Experiment on Hierarchical Transmission Scheme for Visible Light Communication using LED Traffic Light and High-Speed Camera

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***Abstract*— LEDs are expected as lighting sources for next generation, and data transmission system using LEDs attract attention. In this paper, we present hierarchical coding scheme using LED traffic lights and high-speed camera for Intelligent Transport Systems (ITS) application. Further, if each of LEDs in traffic lights is individually modulated, parallel data transmissions are possible using a camera as a reception device. Such parallel LED-camera channel can be modeled as spatial low-pass filtered channel of which the cut-off frequency varies according to the distance. To overcome, we propose hierarchical coding scheme based on 2D fast Haar wavelet transform. As results, the proposed hierarchical transmission schemes outperform the conventional on-off keying and the reception of high priority data is guaranteed even LED-camera distance is further.**

I. 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 [3]–[6]. 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. For examples, LED traffic lights and LED traffic signs broadcast driving assistances data to cars (road-to-vehicle communications), LED car brake lights can transmit warning data to a car behind (vehicle-to-vehicle communications).

One commonly adopted receiving device for wireless optical communication systems is the photo diode (PD). However, PD may not be a good choice as a receiving device for ITS applications, especially for a car. A high-speed camera, composed of two-dimensional CMOS image sensor, is much preferable receiving device [7]. 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, 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.

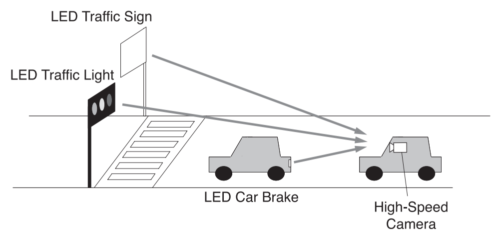

Fig. 1. Road-to-vehicle communication using LED traffic light and high-speed camera.

In this paper, we consider wireless data transmission systems using LED traffic lights and high-speed camera. First, we address a channel characteristic of the parallel LED-camera data transmission system. 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 (car) is far from a transmitter (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, it can be said that these pixels remain the low-frequency components. In other words, this means that 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 propose a hierarchical transmission scheme. 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. The hierarchical transmission can easily be realized by an introduction of two-dimensional orthogonal data modulation. In this paper, we apply two-dimensional fast Haar wavelet transform (2D FHWT) as orthogonal data modulations. Moreover, we investigate that the case of the long distance between the transmitter and the receiver. In other words, to evaluate the proposed method, we perform a implementation experiment and observe the bit error rate (BER).

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II. 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. We explain not only each operation but also the reduction of pixel size and defocus of the LED data pattern depending on the two-dimensional CMOS image sensor.

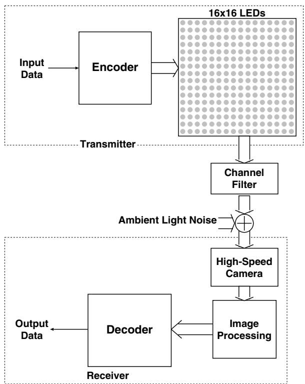


Fig. 2. System Model.

A. Transmitter

The transmitter consists of 256 LEDs in the form of 16×16 square matrix and Encoder. The transmitter LEDs generate nonnegative pulse of which the width is T_b, where T_b is a bit duration. By changing the width of T_b, LED can change the lighting pattern, i.e. the luminance. Thus the transmitter can modulate the information using LED's luminance. Also the data rate is defined as $R_b = 1/T_b$. Since each LED transmits different bit, the bit rate of the transmitter becomes $256R_b$. 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,

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

Transmitted signal arrives at the receiver camera through optical channel. The receiver has the CMOS image sensors, and each pixels 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 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 [2]. We assume $n_{u,v}(t)$ as white Gaussian noise process with double-sided power spectral density $N_0/2$.

B. Parallel LED-Camera Channel

Figure 3 is a traffic image experimentally taken by the high-speed camera at an intersection in Nagoya, Japan. The Photron FASTCAM-1280PCI is used as the receiver and its frame-rate is 500Hz. The location of LED traffic light can easily be obtained. By taking a difference of consecutive images, the background other than LED traffic light can be eliminated.

