High-speed Transmission of Overlay Coding for Road-to-Vehicle Visible Light Communication Using LED Array and High-Speed Camera

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***Abstract*—This paper aims to the improve the data rate for the visible light communication system using LED array and high-speed camera. Previously, we have proposed the decoding algorithm using inverted signals for driving situation. However, using this method the data rate become a half, because we transmit original signals and inverted signals alternately for LED array tracking. In this paper, we propose the data rate improving method for overlay coding which is coding method that overlay two data which are called as the long range data and the short range data. In the proposed method, for the long range data, we transmit original signals and inverted signals alternately. On the other hand, for the short range data, we transmit only original signals while we transmit inverted signals of long range data. We confirm that we can improve data rate as compared with the previous method.**

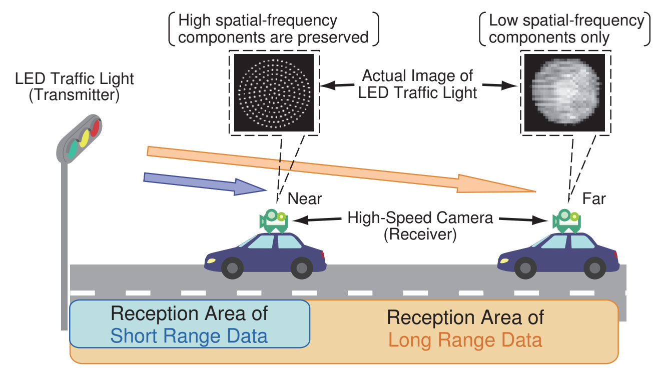

Fig. 1. Image of visible light communication using hierarchical coding.

I. Introduction

Light emitting diodes (LEDs) have the advantages of high power efficiency, long life, low heat generation, and good visibility. These advantages are making the applications of LED popular, particularly on traffic lights. Since LEDs are semiconductor devices, we can control LEDs' intensity electrically at a fast rate. LEDs can be used not only as illuminating devices but also as communication devices. It is expected that LEDs are applied to visible light communications [1], [2].

In this paper, we use an LED array as the transmitter and an in-vehicle high-speed camera as the receiver in visible light communications. In this system, if the distance between a transmitter and a receiver gets longer, the resolution of received images gets poorer. That is, high spatial-frequency components of the images are lost due to the defocusing and the reduction of pixel size. To solve this problem, we have proposed a hierarchical coding [3], [4].

Figure 1 shows a conceptual image of a visible light communication. If the camera (receiver) is nearby the LED array (transmitter), it is easy to distinguish LED individually. In this case, we can obtain a multiple number of data from the LEDs. If the camera is far from the LED array, high spatial-frequency components of the data patterns in received images will be lost, and as a result it will be difficult to distinguish LED individually. However, the low spatial-frequency components are preserved in the images.

To solve the resolution problem, we incorporate the hierarchical coding into the visible light communication. We allocate long range data to low spatial-frequency components, and short range data to high spatial-frequency components. In this way, we can obtain the long range data even if the receiver is far from the transmitter.

An example of long range data is the text information about the waiting time for a traffic light to change from one color to another, about the presence of a vehicle that is going to turn left, etc. Using short range data, we might transmit a video image that a driver might be difficult to see from his vehicle. For data allocation scheme between the high and low spatial-frequency components, we employ the overlay coding [4]. The overlay coding is implemented in the following way: When we consider multiple LEDs combined together as one LED, it is easy to distinguish the combined LED even if the camera is far from the LED array. When the number of LEDs in the combined LED increases, the distance that we can distinguish the combined LED also increases. We allocate a higher number of LEDs for long range data than the number for short range data. Then, by overlaying two lighting patterns for two range data, we can realize the hierarchical coding [4].

Furthermore, we have proposed the decoding algorithm using inverted signals for driving situation [5]. However, using

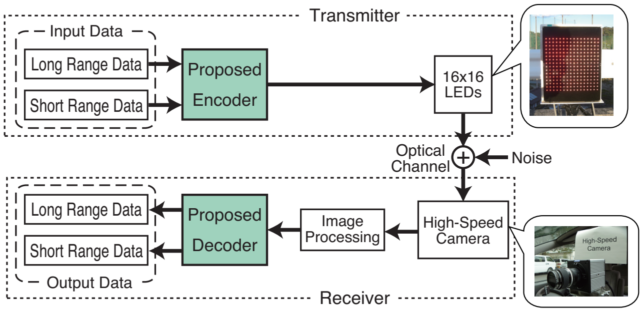

Fig. 2. Block diagram of the proposed system.

