Improved Decoding Methods of Visible Light Communication System for ITS using LED Array and High-Speed Camera

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***Abstract*—In this paper, we consider visible light communication systems using LED array as a transmitter and high-speed camera as a receiver for Intelligent Transport System (ITS). Previously, we have proposed the hierarchical coding scheme which allocates data to spatial frequency components of the image depending on the priority. This scheme is possible to receive information of the high-priority even if communication distance is long. However, we need to distinguish multi-valued data from the received image by using a hierarchical coding. In this paper, we propose two improved decoding methods, and demonstrate to distinguish multi-valued data more correctly in the experiment.**

I. Introduction

Light emitting diodes (LEDs) are expected as lighting sources for next generation. LEDs are superior to conventional incandescent lights due to their low power consumption, strong directivity, good visibility, long life, and low heat generation. This is why, in Japan, many incandescent traffic lights is on the road to replacing with LED traffic lights. Also, LEDs are able to control their intensity electrically at fast rate, since they are semiconductor devices. That is, LEDs can be used not only illuminating device but also communication device. For examples, LED traffic lights broadcast driving assistance data to vehicles: road-to-vehicle communications, LED vehicle brake lights transmit warning data to vehicles behind: 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 LED array as a transmitter and high-speed camera as a receiver [5]. The advantage of using a camera is that it is able to recognize the position of LEDs array easily, because of it's wide viewing angle. Also, if each of LEDs in traffic lights and brake lights are individually modulated, parallel data communication are possible. However, using a camera also has disadvantages. When the camera is far from LEDs array, the received images are blurred due to defocus and reduction of pixel size. It is hard to distinguish adjacent LEDs, namely, high spatial frequency components of images are lost. Even in such a condition, received images contain low spatial frequency components.

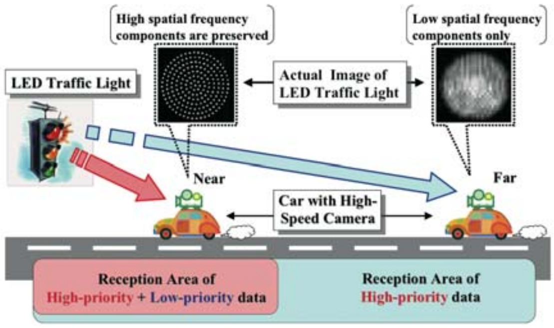


Fig. 1. Visible light communication system using LED traffic light and high-speed camera.

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 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, the effectiveness of the hierarchical coding was confirmed. However, the difference in quality of reception between high-priority data and low-priority data was small. Even for high-priority data, errors occurred when the distance was over 30m. Also, we have achieved 32kbps transmission using 256 LEDs which blink 500Hz. Our goal is to design a system that can receive vehicle and support information for drivers during driving the vehicle. 30m is too short and 32kbps is too slow for the driver to use the received data before reaching the intersection.

In this paper, we explain improved decoding methods. At first, we propose a method of luminance value revision using the mean and variance of the extracted luminance of each LED. This method enables us to recognize multi-valued data which is needed in the hierarchical coding scheme more correctly. Thus, we can lengthen the communication distance. Secondly, we propose a method of luminance extraction to

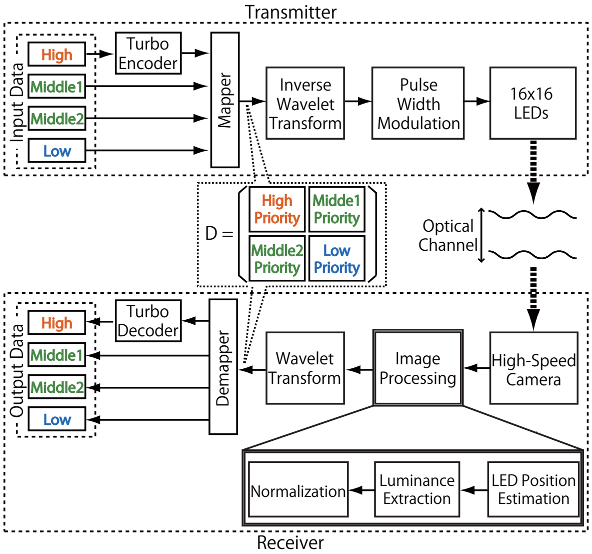


Fig. 2. System model.

resolve the problem of the luminance saturation. This method makes it possible to communicate at a data rate of 128kbps; four times that of the conventional method.

