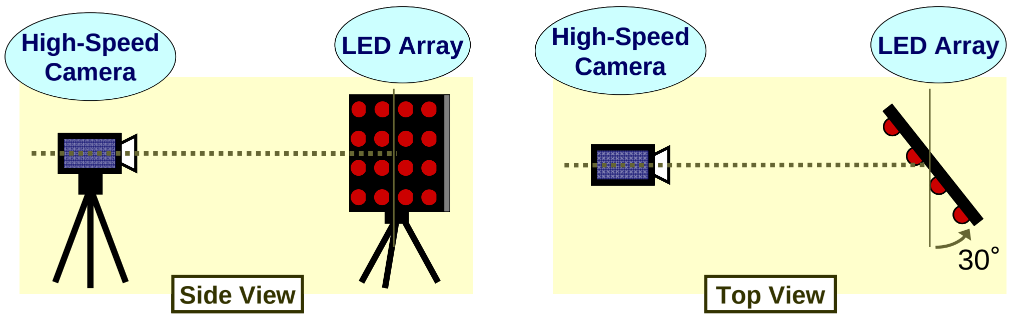


Figure 13. Way of turning the LED array.

THROUGHPUT PERFORMANCE

This section explains the field trials of our R2V-VLC system. We have been performing field trials to confirm the effectiveness of the proposed system on an actual driving situation. We set the LED array on the horizontal ground and the high-speed camera on the dashboard in the vehicle. The vehicle drives straight toward the LED array with the speed of 30km/h as shown in Fig. 14. The communication distance in those field trials ranges from 70m to 20m.

Figure 15 shows the throughput performance in the field trials. The maximum achievable throughput is 15 kbps for our system with the operations explained in previous section. If miss detection occurred, severe degradation in the throughput may be found. Also, if we fail in tracking the LED array, the throughput performance falls down greatly since the LED position can not be estimated correctly and the luminance corresponding to each LED can not be extracted correctly.

From Fig. 15, we confirm that our R2V-VLC system achieves the maximum throughput until the communication distance of 40m and the throughput gradually degrades. We further confirm that even at the communication distance of 70m, the throughput of 12 kbps is achieved. Note that 100% LED array detection and tracking are found. We therefore confirm the robust detection and tracking of the LED array against the camera vibration and the changes in the image size of the LED array while driving. Furthermore, we have achieved error-free communication up to communication distance of 70m when we apply the turbo code with the code rate of one-third.

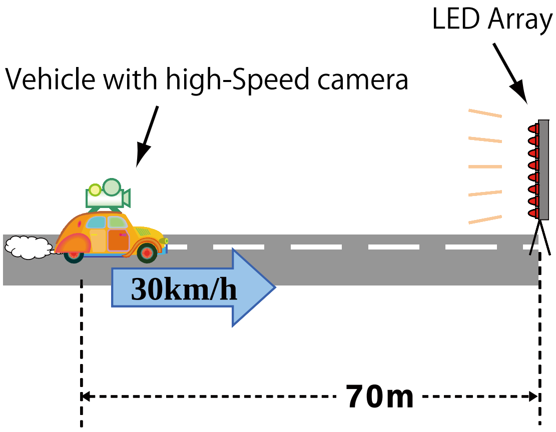


Figure 15. Field trial course.

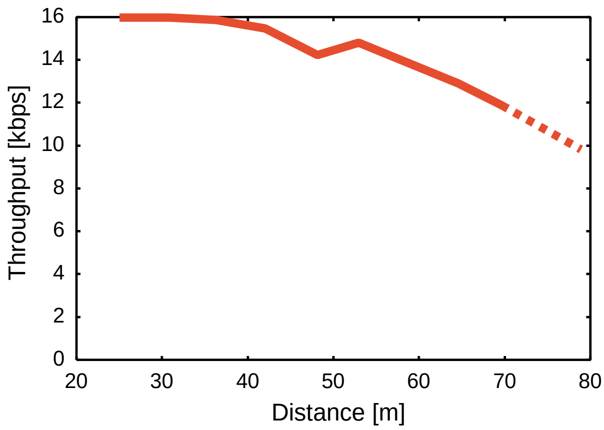


Figure 16. Throughput performance.

CONCLUSIONS

In this paper, we mainly discussed the series of four image processing tasks necessary in an actual driving situation to realize R2V-VLC system using the hierarchical coding. The experimental results have shown these operations are effective. We have achieved 16 kbps in throughput performance and error-free communication up to communication distance of 70m with turbo code. These operations are simple and enable the real-time processing.

We plan to expend tracking method into multiple LED arrays tracking method as further step of this work.

REFERENCES

(1) M. Akanegawa, Y. Tanaka, and M. Nakagawa, “Basic Study on Traffic Information System Using LED Traffic Lights”, IEEE Trans. on Intelligent Transportation Systems, vol. 2, no. 4, pp. 197-203, Dec. 2001.

(2) H. S. Liu and G. Pang, “Positioning Beacon System Using Digital Camera and LEDs”, IEEE Trans. on Vehicular Technology, vol. 52, no. 2, pp. 406-419, Mar. 2003.

(3) M. Wada, T. Fujii, and M. Tanimoto, “Space Division Multiplexing Wireless Optical Communication for ITS”, ITS Symposium 2004, Nagoya, Japan, Oct. 2004, pp. 207-212.

(4) 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.

(5) S. Arai, S. Mase, T. Yamazato, T. Yendo, T. Fujii, M. Tanimoto, Y. Kimura, “Feasible Study of Road-to-Vehicle Communication System Using LED Array and High-Speed Camera”, Proceedings of the 15th World Congress on ITS, Nov. 2008.

(6) T. Nagura, T. Yamazato, M. Katayama, T. Yendo, T. Fujii, H. Okada, “Tracking an LED Array Transmitter for Visible Light Communications in the Driving Situation”, IEEE International Symposium on Wireless Communication Systems, Sep. 2010.

(7) T. Nagura, T. Yamazato, M. Katayama, T. Yendo, T. Fujii, H. Okada, “Improved Decoding Methods of Visible Light Communication System for ITS using LED Array and High-Speed Camera”, IEEE Vehicular Technology Conference, May.