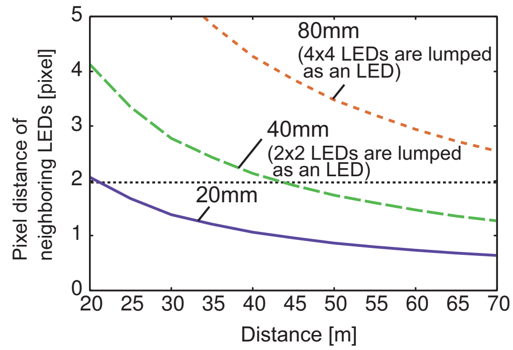

Fig. 3. Pixel-distance of neighboring LEDs versus transmitter-receiver distance, where the LED spacing is 20 [mm].

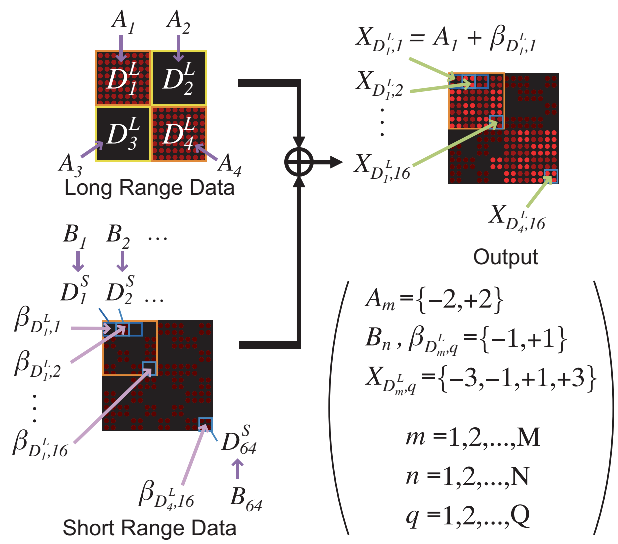

Fig. 4. Illustrated figure of the coding process.

this method the data rate become a half, because we transmit original signals and inverted signals alternately for LED array tracking.

In this paper, we propose the data rate improving method for the overlay coding. In the proposed method, for the long range data, we transmit original signals and inverted signals alternately. On the other hand, for the short range data, we transmit only original signals while we transmit inverted signals of long range data. We confirm that we can improve data rate as compared with the previous method.

II. System Overview

Figure 2 shows a block diagram of the system model. The transmitter consists of the LEDs in the form of a 16×16 square matrix and the encoder. The distance between neighboring LEDs is 20 mm that is the same as the actual LED spacing of an LED traffic light used in Japan. The LEDs can control their intensity electrically and individually.

The receiver consists of a high-speed camera, an image processing unit and a decoder. We represent the LED with row u and column v by $LED_{u,v}$ $(u, v = 1, 2, \cdots, 16)$.

We generate long range data and short range data as input data, and allocate long range data to low spatial-frequency components and short range data to high spatial-frequency components. The input data is coded by overlay coding. The transmitted signal arrives at the high-speed camera (receiver) through an optical channel. The receiver has the CMOS image sensors and its resolution is 128×128 pixels. Each pixel outputs a photo-current corresponding to the received light intensity. One LED luminance signal corresponds to one or several pixels in the received images. After the image processing, we obtain the value of luminance of respective LEDs. We decode using the value of luminance.

III. Overlay Coding

As shown in Fig. 1, if the distance between a transmitter and a receiver gets longer, the resolution of received images gets poorer. That is, high spatial-frequency components of the images are lost due to the defocusing and the reduction of pixel size.

Figure 3 shows the pixel-distance of neighboring LEDs versus the transmitter-receiver distance, where we define the pixel-distance as the number of pixels of two neighboring LEDs in a captured image. The LED spacing is 20 mm and the resolution of the high-speed camera is 128×128 pixels. In order to distinguish two neighboring LEDs separately, at least two pixels are necessary. From Fig. 3, we confirm that if we assign the same data to more LEDs and consider it as one LED, then the transmitter-receiver distance that achieve the pixel-distance of two gets longer.