II. SYSTEM OVERVIEW

Figure 2 shows block diagram of the system model.

A. Transmitter

The transmitter consists of 256 LEDs in the form of a 16×16 square matrix, 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 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

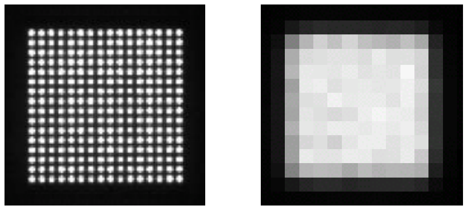
$$x_{u,v}(t) = \sum_k x_{u,v,k} \cdot A \cdot g(t - (k-1)T_b), \quad (1)$$

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,

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

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



(a) 10m (b) 70m

Fig. 3. Received image.

CMOS image sensors and each pixel outputs a photo-current corresponding to the received light intensity. The signal at the u,vth LED is

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

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 white Gaussian noise process with double-sided power spectral density $N_0/2$.

Let us assume that the receiver camera is exactly synchronized with the transmitter LED. Let the image sampling period be T_b and the image light exposure time be τ, where $\tau \le T_b$. The image light exposure can be represented as

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

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

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

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

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

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. We can distinguish each LEDs 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 is longer, high spatial frequency components of images degrade severely.

To take advantage of these channel characteristics, we employed the hierarchical coding scheme using 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 primary data in long distance and also obtain additional data in short distance.

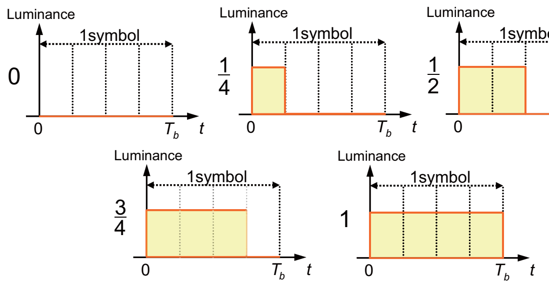


Fig. 4. Pulse Width Modulation.

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

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

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 $\boldsymbol{D}_{11}$ 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

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

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

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

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 five patterns by modulating voltage amplitude because of individual difference of LEDs and pixel gaps in the images. Thus, we express the luminance of five patterns to change 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.

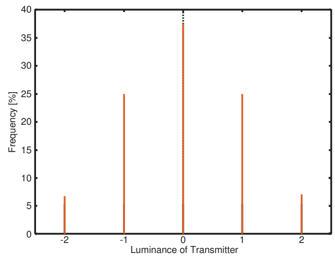
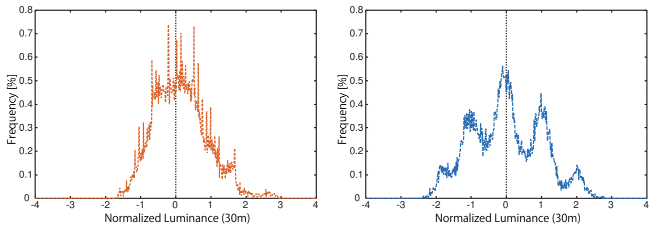


Fig. 5. Transmitted luminance distribution of hierarchical coding.



(a)w/o revision (b)w/ revision

Fig. 6. Received luminance distribution of hierarchical coding (30m).

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

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

By performing this operation, the procession consisting of the received luminance 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. APPLYING AN ERROR CORRECTING CODE

Hierarchical coding has enabled us to divide transmitted data into high and low spatial frequency components, and we confirmed the advantage of the hierarchical coding. But the bit error performance is not enough to realize error-free. To improve the performance, we apply turbo coding which is an error correcting code.

