Feasible Study of Road-to-Vehicle Communication System using LED Array and High-Speed Camera

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ABSTRACT

In this study, we focus attention on the parallel optical wireless communication systems using LED array transmitter and a high-speed camera as the receiver for road-to-vehicle communications in ITS. Previously, we have proposed a hierarchical coding scheme which allocates data to spatial frequency components depending on the priority. This scheme is possible to receive the high priority data even if the receiver is far from the transmitter. However, since vehicles drive on a road in actual road-to-vehicle communications, there are many important works to develop the real-time communication system. For example, it is a difficult to synchronize the timing to release the shutter with the lighting cycle of LEDs, i.e., the sampling of the data. This paper details our road-to-vehicle communication system using the LED array and the high-speed camera and proposes their solutions. Moreover, based on proposed solutions, we perform a driving field trial using the LED array and a vehicle with the high speed camera. As the result, we observe the bit error rate and confirm the reception of the data during the driving.

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. It is because LEDs are superior to conventional incandescent lights due to their low power consumption, long lamp life, good visibility, and low heat generation. Apart from these, data transmission systems using LEDs are under development. Since LEDs are semiconductor devices and are able to control their intensity electrically at fast rate, it is possible to transmit data while illuminating and/or displaying image with a LED display. Such features are well suited for intelligent transport system (ITS) applications (1)-(4). For examples, LED traffic lights and LED traffic signs broadcast driving assistances data to cars (road-to-vehicle communications) or LED car brake lights can transmit warning data to a car behind (vehicle-to-vehicle communications).

This paper focuses attention on the parallel optical wireless communication systems using LED traffic lights and a high-speed camera as the receiver for road-to-vehicle communications (5) (6). As advantages using a camera, the recognition of objects as well as their locations can easily be realized and the reception of LED modulated data is also possible at the same time. Further, if each of LEDs in traffic lights, traffic signs or car brakes is individually modulated, the parallel data transmissions are possible using a camera as a reception device. Figuratively speaking, this is a data transmission system by fast switching of unrecognizable data patterns overlaying on a still visible image and a reception by a high-speed camera.