In Figs. 4 (a) and (b), we show the LED traffic light taken at short distance (about 15m) and at long distance (about 60m), respectively. As we confirm from Fig. 4 (a), we can clearly distinguish each of LED when LED-camera distance is short. On the other hand, because of reduction of pixel size, adjacent LEDs are recognized as one pixel image when LED-camera distance is long (Fig. 4 (b)). In other words, when receive distance is long, only rough portion of image is obtained by the camera. The received image is influenced by the spatial frequency according to the distance between LED traffic light and the high-speed camera. Here, spatial frequency is a number of a repeated times per unit length with a periodic pattern, such as sine wave. The transfer characteristic of the image information on the image sensor changes according to spatial frequency. In general, when the correlation in a image (or spatial) is the highest, i.e. a pattern of the image is vague, it is said the image contains low spatial frequency components. On the other hand, when the correlation in a image is low, for instance, when the monochrome shade of the image is clear, it is said the image contains high spatial frequency components. This characteristic was called characteristic of spatial frequency. Since it can be considered as loss in high spatial frequency components, the channel can be modeled as a low-pass filter of which the cut-off frequency varies according to the distance. We model this channel characteristic by 3×3 Gaussian filter. Thus, recalling Eq. (3), we rewrite it as

$$y_{u,v}(t) = h_{u,v} \sum_{p=-1}^{1} \sum_{q=-1}^{1} G_{p,q} \cdot x_{u+p,v+q}(t) + n_{u,v}(t), \tag{4}$$

where $G_{p,q}$ is convolution kernel of Gaussian filter defined as

$$G_{p,q} = \frac{1}{G_{sum}} \frac{\exp(-\frac{p^2+q^2}{2\sigma_g^2})}{2\pi\sigma_g^2} \tag{5}$$

$$G_{sum} = \sum_{p=-1}^{1} \sum_{q=-1}^{1} G_{p,q}, \tag{6}$$

and σ_g^2 is the variance of filter.

C. Receiver

The receiver consists of the high-speed camera, image processing unit and decoder. The transmitted signals pass spatial channel and is received by the high-speed camera. The camera has CMOS image sensor and outputs as an image the value which changed the optical signal into the electric signal. Here, one LED's optical signal corresponds with one or some pixel size in the image.

Let us assume perfect synchronization between the receiver camera and the transmitter LED and 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

$$f(t) = \sum_i g_{sh}(t-(i-1)T_b), \tag{7}$$

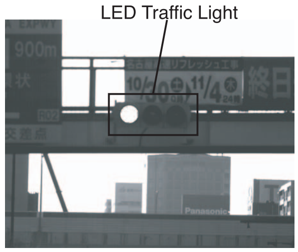
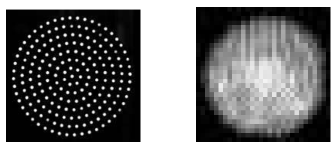
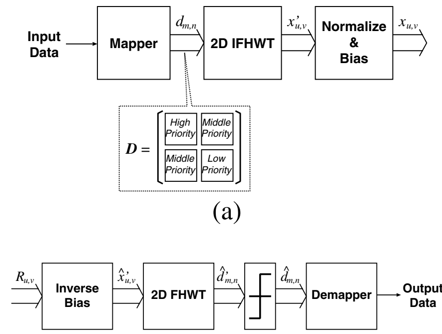


Fig. 3. Received whole image including LED traffic light.



(a) (b)

Fig. 4. Image of LED traffic light; (a) Short distance (15m), (b) Long distance (60m).



(a)

(b)

Fig. 5. Block Diagram of Proposed Method : (a) Encoder, (b) Decoder.

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

$$g_{sh}(t) = \begin{cases} 1 & (0 \le t < \tau) \\ 0 & (\text{otherwise}) \end{cases} \tag{8}$$

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

$$R_{u,v,i} = c \int_{(i-1)T_b}^{iT_b} y_{u,v}(t) \cdot f(t) dt, \tag{9}$$

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

The variance of shot noise from ambient light after integrator is obtained as

$$\sigma^2 \;=\; E\left[\left(c \int_0^{\tau} n_{u,v}(t) dt\right)^2\right] = c^2 \cdot \frac{N_0}{2} \cdot \tau. \tag{10}$$

We define the SNR as follows

$$\text{SNR} = \frac{(Ac\tau \cdot h_{u,v} \cdot x_{u,v,k})^2}{2\sigma^2}. \tag{11}$$

III. Proposed Hierarchical Transmission Scheme using 16×16 2D FHWT

A. Motivation

As described, high spatial frequency components of the received image decreases when the camera is far from LED traffic light. As mentioned, this LED-camera channel is a low-pass filtered channel.

