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Error Correcting Scheme for Road-to-Vehicle Visible Light Communication using LED Array

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Abstract—**In this paper, we propose an improved coding scheme for optical wireless communication systems using a LED array transmitter and a high-speed camera as the receiver on a vehicle. Previously, we have proposed a hierarchical coding scheme which allocated the data to spatial frequency components depending on the priority. In that scheme, the high-priority data can be received even if the receiver was far from the transmitter. We confirmed the advantage of the hierarchical coding scheme, but the bit error performance was not sufficient. In this paper, we divide the data into spatial frequency components, and use error correcting code for each spatial frequency components' data. Experimental evaluation demonstrates the improvement in BER performance. This improvement implies that the system range increased compared to the previous method.**

I. INTRODUCTION

Light emitting diodes (LEDs) are expected to be the light source for the next generation. LEDs are superior to conventional incandescent lights due to their low power consumption, long life, good visibility, and low heat generation. This is why, in Japan, many incandescent traffic lights have been already replaced with LED traffic lights. Also, LEDs' intensity can be changed very quickly, since they are semiconductor devices. That is, LED light can be modulated with encoded data. Because of that, optical wireless communication systems using LED lights are studied [1]–[4]. The main application considered is a system broadcasting the information on the state of traffic to the drivers.

In this paper, we consider a parallel optical wireless communication system using a LED traffic light and a high-speed camera attached to a vehicle as a receiver [5], [6]. The advantage of using a camera is that because of it's wide viewing angle, it is able to recognize the position of LED traffic light easily. Also, since a camera can distinguish a number of light sources, the parallel data transmissions through each of traffic light's LEDs is possible. That is, we expect high-speed communication to be feasible because it is possible to transmit the data in parallel depending on the number of LEDs.

But unsurprisingly, the communication system using LED traffic lights and a high-speed camera has also disadvantages. When a receiver is far from LED traffic lights, the received data are degraded due to reduction of pixel size and defocus. It is hard to distinguish adjacent LEDs. In other words, high spatial frequency components are severely degraded. Even in such condition, low frequency components can still be retrieved. A high-speed camera can receive the data contained the low frequency components from the image, 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 for big LED-camera distance. As the camera gets closer to the LED transmitter, low-priority data also can be received. Fig. 1 shows that communication system.

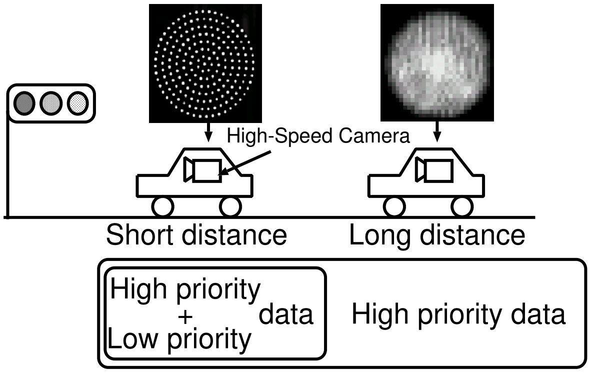


Fig. 1. Optical Wireless Communication using Traffic Light and High-Speed Camera.

In our previous research, the effectiveness of the hierarchical coding was confirmed. But 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. Our goal is a system that can receive the information during driving the vehicle. 30m is too short a distance for the driver to be able to use the transmitted data before reaching the intersection. In order to take advantage of the received data, it is preferable to be able to receive the data from farther away.

In this paper, a system using error correcting code is proposed. The system can receive the data from farther away by improving the BER performance. In particular, the data are divided according to priority and encoded with error correcting code depending on priority level. The data is allocated to LED array matrix and Inverse Fast Haar Wavelet Transform(IFHWT) is applied. High-priority data are encoded by a high error correcting code, and the BER performance of these data is better than of other priorities. Basing on experimental results, we confirm that our error correcting scheme is effective.

II. SYSTEM OVERVIEW

Fig. 2 shows block diagram of the system model. This system consists of three blocks, transmitter, optical channel and receiver.