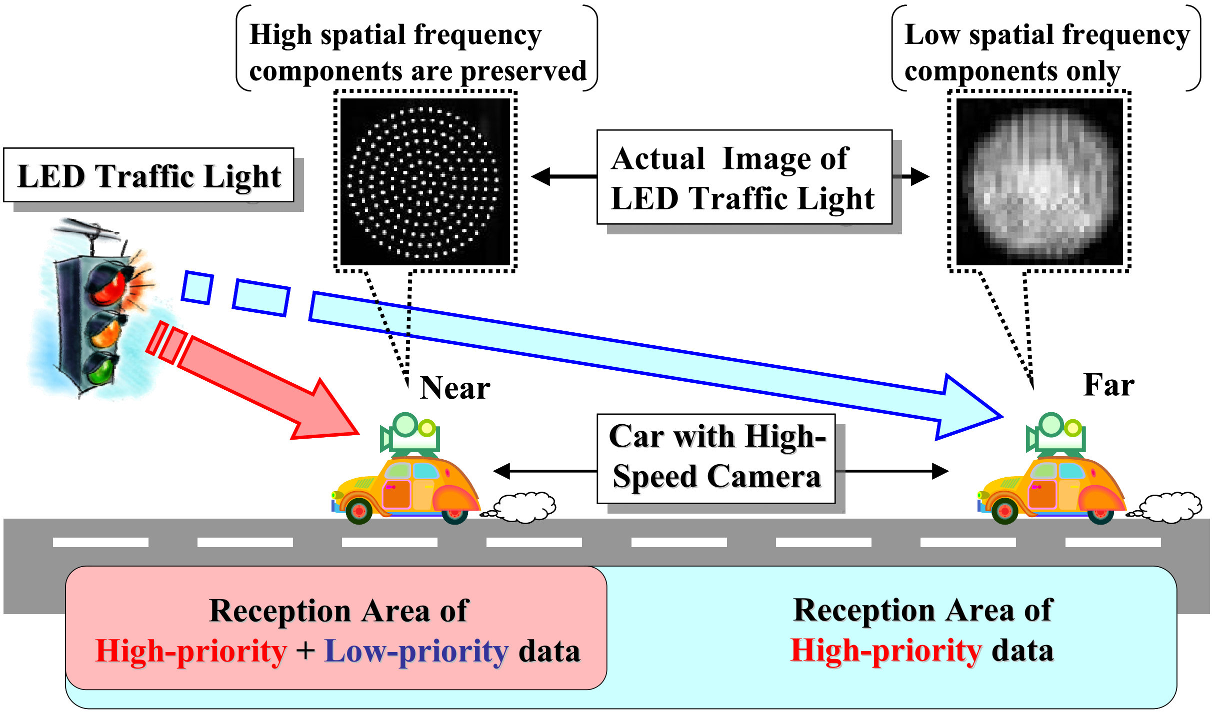


Figure 1. Optical Wireless Communication Systems in ITS.

Unsurprisingly, the communication system using LED traffic lights and the high-speed camera has disadvantages. Especially, a channel characteristic of this system using the camera is different from conventional communication systems, i.e., this channel is atypical. As we mentioned, the high-speed camera is adopted as a reception device and it retrieves data by recognition of its pattern. Unfortunately, if a receiver is far from LED traffic lights, the received data pattern degrades due to reduction of pixel size and defocus of the LED data pattern, namely, it is hard to distinguish adjacent LEDs. They are recognized as one pixel image and high spatial frequency components of data pattern are lost. However, the low-frequency components are retrieved from the image. In other words, the high-speed camera can receive the LED data pattern contained the low-frequency components from these pixels, even if a receiver is far from a transmitter.

To take advantage of these channel characteristics, we proposed a hierarchical coding scheme in our previous research (7). If we allocate high-priority data to low frequency components and low-priority data to high frequency components, the reception of high-priority data can be guaranteed even when the LED-camera is further. When the car comes near the LED traffic light, then additional low-priority data can be received, as shown in Fig. 1. The hierarchical transmission can easily be realized by an introduction of two-dimensional orthogonal data modulation. To evaluate the performance of the hierarchical coding, we assembled the LED array transmitter which modeled LED traffic lights and performed the implementation experiment by fixing the LED array and the camera. As results, it succeeded in reception of the data, and the effectivity of the hierarchical coding was confirmed. When car is moving, it vibrates and so does the received images.

Further, the size and luminance of the received images of LED array vary due to change in distance. The car vibration leads difficulty in tracking of the received LED array images and the change in distance to the LED array give difficulties in bringing the received image into focus and as well as extraction of actual position of each LED and its luminance, that is used for retrieving data.

To confirm technical feasibility of the road-to-vehicle communication system using LED array and high-speed camera, in particular the hierarchical coding scheme, we have conducted field trials. The high-speed camera was set in a car and reception of data in moving condition was evaluated. Thanks to the high-speed camera, the effect of car vibration is not much so the tracking of the LED array image can be done with an appropriate template-matching algorithm. The extraction of position of each LED and its luminance were also successfully obtained. The out-of-focus also does not affect much to the performance. However, due to the difference in clock timing between the transmitter and the receiver (high-speed camera), we cannot retrieve the data at the half-rate of the LED lighting cycle. We thus retrieve the data at 4 times higher rate (over sampling). This will lower the data rate, but we found that this technique leads to robust reception of luminance. As results, we confirm that our hierarchical coding scheme is effective.

SYSTEM OVERVIEW

In this section, we introduce the data transmission system model using LEDs. Figure 2 shows the block diagram of the system model. This system consists three blocks, Transmitter, Channel and Receiver.