To take advantage of these channel characteristics, we propose a hierarchical transmission scheme using 2D FHWT assigned high-priority data to low spatial frequency components and low-priority data to high spatial frequency components.

Figure 5 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

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

where $\boldsymbol{D}_{11}$, $\boldsymbol{D}_{12}$, $\boldsymbol{D}_{21}$, and $\boldsymbol{D}_{22}$ 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 $\boldsymbol{D}_{11}$ corresponds to the block that has the highest priority, and their data rate is $64R_b$. The matrix $\boldsymbol{D}_{12}$ and $\boldsymbol{D}_{21}$ correspond to the block that has the middle priority and their data rate is $128R_b$. The matrix $\boldsymbol{D}_{22}$ is the block that has the lowest priority and their data rate is $64R_b$.

B. Encoding

Second, we explain the proposed encoding process (Fig. 5(a)). The input data matrix $\boldsymbol{D}$ is transformed into matrix $\boldsymbol{X'}$ by 2D fast Haar wavelet transform (2D FHWT). The element of $\boldsymbol{X'}$ with row u column v is

$$x'_{u,v} = \frac{1}{2} \sum_{m=1}^{16} \sum_{n=1}^{16} d_{m,n} H^{16}_{n,v} H^{16}_{m,u}, \tag{13}$$

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

$$\boldsymbol{H^{16}} = \begin{Bmatrix} 1 & 1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 1 & -1 \end{Bmatrix}. \tag{14}$$

As a result of this processing, the range of $x'_{u,v}$ becomes 5 patterns $\{0, \frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1\}$. 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

$$x_{u,v} = \frac{(x'_{u,v} + 2)}{4}. \tag{15}$$

In this paper, although we realized the hierarchical coding by 2D IFHWT of scale 1, it is also possible to increase a hierarchy by enlarging a scale. Note that since LED's lighting pattern increases according to a hierarchy, the encoding or decoding process becomes complicated.

C. Decoding

Finally, we explain the proposed decoding process (Fig. 5(b)). 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

$$\hat{x'}_{u,v} = R_{u,v} - b. \tag{16}$$

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

$$\hat{d'}_{m,n} = \frac{1}{2} \sum_{u=1}^{16} \sum_{v=1}^{16} \hat{x'}_{u,v} H_{n,v}^{16} H_{m,u}^{16}. \tag{17}$$

By performing this operation, the procession consisting from 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 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.

IV. Experiment using proposed method

In this section, we explain the experiment setup of the proposed method and evaluate its BER performance. We have developed two LED transmitters, each having number of LED for 64 and 256. Using these LED transmitters, we perform two different experiments.

A. Experimental setup

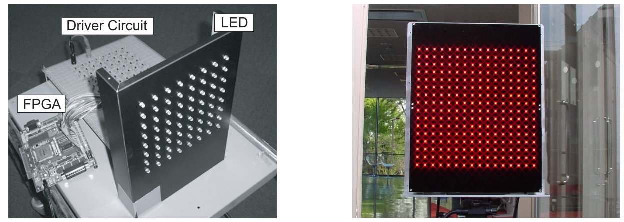
1) Experiment 1: For the experiment 1, we set the camera focus to infinity. This will demonstrate the effectiveness of our hierarchical coding. In addition to the degradation by a long LED-camera distance, the blurred received picture due to the out-of-focus represents a sever degradation of high spatial frequency components. Even in such condition, we can transmit data assigned to the low spatial frequency components for our hierarchical coding. The experiment is carried out in in-door environment using 64 LED transmitter.

Figures 6(a) and 7(a) show the LED transmitter and the high-speed camera for the experiment 1. The specifications of the high-speed camera is given in Table I.