A. Transmitter

The transmitter consists of turbo encoder, interleaver and 256 LEDs in the form of 16×16 square matrix. The transmitter generates nonnegative pulse with a width of T_b, where T_b is a bit duration. We change luminance of LED by changing the width of T_b. 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 $k = 1, 2, \dots$ is an index of LED pattern, $x_{u,v,k}$ 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 On-Off Keying(OOK) in modulation, $x_{u,v,k} = \{0, 1\}$. A pulse function $g(t)$ is defined as follows,

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

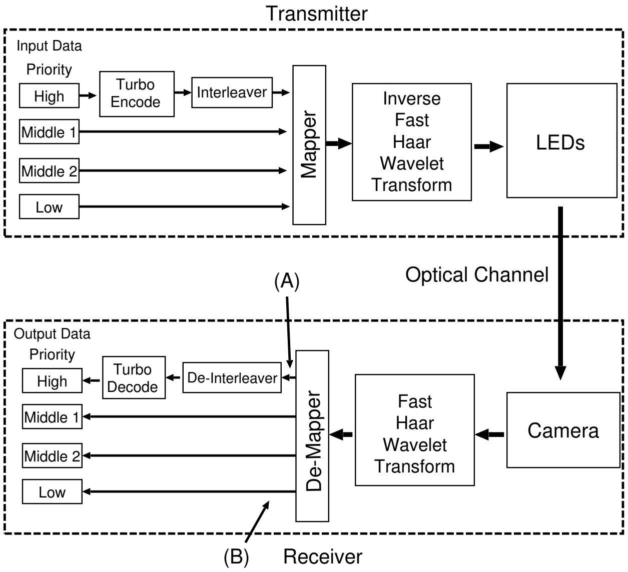


Fig. 2. System model.

B. Receiver

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 received signal at the 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 noise [8]. 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 camera is exactly synchronized with the transmitter. 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

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

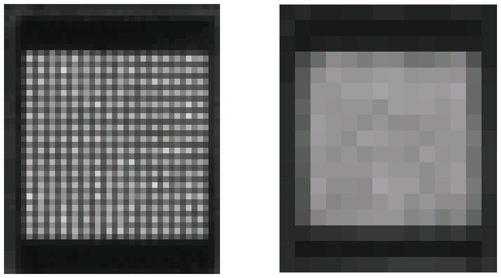
where $i = 1, 2, \dots$ is an index of image exposure intervals. A shutter pulse $g_{sh}(t)$ is

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

III. TRANSMISSION SCHEME

At longer distances, received LED light's image loses most of the high frequency components. Decoding errors appear because of lumping together of neighboring LEDs. To improve the BER performance, we considered applying error correcting code to the whole LED array. However, the BER performance did not improve. This is because the degradation of received image's high frequency components (low-priority data) affects also the data of low frequency components (high-priority data).

We explain what the degradation is. Fig. 3(a) and (b) show the received images for the communication distance of



(a) (b)

Fig. 3. Received image: (a)20m (b)60m.

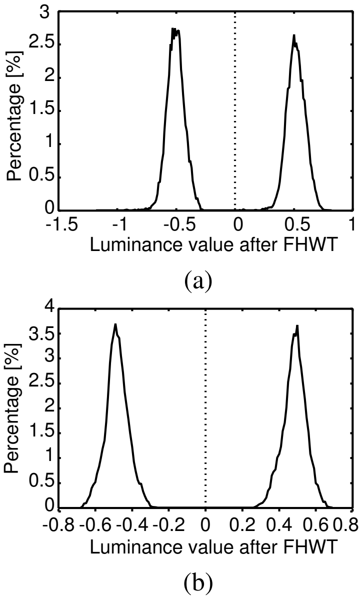
20m and 60m. We can distinguish each LEDs in Fig. 3(a). But, in Fig. 3(b), we cannot distinguish because LEDs are lumped in with neighboring ones. We examined distributions of luminance values after FHWT. Here, we show distributions of high and low priority data. Analyzed points are shown in Fig. 2(A) and (B), respectively for high-priority data and low-priority data. Fig. 4 and Fig. 5 show the distributions. As we can see in Fig. 4(a) and (b), the values of both priority are distributed around two mean values. We can recognize two groups clearly when the communication distance is 20m. If we set threshold at the center of two groups, error-free decoding is possible. But, for the distance of 60m, we cannot divide the values into two groups. The low-priority data in Fig. 5(b) are degraded badly, and this degradation affects the high-priority data(Fig. 5(a)). This is why errors occur severely even high-priority data, and are beyond error correcting capacity.

To manage this problem, we divide data into high and low frequency components in advance, and apply different error correcting codes to both groups. By doing this, we avoid the influence of high frequency components degradation on low frequency components data. 2D FHWT is used to allocate high-priority data to low frequency components and low-priority data to high frequency components.