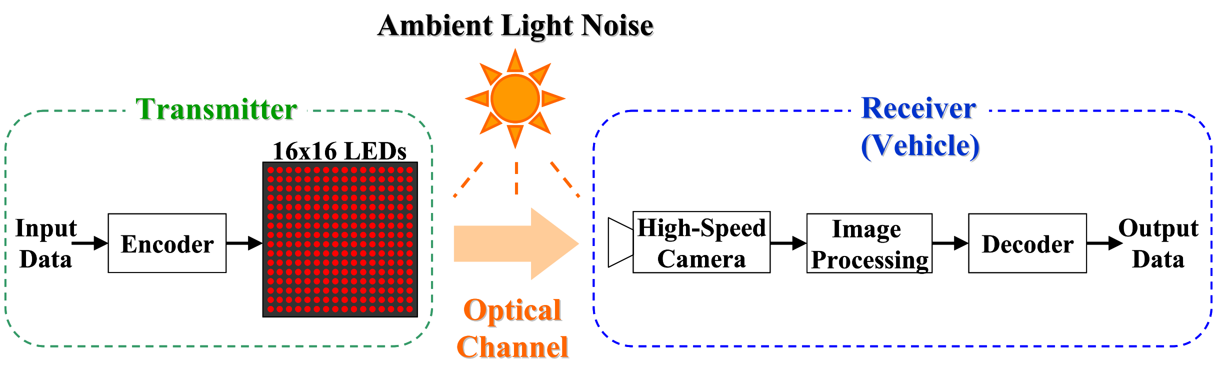


Figure 2. System Model.

LED Array Transmitter

The transmitter consists of 256 LEDs in the form of 16×16 square matrix and the encoder. The transmitter generates nonnegative pulse of which the width is T_b, where T_b is a bit duration. By changing the width of T_b, we can change the LED lighting pattern, i.e. the luminance. Thus the transmitter can modulate the information using LED's 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 different bit. The transmit power emitted by LED with row u column v at time t is

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

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

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

Transmitted signal arrives at the receiver 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 output of the pixel corresponding u, vth LED is

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

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

Receiver

The receiver consists of the high-speed camera, image processing unit and decoder. The transmitted signals pass the optical channel and are received by the high-speed camera. The camera has CMOS image sensor and outputs as an image

Let us assume perfect synchronization between the receiver camera and 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

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

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

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

HIERARCHICAL TRANSMISSION SCHEME

Figure 3 shows the block diagram of the proposed hierarchical transmission system using 2D FHWT. The input data is orthogonally transformed to determine the coefficient $x_{u,v}$ that represents the intensity of transmitter LED. In this paper, we arrange 256 LEDs in the form of 16×16 square matrix, as shown Fig. 2. The input binary data is

$$D=\begin{Bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{Bmatrix}=\begin{Bmatrix} d_{1,1} & d_{1,2} & \cdots & d_{1,16} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,16} \\ \vdots & \vdots & \ddots & \vdots \\ d_{16,1} & d_{16,2} & \cdots & d_{16,16} \end{Bmatrix}, \tag{6}$$

where D_{11}, D_{12}, D_{21}, and D_{22} are 8 × 8 matrix, and $d_{m,n} = \{-1, 1\}$, 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 D_{11} corresponds to the block that has the highest priority and their data rate is $64R_b$. The matrix D_{12} and D_{21} correspond to the block that has the middle priority and their data rate is $128R_b$. The matrix D_{22} is the block that has the lowest priority and their data rate is $64R_b$.

Encoder

Second, we explain the proposed encoding process (Fig. 3(a)). The input data matrix D is transformed into matrix x' by 2D fast Haar wavelet transform (2D FHWT). The element of x' with row u column v is

$$x'_{u,v}=\frac{1}{2}\sum_{m=1}^{16}\sum_{n=1}^{16}d_{m,n}H^{16}_{n,v}H^{16}_{m,u}, \tag{7}$$

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

$$H^{16}=\begin{Bmatrix} 1 & 1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & -1 \end{Bmatrix}. \tag{8}$$

As a result of this processing, the range of $x'_{u,v}$ becomes 5 patterns $\{0,1/4,1/2,3/4,1\}$. Because the range varies $x'_{u,v}$ from −4 to 4, we must bias and normalized it to set the range of $x'_{u,v}$ from 0 to 1. Finally we get $x_{u,v}$ as

$$x_{u,v}=\frac{(x'_{u,v}+2)}{4}. \tag{9}$$

Here, we explain how to light the luminance of 5 patterns using LED array. To change the luminance of LED array, we change the lighting cycle of each LED as shown in Fig. 4. Here, T_b' on Fig. 4 means the maximum lighting cycle per 1 symbol, i.e., the luminance "1". Arbitrary luminance is shown based on T_b. As the example, to light the luminance "1/2", the transmitter sets the half of T_b'.