The LED transmitter of Fig. 6(a) was made using FPGA. This transmitter consists of 64 LEDs and allocated spacing of each LED is 2cm. This LED spacing is the same as the actual traffic light. The half-value angle of LED is $11.5°$. We use the 35mm lens, as shown in Fig. 7(a). We experiment under lighting of the fluorescent light inside building. The fixing angle of the camera is 0 degree, i.e. horizontal on the ground. Table II summarize the experimental parameters.

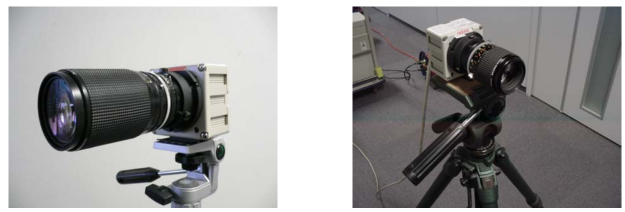
2) Experiment 2: We carry out the experiment in outside for the experiment 2. In this case, we manually set the focus so no blurred image is received but the high spatial frequency component may be lost due to the longer LED-camera distance.

Figures. 6(b) and 7(b) show the LED transmitter and the high-speed camera for the experiment 2. The LED transmitter consists of 256 LEDs allocated spacing of each LED is 2cm, i.e. 4 times the number of LED of Fig. 6(a). The half-value angle of LED is $26°$. This angle is almost the same as the actual LED traffic lights. We performed the experiment under the sun, namely, outside building. This is because to observe the influences of the solar light on the LED's luminance. In a similar way of Experiment 1, Experiment 2 is performed in a quiescent environment. However, the LED transmitter is put in the place about 3.5m high to near the actual environment.



(a) (b)

Fig. 6. LED transmitter (a) LED:64 (using FPGA) (b) LED:256



(a) (b)

Fig. 7. High-speed camera (a) 35mm (b) 105mm

TABLE I
High-speed camera specifications.

Camera model	FASTCAM-1280PCI manufactured by Fotron
Lens model	Ai Zoom Nikkor manufactured by Nikon
Censor type	CMOS
Shutter speed	60∼16000fps
Resolution	Max 1280×1024pixel

B. Results

1) Experiment 1: Figure 8 shows received images when the communication distance is 10m, 30m and 50m, with all 64 LEDs are at the max luminance. The size described under these images of Fig. 8 is the pixels, which captured the area of 64 LEDs in these images. For instance, since the size is 32×32 pixels for 64 LEDs at 30m, each LED's pixel size is 2×2. In the experiment, we set the focus of the camera to infinity. Thus the LED size in the image is smaller according to the distance. The actual defocus is not uniform at all over the image, as shown in Fig. 8.

Figure 9 shows the BER versus the communication distance. By way of comparison, we also evaluate the BER performance of OOK (On-Off-Keying). When the communication distance is shorter than 30m, we confirm no error. The LED's pixel size in the received image is 32×32 at 30m which is the furthest in the errorless area. Moreover the error happened from the communication distance over 30m because the adjacent LED's

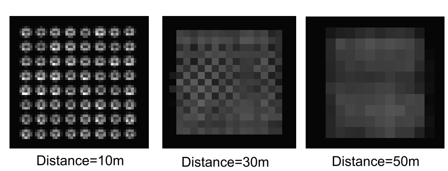


Fig. 8. Examples of received images.

TABLE II
EXPERIMENTAL PARAMETERS.

	Experiment 1	Experiment 2
Experimental place	Nagoya University Integrated Building North 9th-floor hallway	Nagoya University Integrated Building Center Roof of 2nd-floor
Lighting interval of the LED Transmitter	1/2000s	1/500s
Data rate	128kbps	128kbps
Shutter speed of the high-speed camera	4000fps (twice frequency of the lighting LED)	
The number of pixel of the high-speed camera	160 × 128 pixel	
Focus of a lens	infinity	in focus
Focal length of a lens	35mm	105mm
Lens diaphragm	3.5	4.0
Communication distance	10 ∼50m	50 ∼70m

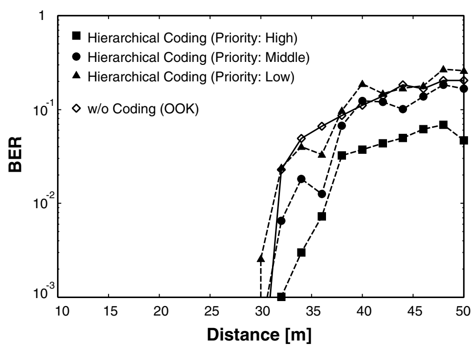
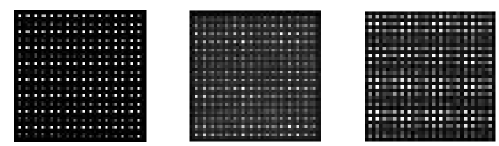


Fig. 9. BER performance of experiment.