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

$$\boldsymbol{D}=\left\{\begin{array}{cc} \boldsymbol{D}_{11} & \boldsymbol{D}_{12} \\ \boldsymbol{D}_{21} & \boldsymbol{D}_{22} \end{array}\right\}=\left\{\begin{array}{cccc} d_{1,1} & d_{1,2} & \cdots & d_{1,16} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,16} \\ \vdots & \vdots & \ddots & \vdots \\ d_{16,1} & d_{16,2} & \cdots & d_{16,16} \end{array}\right\} \quad (6)$$

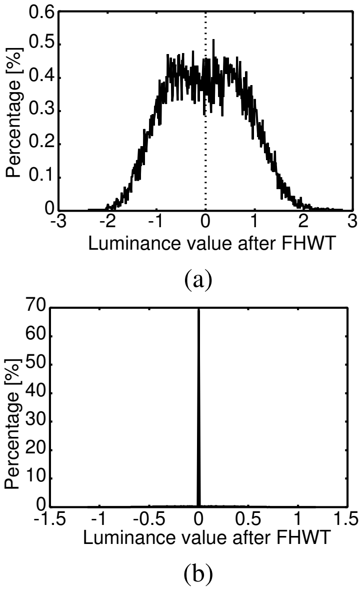
where $\boldsymbol{D}_{11}$, $\boldsymbol{D}_{12}$, $\boldsymbol{D}_{21}$ and $\boldsymbol{D}_{22}$ are 8×8 matrices, $d_{m,n} = \{-1, 1\}$, and $d_{m,n}$ is assumed to be independent and identically distributed(i.i.d.). When using 2D FHWT, input data is divided into 3 blocks depending on priority. The matrix $\boldsymbol{D}_{11}$ corresponds to the highest priority block with data rate of $64R_b$. The matrices $\boldsymbol{D}_{12}, \boldsymbol{D}_{21}$ correspond to the middle priority block with data rate of $128R_b$. The matrix $\boldsymbol{D}_{22}$ is the lowest priority block with data rate of $64R_b$.



(a)

(b)

Fig. 4. Distribution of (a)high-priority data at 20m (b)low-priority data at 20m.



(a)

(b)

Fig. 5. Distribution of (a)high-priority data at 60m (b)low-priority data at 60m.

A. Assignment of data matrix

The easiest way to apply an error correcting code is to encode only high-priority data. In this paper, turbo code is applied to only high-priority data. But we also can use error correcting code to each priority data. As per block diagram depicted on Fig. 2, high-priority data are first turbo-coded [9] and interleaved and then, together with uncoded low and middle priority data transformed into spatial frequency domain using IFHWT.

The part of high-priority data block consists of 64 data point in the form of 8×8 square upper left matrix in (6). The amount of transmitted high-priority data (N_H) is

$$N_H = \frac{(S \times 64) + k}{R_t} \tag{7}$$

where S is the number of transmitted symbols, R_t is the turbo code rate and k is the memory length of turbo encoder.

Turbo-coded sequence is fed to the interleaver. Then the sequence is split into 64 bits blocks and allocated to high-priority part. If we split the sequence into 64 bits blocks, k/R bits are left unassigned. To transmit the leftover bits, we add an additional symbol. Unused high-priority bits of the additional symbol are set to a simple pattern. In short, we transmit $S+1$ symbols.

At the same time, we assign $N_M = (S/R_t + 1) \times 128$ bits to middle-priority data and $N_L = (S/R_t + 1) \times$ 64 to low-priority data. Low and middle priority data are allocated to symbols containing high-priority data as previously discussed. Now, the data point array contains 256 bits of all levels of priority. Whole code rate (R_w) is

$$R_w = \frac{N_L + N_M + R_t N_H}{N_L + N_M + N_H} \tag{8}$$

Next, IFHWT is applied to the array in order to transform the data into spatial frequency domain.

B. Extracting received data

At receiver side, firstly, we extract each normalized LED luminance from received images. And then, we apply FHWT and divide the received data according to priority. Middle and low priority data are output directly after FHWT. High-priority data 64 bits blocks of each of the symbols are linked together and k/R bits sequence from the last symbol is attached to form N bits sequence.

After reconstructing N bits high-priority sequence, it is fed to de-interleaver and turbo decoder. Turbo decoder outputs the decoded sequence. We compare the sequence with the original transmitted sequence.

IV. EXPERIMENT

We performed a field trial of optical wireless communication using hierarchical coding with error correcting code. We observed the BER performance and evaluated the proposed system. To show the effectiveness of the proposed system, we also show the results without error correcting code.