Decoder

Finally, we explain the proposed decoding process (Fig. 3(b)). The demodulation is performed in following procedure; First, the received optical power ($R_{u,v}$) of each LED is determined from received image. Second, inverse bias b is added to $R_{u,v}$. Hence, the biased value $\hat{x}'_{u,v}$ obtained as

$$\hat{x}'_{u,v} = R_{u,v} - b \qquad (10)$$

Here, the inverse bias b is calculated from the average of $R_{u,v}$. Note that it is also necessary to average temporally to calculate the suitable inverse bias b. Next, 2D FHWT is performed to the matrix that consists of $\hat{x}'_{u,v}$. After the transformation, the element of output matrix with row m column n is

$$\hat{d}'_{m,n} = \frac{1}{2}\sum_{u=1}^{16}\sum_{v=1}^{16}\hat{x}'_{u,v}H_{n,v}^{16}H_{m,u}^{16}. \qquad (11)$$

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

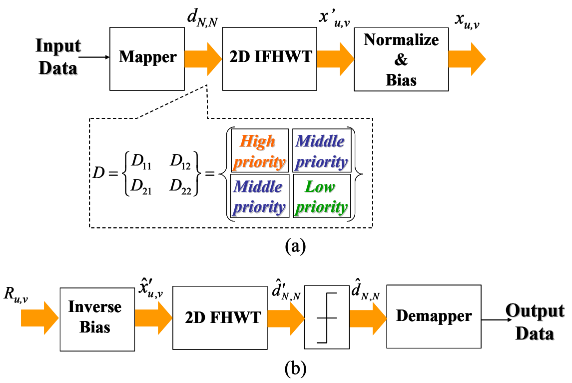


Figure 3. Hierarchical Transmission Scheme: (a) Encoder, (b) Decoder.

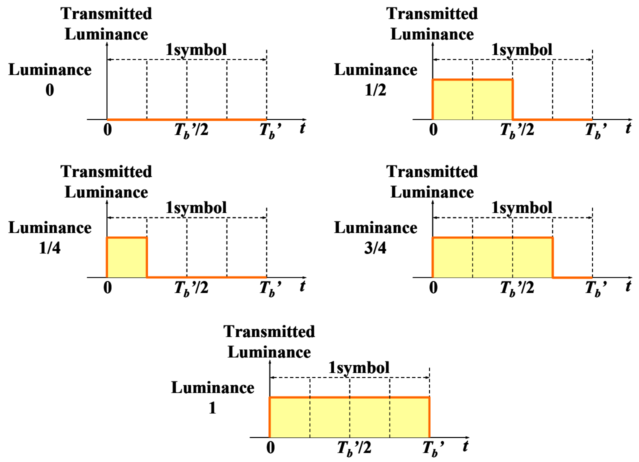


Figure 4. Luminance: lighting Patterns.

FIELD TRIAL

This section explains the field trial of the road-to-vehicle communication using the hierarchical coding. First of all, we describe important issues for realizing the reception of the data during driving a car and propose their solutions. Second, based on their solutions, the field trial is performed. In this study, we focus to receive the data accuracy in the field trial, even if the data rate decreases. Finally, we observe BER and evaluate the system.

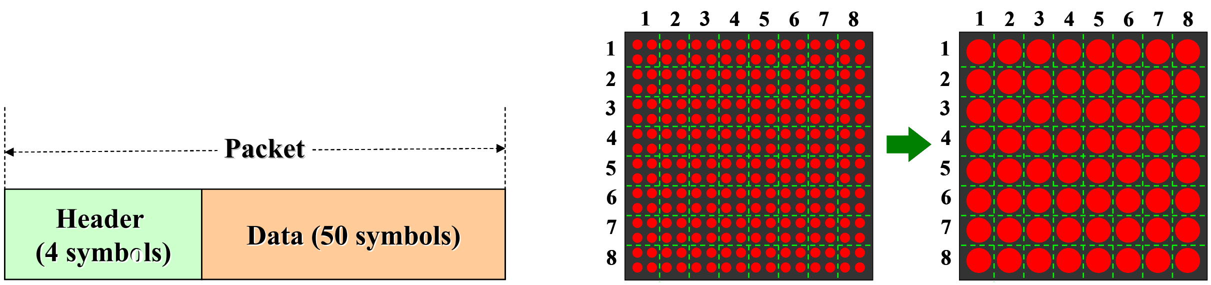
Proposed Schemes for Reception of Data during Driving a Vehicle

Reception of header

Since many vehicles are driving in actual environment, it is difficult to synchronize the lighting cycle with the timing to release the shutter of each vehicle. To solve this issue, we set arbitrary lighting pattern for informing the start as the header. The receiver can know the start of data by extracting the arbitrary pattern from the header part of the packet. Figure 5(a) shows the packet format. In this study, we set the lighting pattern of all LED light or extinction in front of the packet, and LED array lights these patterns twice alternately. In addition, using all LED light, the receiver can adjust the luminance for decoding. This is because the pixel size of LEDs is different due to the accuracy of the camera or received image accordance with the communication distance. Since the receiver can decode the data based on all LED light for every packet, the accuracy of decoding improve.