To take advantage of these channel characteristics, we employed the hierarchical coding scheme using overlay coding in our previous research [4]. The overlay coding is employed to allocate long range data to low-spatial frequency components and short range data to high-spatial frequency components. Hence, we can obtain the long range data even if the receiver is far from the transmitter.

The overlay coding is realized through the procedures of coding and decoding as follows.

A. Coding

Figure 4 shows the coding process. In this scheme, we transmit long range data and short range data. We then assign long range data to a flexible number of LEDs. We set the number so that the pixel-distance of neighboring LEDs is more than two in the desired error-free range of long range data.

Let D_m^L be the area of the LEDs that represents the long

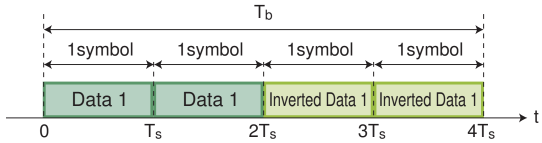

Fig. 5. Actual transmission data frame of one data.

range data and let D_n^S be the area of the LEDs that represents short range data, where the number of D_m^L is M and the number of D_n^S is N, respectively, for $(m = 1, 2, \cdots, M, n = 1, 2, \cdots, N)$. We allocate the same data $\{-2, +2\}$ to D_m^L and $\{-1, +1\}$ to D_n^S. If we denote R_b as the transmission bit rate of a single LED, then MR_b is the data rate of long range data and NR_b is that of short range data, respectively.

Let us now focus on individual LED, say $LED_{u,v}$ in kth symbol $(k = 0, 1, 2, \ldots)$. Let $A_m[k]$ be the long range data and $a_{u,v}[k]$ be the long range data signal that is assigned to $LED_{u,v}$. We assign $A_m[k]$ to D_m^L. Similarly, Let $B_n[k]$ be the short range data and $b_{u,v}[k]$ be short range data signal that is assigned to $LED_{u,v}$. We assign $B_n[k]$ to D_n^S. Then we obtain the following equation for the data assignment.

$$\begin{cases} a_{u,v}[k] = A_m[k] & (LED_{u,v} \in D_m^L) \\ b_{u,v}[k] = B_n[k] & (LED_{u,v} \in D_n^S) \end{cases} \tag{1}$$

We focus on the area of D_m^L in kth symbol. Suppose there are Q LEDs in this area. We rewrite $\beta_{D_m^L,q}[k] (q = 1, 2, \cdots, Q)$ as the short range data that are within the area of D_m^L. We overlay those long range data signal and short range data signal to obtain the output signal $X_{D_m^L,q}[k]$, that drives each of LED and can be written as the following.

$$X_{D_m^L,q}[k] = A_m[k] + \beta_{D_m^L,q}[k] \tag{2}$$

In this paper, we allocate one bit $\{-2, +2\}$ to the long range data and one bit $\{-1, +1\}$ to short range data, respectively. So the overlaid signal takes value of $\{-3, -1, +1, +3\}$. These data are expressed by four grades of luminance that rescaled by following equation:

$$X'_{D_m^L,q}[k] = \frac{X_{D_m^L,q}[k] + 3}{6}. \tag{3}$$

Therefore, these data are expressed by four grades of luminance of $\{0, 1/3, 2/3, 1\}$ [4].

The transmitter's LEDs generate a nonnegative pulse with a duration of T_s, where T_s is the bit duration. We achieve four grades of luminance by changing the width of the pulse.

Figure 5 shows the actual transmission data frame of one data. As we must follow the sampling theorem, the same data are transmitted twice. For the detail discussion on this, please refer to [6]. We further add the inverted signals that are mainly used for LED array detection and tracking [5]. In Sec. IV-A, we discuss the detail on inverted signals. Because of these, we achieve the data rate of overlay coding as $(M + N)/4T_s$.