If we apply turbo coding to all data including high and low spatial frequency components, the degradation of high spatial frequency components will affect the correcting capacity. Hence, we apply turbo coding to data divided into each priority, and improve the bit error performance.

(a)Luminance “1” (b)Luminance “1/4”

Fig. 7. Several pixels of received images corresponding to one LED (15m).

Fig. 8. LED array.

Fig. 9. High-speed camera.

TABLE I
HIGH-SPEED CAMERA SPECIFICATIONS.

Camera model.	FASTCAM-1280PCI made by Photron
Lens model	Ai Zoom Nikkor made by Nikon
Sensor type	CMOS
Focus	35mm∼200mm
Shutter speed	60∼16000fps
Resolution	Max 1280×1024 pixel

TABLE II
EXPERIMENTAL PARAMETER.

	conventional	proposed
Number of extraction pixels	fixed	variable
Lightning frequency of LED	500Hz	4kHz
Data Rate R	32kbps	128kbps
Shutter speed	1000fps	
Turbo code rate	1/3	
Focal length of a lens	35mm	
Focus of a lens	infinity	
Lens diaphragm	11	
Resolution	128×128pixel	
Communication distance	10m-120m	

V. IMPROVEMENT OF PERFORMANCE

A. Method of luminance value revision

The range of the extracted luminance $r_{u,v}$ varies from 0 to 255. Before 2D FHWT, we need to normalize the range of $r_{u,v}$ from -1 to 1. In our previous research, we obtained a standard from the maximum received luminance which lights all 256 LEDs, and normalized by the standard. However, some revision is necessary to suppress variations in the luminance of LEDs and influence due to interferences between LEDs.

In this paper, we propose a method of luminance value revision using the mean $E_{u,v}$ and variance $V_{u,v}$ of the extracted luminance $r_{u,v}$ of each LED . The normalized value using the luminance value revision method with row u and column v of sth transmitted symbol is

$$\hat{x}_{u,v}(s) = \frac{r_{u,v}(s) - E_{u,v}}{\sqrt{V_{u,v}}}, \tag{11}$$

when we suppose the transmitted data are binary variable, the transmitted luminance distribution of hierarchical coding corresponds to a Bernoulli distribution (Fig. 5).

Figures 6 (a) and (b) show the received luminance distribution of the hierarchical coding when the communication distance is 30m. As we can see in Fig. 6 (a), we cannot recognize five transmitted peaks. Thus it is difficult to decode the transmitted data using the conventional method without revision, while we can recognize five transmitted peaks using the proposed method with revision in Fig. 6 (b). That is to say, proposed method makes it possible to decode more correctly.

B. Method of luminance extraction

In this system, we need to extract five patterns $\{0, \frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1\}$. We have expressed these patterns through four received images up to now, thus data rate was 32kbps. As lightning frequency of each of the 256 LEDs is 500Hz, maximum data rate is 128kbps. To realize a 128kbps transmission, we express five patterns by one received image. However, it is difficult to decide the five patterns from each received image, because luminance gets higher as the transmitter gets closer to the receiver and becomes saturated in short distance.

This is caused by extracting the luminance from one pixel corresponding to one LED. For example, we consider the luminance extraction in short distance (15m). Figure 7 shows several pixels of two received images corresponding to one LED in this distance (15m). In this case, luminance is extracted from the central pixel, and both luminance values are detected as “1”.

Nevertheless, the actual transmitted values are “1” and “$\frac{1}{4}$” in Fig. 7 (a) and (b) respectively. Hence, the receiver misleads five transmitted patterns in short distance.

We propose a method of luminance extraction to resolve it. We extract the luminance value from neighboring pixels which consist of unsaturated ones. That is, we receive luminance more correctly by extracting from the number of variable pixels. The sample output given by Eq. 6 may be written in the form

$$r_{u,v,i} = c \sum_{u'=u-s}^{u+s} \sum_{v'=v-s}^{v+s} \int_{(i-1)T_b}^{iT_b} y_{u',v'}(t) \cdot f(t) dt. \tag{12}$$

This method increases the number of the pixels per LED in the short distance and we sum the luminance of neighboring pixels depending on the distance. In the example of Fig. 7, we extract luminance from 3 × 3 square pixels. Thus, we recognize five patterns more correctly.