Extraction of the luminance of each LED

The receiver picks up LED array in the received image and extracts the luminance. As mentioned above, since the pixel size of LEDs is different due to the accuracy of the camera or received image accordance with the communication distance, the receiver can not extract the sufficient luminance to decode the data from the received image. To extract the stable luminance for decoding, we represent the luminance of 4LEDs (2x2LEDs) as a single luminance, as shown in Fig. 5(b). Using 4 LEDs, the effectively of this method is expected not only extraction of the stable luminance even if the communication distance is far, but misalignment of the pixel from the movement of a vehicle.



(a)Packet Format. (b) Luminance is represented by 4 LEDs.

Figure 5. Operation of LED array.

Received Image sampling and decision of the luminance

We consider the sampling of the data during driving a vehicle. As mentioned above, it is impossible to synchronize the lighting cycle with the timing to release the shutter of a vehicle. Then, we propose that the high-speed camera photographs extra images than the lighting cycle of actual LED array.

As an example, we explain the case where the camera photographs LED array at double the cycle, as shown in Fig. 6(a). Here, the top of the figure shows lighting cycle of LED. In addition, the dotted line means the timing to release the shutter, i.e., the sampling interval. The center of the figure shows the luminance in the sampling interval. As one can see, if LED array and the camera do not synchronize, the luminance of LED is photographed over the sampling interval. In this case, the either image in 2 successive images is photographed the change of the luminance accuracy. Therefore, the receiver picks up the luminance accuracy from the received image.

Next, we consider the application of the sampling method in the change of the luminance with the hierarchical coding. Figure 6(b) and (c) show the sampling method in the case of 5 patterns. In this case, since the luminance "0" is not light, LED array should set the lighting cycle as $T_b'/4$. Thus, the receiver should set the sampling interval as $T_b'/8$, namely, the high-speed camera photographs 8 images per 1 symbol. In addition, the receiver chooses 4 images in 8 images, extracts the luminance and decodes the data.

In this study, to extract the luminance in the driving field trial, the camera captures the data at 4 times higher rate (over sampling). The reason for this is attributed to the capability of the field trial instructions. In other words, due to the difference in clock timing between LED array and the camera, we can not extract the luminance. Consequently, since we apply the 4times over sampling, the extraction of more accurate luminance is expected.

Note that the data rate of the communication system using this sampling method decrease since the high-speed camera photographs extra images than the lighting cycle of LED array. However, since the luminance with the high accuracy can be extracted, it can be said that this is the sampling method effective for the road-to-vehicle communication systems.