B. Decoding

The transmitted signal arrives at the high-speed camera (receiver) through the optical channel. The receiver converts the signal into electrical signal corresponding to the received light intensity by the CMOS image sensors and outputs images. After we estimate the position of each LED and obtain the luminance from each image, we normalize the luminance values [7]. The normalization can get rid of the stationary noise. Furthermore ambiance noize can be ignored because the value of the lens diaphragm we use is big. We decode using the normalized luminance value of $\widehat{Y}_{D_m^L,q}[k]$.

We focus on the qth LED in the area of the long range data D_m^L at kth symbol. We first calculate an average of the normalized luminance in the area of D_m^L, and that is represented by below equation.

$$\frac{\sum_q \widehat{Y}_{D_m^L,q}[k]}{Q} = \tilde{A}_m[k] + \frac{\sum_q \tilde{\beta}_{D_m^L,q}[k]}{Q} \tag{4}$$

In the Eq. (4), the first term represents the long range data in the area of D_m^L in kth symbol, the second term represents the average of the short range data in the area of D_m^L in kth symbol. We then obtain the long range data as follows.

$$\tilde{A}_m[k] = \frac{\sum_q \widehat{Y}_{D_m^L,q}[k]}{Q} - \frac{\sum_q \tilde{\beta}_{D_m^L,q}[k]}{Q} \tag{5}$$

The influence of short range data to long range data is small, since short range data takes value of $+1$ or -1 whereas long range data takes a value of $+2$ or -2. Furthermore the transmitted short range data is binomial distribution with -1 and $+1$. Thus, the second term of right-hand side of Eq. (5) converge to zero. Therefore, we can obtain the long range data by below equation.

$$\tilde{A}_m[k] \simeq \frac{\sum_q \widehat{Y}_{D_m^L,q}[k]}{Q} \tag{6}$$

We perform threshold processing to the long range data $\tilde{A}_m[k]$. We decode the data as $+2$ if it is plus, and decode as -2 if it is minus.

Since the transmitted data is overlaid, the short range data can be calculated by using the long range data.

$$\tilde{\beta}_{D_m^L,q}[k] = \widehat{Y}_{D_m^L,q}[k] - \tilde{A}' \tag{7}$$

where $\tilde{A}'$ is the value of long range data subtracted from the normalized luminance value. In order to further reduce the influence of short range data on long range data, as the value of $\tilde{A}'$, we use the average of the normalized luminance value $\widehat{Y}_{D_m^L,q}[k]$ not only in one area of long range data at kth symbol but also in all areas where the result of threshold processing of $\tilde{A}_m[k]$ is same through all transmitted symbols. Hence, $\tilde{A}'$ is represented by below equation.

$$\tilde{A}' = \begin{cases} \frac{\sum_{m,k \in \{m,k | \tilde{A}_m[k] > 0\}} \sum_q \widehat{Y}_{D_m^L,q}[k]}{(M \cdot K)_+ \cdot Q} & (\tilde{A}_m[k] > 0) \\ \frac{\sum_{m,k \in \{m,k | \tilde{A}_m[k] \leq 0\}} \sum_q \widehat{Y}_{D_m^L,q}[k]}{(M \cdot K)_- \cdot Q} & (\text{otherwise}) \end{cases} \tag{8}$$

where $(M \cdot K)_+$ and $(M \cdot K)_-$ are the number of areas whose results of threshold processing of $\tilde{A}_m[k]$ are $+2$ and -2 among all the transmitted symbols, respectively. We perform threshold processing to the short range data $\tilde{\beta}_{D_m^L,q}[k]$. We decode the data as $+1$ if it is plus, and decode as -1 if it is minus.

IV. Data Rate Improvement Method

A. LED Array Tracking and Inverted Signals

To achieve robust tracking, it is necessary to track the position of the LED array in each frame, because of camera (vehicle) vibrations and changes in the size of the LED array during the driving situation. We employ the LED array tracking method using inverted signals [5].

Figure 6 shows the LED array tracking method using inverted signals. In Fig. 6, the original signals are depicted as "Data" and The inverted signals are depicted as "Data*". At the transmitter, we make an inverted pattern of each signal. The inverted signal takes the reversed luminance of the original signal. And we transmit the original signals and the inverted signals alternately.

At the receiver, those two patterns are added together to generate all-LEDs-on pattern. In this way, the robust LED array tracking can be performed using the generated all-LEDs-on pattern.