VI. EXPERIMENTAL RESULTS

We performed a field trial of visible light communication using two improved decoding methods described in the previous section. We performed measurements for distances from 10m to 120m, every 5m. We evaluate the results of experiments by bit error rate (BER) and throughput performance.

Figures 8 and 9 show field trial instruments; the LED array transmitter and the high-speed camera. The LED 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.

A. Experiment 1

Figure 10 shows the BER performance with/without luminance value revision. In this experiment, we apply turbo code as an error correcting scheme with a code rate of one-third.

We can see that without the luminance value revision, bit errors occur for a communication distance over 50m. With the luminance value revision, we can receive error-free data for a distance up to 65m. Then, we also confirm that the error-free range is 20m lengthened by applying the luminance value revision and the turbo code.

B. Experiment 2

We demonstrate the effectiveness of the luminance extraction experimentally. Figure 11 shows a throughput performance with fixed and variable extraction pixels. Throughput with 256 LEDs is defined as

$$S = 256R_b(1 - P_s), \qquad (13)$$

where, P_s is the symbol error rate which consists of 8 bits.

At first, we compare the conventional method with the fixed extraction pixel. The difference between these is data rate. In the conventional method, we only need a binary decision, whereas, in the method of fixed extraction pixel, we need five-valued decision. This is why, we can see in Fig. 11, a degradation of throughput performance with the fixed extraction method in short distance. This is because of the luminance saturation.

We resolve this problem by extracting luminance from the number of variable pixels. Fig. 11 implies that we got rid of the degradation of the throughput performance caused by the luminance saturation in a short distance. In case we apply a turbo code with a code rate of one-third, we can maintain a high throughput of 42.7kbps up to 65m.

VII. Conclusion

In this paper, we have proposed two improved decoding methods for a visible light communication system for driving safety support at intersections. Experimental results have shown these two improved decoding methods are effective.

The first method with the luminance value revision improved the whole BER performance. The second method with variable extraction pixels makes it possible to realize at data rate of 128kbps without degradation of throughput performance.

Acknowledgment

This work is supported in part by “The SCOPE by the Ministry of Internal Affairs and Communications”. The authors would like to thank Dr. Masayuki TANIMOTO of Nagoya University.

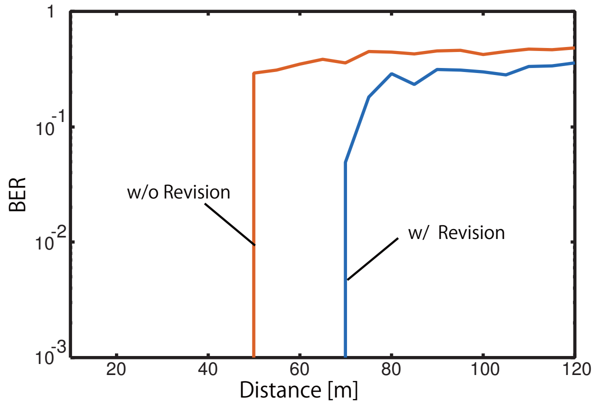


Fig. 10. BER performance using the luminance value revision.

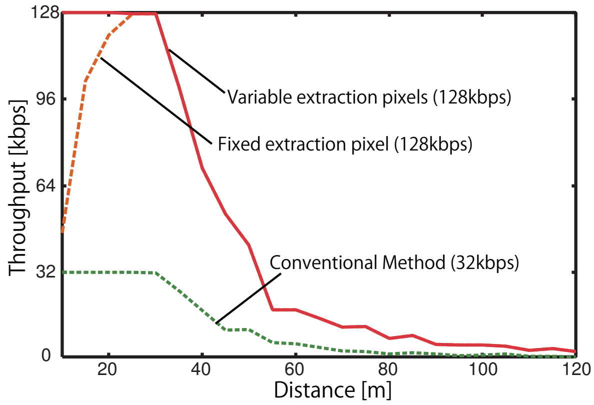


Fig. 11. Throughput performance with variable extraction pixels.

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