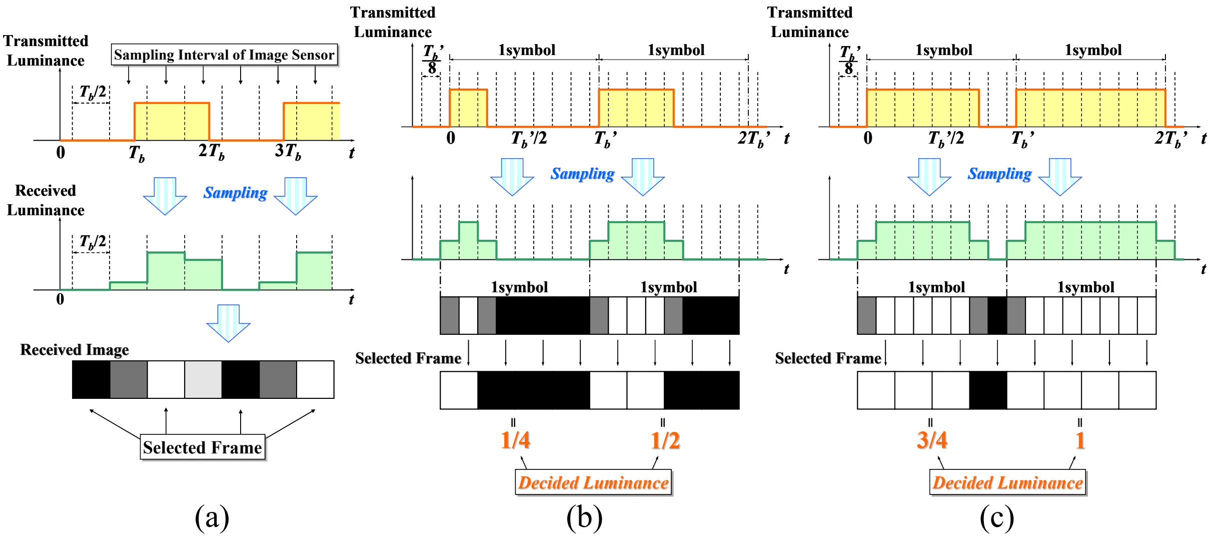


Figure 6. Sampling Method: (a) On-Off, (b) Luminance 1/4 and 1/2, (c) Luminance 3/4 and 1.

Field Trial Set up

This section performs the driving field trial based on the above mentioned solutions. Figure 7 shows field trial instruments; LED array transmitter, the high-speed camera and the car. As the high-speed camera, we use Photron FASTCAM-1024PCI 100K. Table 1 summarizes the set up parameters of the field trial. The LED array consists of 256 LEDs allocated spacing of each LED is 2cm. Also, the half-value angle of LED is 26°. These parameters are almost the same as the actual LED traffic lights. Figure 8 shows the field trial course. We put the LED array on the horizontal ground. The camera is set on the dashboard in the car, as shown in Fig. 7(c). The car drives from 60m to 10m at 30km/h and take images with the high-speed camera. In the field trial, the car moves the straight-ahead only.

In this study, to track of the lighting area of LED array, we apply the template matching method (8). This method captures LED array's area by matching the template image which was decided by geometrically calculated in advance. To apply the template matching, LED array lights its fringe as the marker during the field trial as shown in Fig. 9. This is because the template matching needs the strong and stable luminance area in the received image. Thus, LED array is used only the inner 64LEDs for the transmission of data. Additionally, since we define the luminance per bit using 4 LEDs (2x2LEDs), the transmitter allocates the 4x4 square matrix to LED array for the hierarchical coding.

(a) (b) (c)

Figure 7. Field trial instruments: (a) LED array transmitter, (b) High-speed camera, (c) Car.

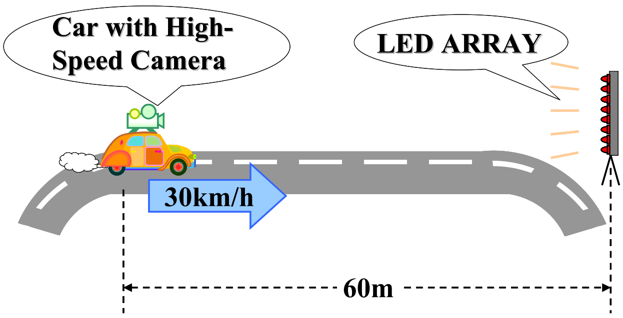


Figure 8. Field trial course.

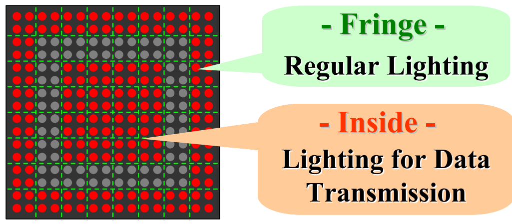
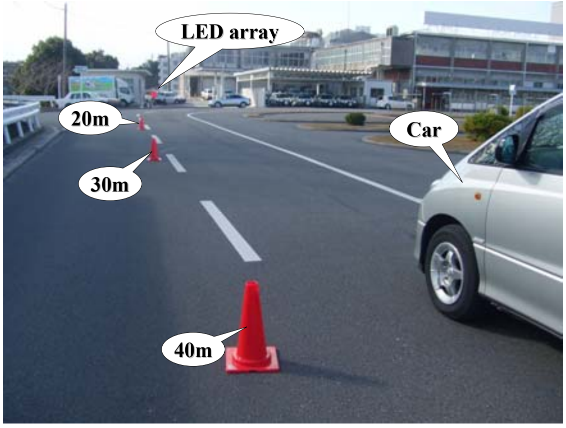