We apply this method to the overlay coding. Recalling Eq. (2), the output signals in $2k$th and $2k+1$th symbol are

$$X_{D^L_m,q}[2k] = A_m[k] + \beta_{D^L_m,q}[k] \quad (9)$$
$$X_{D^L_m,q}[2k+1] = A^*_m[k] + \beta^*_{D^L_m,q}[k] = X^*_{D^L_m,q}[2k] \quad (10)$$

where $A^*_m[k]$ is the reversed version of $A_m[k]$ and $\beta^*_{D^L_m,q}[k]$ is the reversed version of $\beta_{D^L_m,q}[k]$. The output signal $X_{D^L_m,q}[k]$ rescaled by Eq. (3) takes the value of $\{0, 1/3, 2/3, 1\}$, then its inverted signal $X^*_{D^L_m,q}[k]$ rescaled by Eq. (3) takes the value of $\{1, 2/3, 1/3, 0\}$, respectively. In this case, the additional luminance between $X_{D^L_m,q}[2k]$ and $X_{D^L_m,q}[2k+1]$ rescaled by Eq. (3) representively become "1", that is all-LEDs-on. However, using this method the data rate become a half, because we transmit original signals and inverted signals alternately. In this paper, we propose the data rate improvement method for the overlay coding.

B. Data Rate Improvement Method

We improve the data rate of the short range data. Figure 7 is the illustrated figure of the data rate improvement process. For the long range data, we transmit the original signals and the inverted signals alternately. This is the same method as the overlay coding with the LED array tracking method for the long range data. On the other hand, for the short range data, we transmit only the original signals while inverted signals of long range data are transmitted. Using overlay coding, long range data and short range data are overlaid and transmitted. Recalling Eq. (2), the output signals in $2k$th and $2k+1$th symbol are

$$X_{D^L_m,q}[2k] = A_m[k] + \beta_{D^L_m,q}[2k] \quad (11)$$
$$X_{D^L_m,q}[2k+1] = A^*_m[k] + \beta_{D^L_m,q}[2k+1]. \quad (12)$$

In order to generate all-LEDs-on pattern, at the receiver, we add together two patterns which long range data is inverted. In this case, the additional luminance between $X_{D^L_m,q}[2k]$ and $X_{D^L_m,q}[2k+1]$ rescaled by Eq. (3) representively become

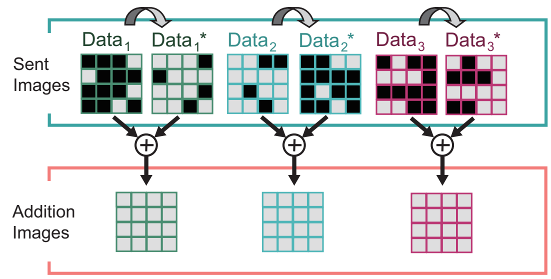

Fig. 6. Illustrated figure of the LED array tracking method using the inverted signals.

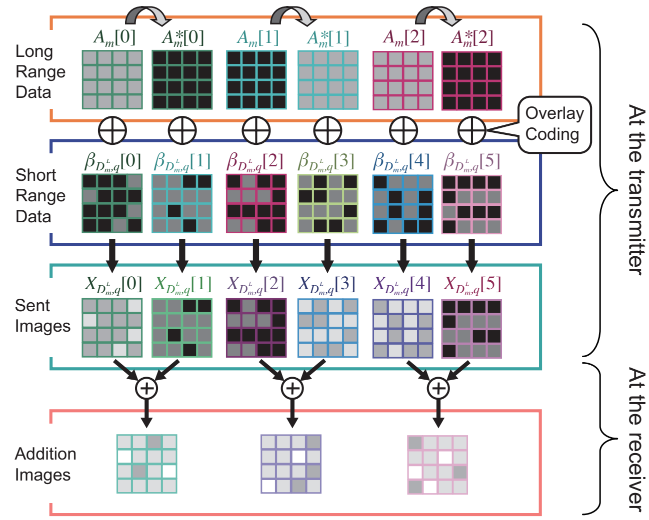

Fig. 7. Illustrated figure of the data rate improvement process.

$\{2/3, 1, 4/3\}$. In the generated additional images, the luminance value of LEDs is inequable since the short range data is not inverted. However, all LEDs is lighted since long range data is inverted. Therefore, we can tracking using the generated additional images.