A. Experiment set up

First of all, we explain the initialization of communication. It is difficult to synchronize the transmitter with the receiver. To solve this problem, we set an arbitrary lighting pattern as the start header. The receiver can know the start of data by recognizing the arbitrary start pattern in the header part of the packet. In this study, the lighting pattern is: all LEDs on, all LEDs off, all LEDs on, all LEDs off. After the header, the data are transmitted.

Fig. 6 and Fig. 7 shows field trial instruments; the LED array transmitter and the high-speed camera. Table I shows the specifications of the high-speed camera. The LED array consists of 256 LEDs. LED spacing is 2cm. The 3dB angle of LED is 22.6°.

The experiment was performed at a driving training grounds, with both transmitted and receiver immobile. We performed measurements for distances from 20m to 80m, every 10m. To evaluate the effect of error correcting code, we examine the proposed system and the system without error correction. Table II shows the experiment parameters. From (8), whole code rate R_w is 0.834. The received data are decoded off-line after the experiment. Also, LED positions were set manually.

B. Results

We present the results illustrating the BER performance with error correcting code and without error correcting code. First, in Fig. 8, we show the BER performance without error correcting code.

As we can see in Fig. 8, error-free reception is possible up to the distance of 20m. The bit errors occurring for communication distances over 30m. The high-priority data shows the best BER performance. This is the result of the hierarchical coding.

Next, we show the BER performance with error correcting code. Fig 9 shows the BER performance with/without error correcting code of high-priority data.

In Fig. 9, we can see that without error correcting code, errors occur for distances over 30m. With error correcting code, we can receive error-free data for distances up to 60m. By using error correcting code, error-free range is lengthened. The difference of the distance is 40m. Compared with other priority data in Fig. 8, high-priority data with error correcting code has longer range. Still, despite error correcting code for ranges over 70m, iterative decoding does not work. In other words, errors that are beyond error correcting capacity

Fig. 6. LED transmitter.

Fig. 7. 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 $\sim$ 200mm
Shutter speed	60 $\sim$ 16000 fps
Resolution	Max 1280 × 1024 pixel

TABLE II
EXPERIMENTAL PARAMETER.

Focus	35mm
Shutter speed	1000 fps
Lens diaphragm	11
Resolution	128 × 128
Communication distance	20m ∼ 80m
The number of transmitted symbol	150
Memory length of encoder	4
Turbo code rate	$\frac{1}{3}$
The number of decoder iterations	6

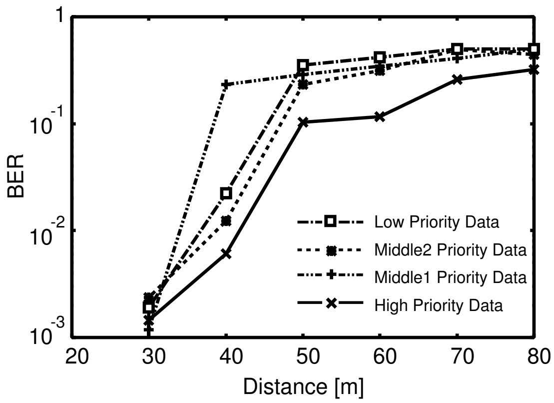


Fig. 8. BER performance without error correcting code.

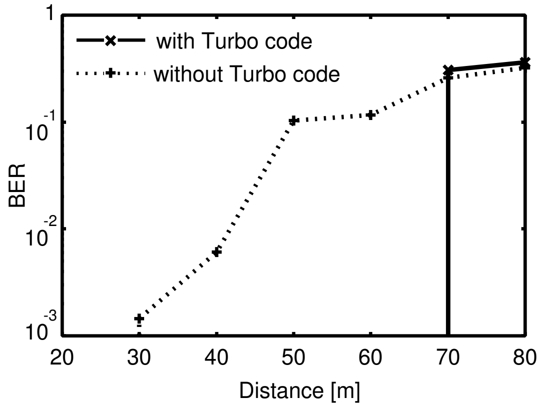


Fig. 9. Comparison the BER performance with/without turbo code.

occur. Although effect of iterative decoding cannot be seen, lengthening of error-free distance is a big achievement. We confirm the effectiveness of the error correcting code.

V. CONCLUSION

We discussed the performance of using error correcting code with hierarchical coding. We proposed that error correcting code is applied to high-priority data. Experimental results have shown error correcting code is effective. That is, turbo-coded high-priority data can be received from farther away than non turbo-coded data. By applying error correcting code, error free range is lengthened.

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