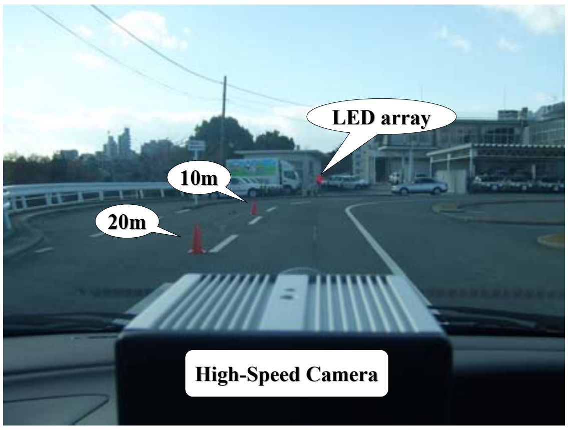
Figure 9. Fringe lighting for the template matching.

Table 1. Set up parameters of field trial.

	Driving Field Trial	Static Field Trial
Lighting interval of LED array	1.6×10^{-2}	
Half-value angle of LED	26°	
Data rate	1kbps	16kbps
Shutter speed	1000fps	
Focus of lens	35mm	
Lens diaphragm	11	
Focus of a lens	Infinity	
Resolution	1024×512 pixel	256×256 pixel
Communication distance	10m~60m	
Vehicle speed	30km/h	



(a)



(b)

Figure 10.Landscapes of field trial: (a) Outside of Car, (b) Inside of Car.

Field Trial Results

Before the driving field trial, we perform the field trial which the car does not move (static field trial). This is because we confirm the performance the hierarchical coding in the road-to-vehicle communication and obtain the measure of the driving field trial by performing the static field trial in the ideal environment such as the camera can capture LED array easily. This trial set up parameters are shown the right side of Table 1. In the static field trial, the transmitter allocates the 16x16 square matrix to LED array to transmit the hierarchical coding data at the max data rate. The luminance is extracted from the received images and is decoded in the off-line data processing. Here, the position of each LED is decided manually from the received images. We fix the car with the camera and photograph LED array changed by the pattern according to the hierarchical coding. The static field trial is performed by changing distance in 10m to 60m.

Table 2. BER of Static field trial.

Distance	BER of Each Priority			BER of OOK
	High	Middle	Low	
10m	0.0	0.0	0.0	0.0
20m	0.0	0.0	0.0	0.0
30m	1.88×10^{-3}	2.03×10^{-2}	2.34×10^{-2}	2.25×10^{-2}
40m	6.94×10^{-2}	1.27×10^{-1}	1.68×10^{-1}	1.16×10^{-1}
50m	5.91×10^{-2}	1.44×10^{-1}	2.04×10^{-1}	2.63×10^{-1}
60m	9.13×10^{-2}	2.82×10^{-1}	3.76×10^{-1}	4.98×10^{-1}

Table 2 shows the BER performance of the static field trial on the distance. By way of comparison, we also show the BER performance of On-Off-Keying (OOK). When the communication distance is shorter than 20m, we confirm no error. We also confirm that the error occurs beyond 30m. Here, let us consider the case of the actual environment. If a vehicle stops at an intersection, a distance between a vehicle and a traffic light is about 20~30m. This means that the error hardly occurs in a vicinity of an intersection. Next, we compare the BERs of each priority data. As one can see, the BER of the high priority data shows the best as compared with other priority data and OOK. While for the low priority data, which is transmitted at high frequency component, degrade badly. We confirm that the high frequency component degrade accordance with the communication distance. It can be said that the effectivity of the hierarchical coding is reconfirmed.

Let us now return to the driving field trial. The driving field trial is performed based on the set up of the left side in Table 1. In the same way of the static field trial, the luminance is extracted from the received images and is decoded in the off-line data processing.

First, we observe the received image and the zoom of LED array, as shown in Fig. 11, where these zooming images mean the change of the luminance according to the hierarchical coding, T_b' corresponds to the change of the luminance in Fig. 4. Since the 4 times over sampling is applied, the camera can capture the luminance of each T_b' from received image. In addition, due to the luminance per bit using 4 LEDs (2x2LEDs), we can confirm clearly the change of the luminance even if the communication distance is far. In this case, the extracted luminance becomes the matrix on the figure.