V. Experiment

A. Experimental Parameter

We performed measurements for distances from 20m to 70m, every 5m on a static condition. We evaluate the results of experiments by throughput performance. Table I shows the specifications of the high-speed camera. And Table II, Table III and Table IV show the experimental parameters.

In this experiment, we use division of the LED array that have the condition which shown in Table III. Figure 8 shows the division of LED array.

B. Experimental Results

Figure 9 shows the throughput performances of the long range data and the short range data of overlay coding method and overlay coding with data rate improvement method. Throughput for the long range data and the short range data is defined as

$$S^L = MR_b(1 - P^L_s) \quad (13)$$
$$S^S = NR_b(1 - P^S_s) \quad (14)$$

TABLE I
HIGH-SPEED CAMERA SPECIFICATIONS.

Camera model.	FASTCAM-1024PCI 100K made by Photron
Sensor type	CMOS
Lens model	NIKKOR 35mm f/1.4 made by Nikon
Focus	35mm
ND filter	Screw-in Filter ND4-L/4x made by cannon

TABLE II
EXPERIMENTAL PARAMETER.

Lightning frequency of LED	3kHz
Shutter speed	1000fps
Focal length of a lens	35mm
Focus of a lens	infinity
Lens diaphragm	11
Filter of a lens	ND4L filter
Resolution	128×128pixels
Communication distance	20m-70m at intervals of 5m
Condition of experiment	static

where, P_s^L is the symbol error rate for the long range data which consists of 8 bits, and P_s^S is the symbol error rate for the short range data which consists of 24 bits. Almost an even performance of the throughput is obtained in the transmission of the long range data. On the other hand, the throughput of the short range data of proposed method is almost twice that of conventional method. We can see the degradation of the throughput performance caused by the luminance saturation at 20m and a moire at 35m and 40m. We confirm that we can improve data rate of the short range data as compared with the conventional method.

VI. CONCLUSION

In this paper, we proposed a data rate improvement method for the overlay coding.

In the proposed method at the transmitter, for the long range data, we transmit the original signals and the inverted signals alternately. On the other hand, for the short range data, we transmit only the original signals while inverted signals of long range data are transmitted. Using overlay coding, the long range data and the short range data are overlaid and transmitted. At the receiver, we add together two patterns which the long range data is inverted. Using generated additional images, we can track LED array. The experimental result shows that, we can improve data rate as compared with the previous method.

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TABLE III
DIVISION OF LED ARRAY.

	(L16_S64)	
Data	Long Range	Short Range
The number of LED corresponded 1bit	16	4
The number of bits per 1symbol	16bit (M=16)	64bit (N=64)

TABLE IV
DATA RATE.

	Conventional Method		Proposed Method	
Data	Long Range	Short Range	Long Range	Short Range
Data Rate	4	16	4	32

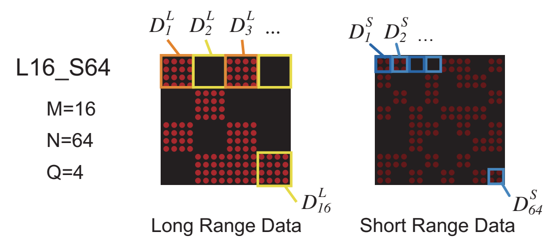

Fig. 8. Image of division of LED array.

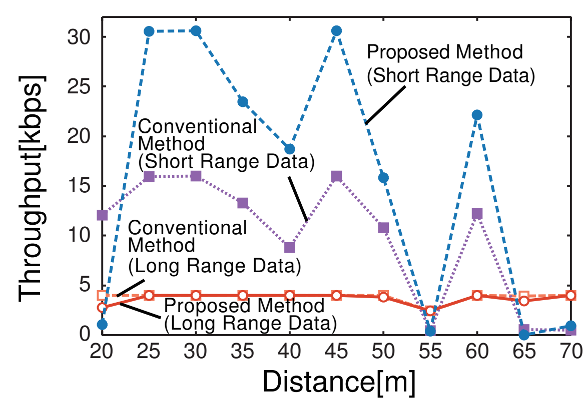

Fig. 9. Throughput performance.

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