TABLE III
DISTANCE PROPERTY

Distance	BER of Each Priority		
	High	Middle	Low
50m	0.00	0.00	0.00
60m	0.00	1.525×10^{-4}	2.899×10^{-3}
70m	0.00	8.85×10^{-4}	1.07×10^{-4}



(a)50m (58×58pixel) (b)60m (48×48pixel) (c)70m (37×37pixel)

Fig. 10. Examples of received images (visually in focus).

luminance interferes and LED's interval becomes under the 1 pixel.

Next we compare the BERs of each priority data. From Fig. 9, we observe the BER of the high priority data show the best as compared with other priority data. While for the low priority data, which is transmitted at high frequency component, degrade badly. Hence, we can confirm that the high frequency component degrade according to the communication distance.

In this paper, since we do not apply any error correcting method, we assume the requested BER to be 10^{-2}. In the case of non-coding (OOK), BER is 2.3×10^{-2} at 32m, as shown in Fig. 9. Thus BER already exceed the requested BER. On the other hand, in the case of hierarchical coding, BER of the highest priority data is 1.0×10^{-3} at 32m. In addition, this BER of the highest priority is 7.2×10^{-3} at 36m, namely, this is less than the requested BER. In the case of OOK, the rise of BER begin to becomes slow at near BER$= 1 \times 10^{-1}$. However, in the case of hierarchical coding, BER begin to becomes slow at near BER5×10^{-2}. Therefore, we observe that the effectiveness of our proposed hierarchical coding.

2) Experiment 2: Table III shows the BER performance of each priority on the distance. From this table, we confirm that the high priority data is received accurately, even if distance becomes long. However, we also confirm that the BERs of the middle and low priority data are different at each distance. As a reason, we consider the influence of the lens of the camera. Figure 10 shows the picture, which the camera actually received. As one can see, the received image size becomes small according to the distance. In addition, the contrasting density of LED luminance is different each distance. Even in such condition, we can obtain the high priority data. Therefore we confirm that good distance property is obtained irrespective of the distance. From these results, we expect that the high priority data can be received even if distance becomes 100m or more.

V. CONCLUSIONS

In this paper, we have proposed the hierarchical transmission scheme of parallel wireless optical communication using LED traffic lights and high-speed camera. To take advantage of characteristic of spatial frequency, we have realized the hierarchical transmission scheme using two-dimensional fast Haar wavelet transform (2D FHWT). As the result, the proposed hierarchical transmission scheme outperforms the conventional on-off keying and the reception of high priority data is guaranteed even LED-camera distance is further. Moreover we have confirmed that good distance property is obtained.

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REFERENCES

[1] W. Mao and J. M. Kahn, "Free-Space Heterochronous Imaging Reception of Multiple Optical Signals", IEEE Trans. on Communications, Vol. 52, No. 2, pp. 269-279, Feb. 2004.
[2] J. M. Kahn and J. R. Barry, "Wireless Infrared Communications", Proc. IEEE, Vol. 85, pp. 265-298, Feb. 1997.
[3] 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.
[4] T. Komine and M. Nakagawa, "Integrated System of White LED visible light communication and power-line communication", IEEE Trans. on Consumer Electronics, Vol. 49, No. 1, pp. 71-79, Feb. 2003.
[5] 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.
[6] G. Pang, C. Chan, and T. Kwan, "Tricolor Light Emitting Dot Matrix Display System With Audio Output", IEEE Trans. on Industry Application, Vol. 37, No. 2, pp. 534-540, Mar./Apr. 2003.
[7] 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
[8] M. Wada, T. Yendo, T. Fujii, M. Tanimoto, "Road-to-Vehicle Communication Using LED Traffic Light," Proc. of IEEE Intelligent Vehicles Symposium 2005,