Next, we evaluate the BER performance of the driving field trial shown in Table 3. To compare the performance of the hierarchical coding, Table 3 also shows the BER of OOK. As with the static field trial, we can confirm that the BER of the high priority data shows the best as compared with other priority data and OOK. Here, what is important is that the reception of the data is possible during the driving, namely, the tracking by the template matching is capable. This means that the proposed solutions for the driving are operated capably. Note that we do not apply any error correcting method in this study. Let us assume the requested BER to be 10^{-2}. In the case of OOK, the BER is 2.09×10^{-2}. Thus, the BER of OOK exceeds the requested BER. On the other hand, in the case of hierarchical coding, the BER of the highest priority data is 5.0×10^{-3}, namely, this is less than the requested BER. Therefore, we can confirm that the effectiveness of the hierarchical coding during the driving. In addition, we can say that the reception of the data during the driving has been achieved in the off-line data processing.

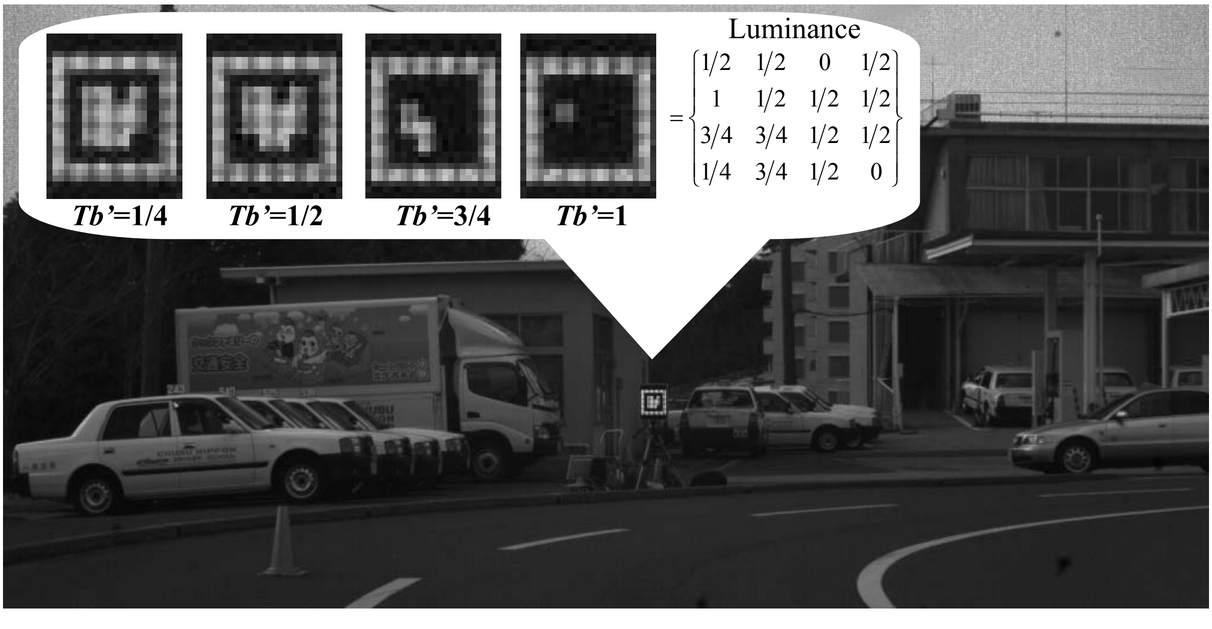


Figure. 11. Received images of driving field trial.

Table 3. BER Performance of driving field trial.

Distance	BER of Each Priority			BER of OOK
	High	Middle	Low	
10m~60m	5.0×10^{-3}	6.75×10^{-2}	6.0×10^{-2}	2.09×10^{-2}

CONCLUSIONS

We have discussed the driving field trial of the road-to-vehicle communication using the hierarchical coding. In addition, we have described important problems for realizing the reception of the data during the driving and proposed their solutions. As results from the driving field trial, the effectiveness of the hierarchical coding has been confirmed and the reception of the data during the driving has been achieved in the off-line data processing. In this study, since the car has moved the straight-ahead only, we will perform the field trial in the curve. Moreover, developing the road-to-vehicle communication system using the hierarchical coding in the real-time data processing system is our goal of the study.

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