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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 improve the visible light communication system using LED array and high-speed camera by proposing what we call "overlay coding". "Overlay coding" is a new coding method to realize a hierarchical coding, through which a high-priority data can be received even if the receiver is far from a transmitter. Conventionally, the hierarchical coding has been realized through the wavelet transform that has a limitation of number and disposition of LEDs, and as a result it does not always match with the design of the transmitters (e.g. traffic lights, etc.) used in real life. To solve the limitation problem, we propose a more flexible way of designing the application of LEDs depending on the transmitters. In particular, overlay coding is realized through the procedures of coding and decoding. In coding, we replace one LED with a flexible number of LEDs, and the number depends on whether the data is high-priority or low-priority, then high-priority data and low-priority data are overlaid (section III-B1). In decoding, we first obtain the high-priority data, and then the low-priority data using retrieved high-priority data (section III-B2). The experimental result shows that the distance for receiving error-free data is extended from 30m to 70m in the overlay coding (section IV-B).**

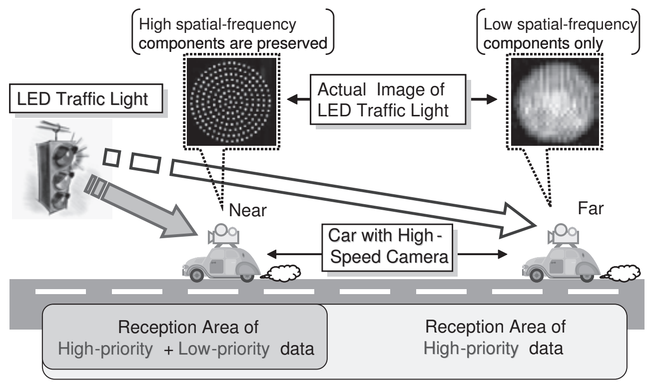

Fig. 1. Image of visible light communication using hierarchical coding.

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 a 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].

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 high-priority data to low spatial-frequency components, and low-priority data to high spatial-frequency components. In this way, we can transmit the high-priority data even if the receiver is far from the transmitter.

An example of high-priority 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 low-priority 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 two-dimensional fast Haar wavelet transform (2D FHWT) in our previous researches [3]. However, the conventional method has a limitation problem: The number of LEDs has to be the power of 4 and the disposition of LEDs must be square matrix. But in the actual case, we use LED traffic light as a transmitter whose disposition of the LEDs is circle.

To solve the limitation problem, we propose a more flexible way of designing the application of LEDs depending on the kind of transmitters. In particular, overlay coding is implemented in the following way: When we consider several 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 high-priority data than the number for low-priority data. Then, by overlaying two lighting patterns for two priority data, we can realize the hierarchical coding.

In the decoding, we implement the following two operations: First, we can obtain the high-priority data by averaging the received data which correspond to the considered LED for the high-priority data. Second, we obtain the low-priority data by using the retrieved high-priority data.

The paper is organized as follows. In Sec. III, we introduce a new coding method that we call "overlay coding". The overlay coding realizes a hierarchical coding by a simple overlay of several lighting patterns for several data priorities. As a result, the proposed scheme does not have a limitation of number and disposition of LEDs. In Sec. IV, the experiment results evaluated by bit error rate (BER) are presented. Finally, we conclude this paper in Sec. V.

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 are 20mm 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 the high-speed camera and the decoder. We represent the LED with row u and column v by $LED_{u,v}$ $(u, v = 1, 2, \cdots, 16)$.

We generate and allocate high-priority data to low spatial-frequency components and low-priority data to high spatial-frequency components. The input data, divided into two priorities, is coded by proposed 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 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

Conventionally, the hierarchical coding has been realized through the wavelet transform that has a limitation of number and disposition of LEDs, and as a result it does not always match with the design of the transmitters (e.g. traffic lights,

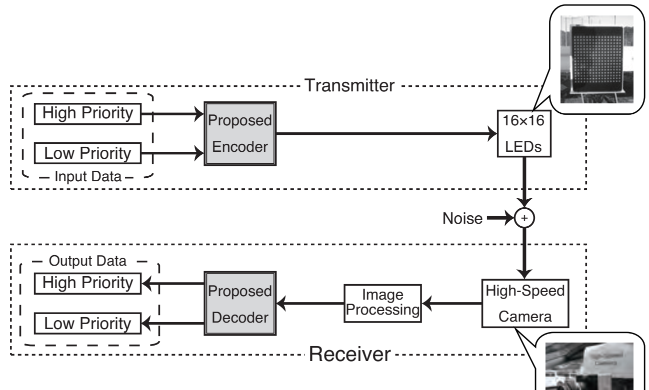

Fig. 2. System model.

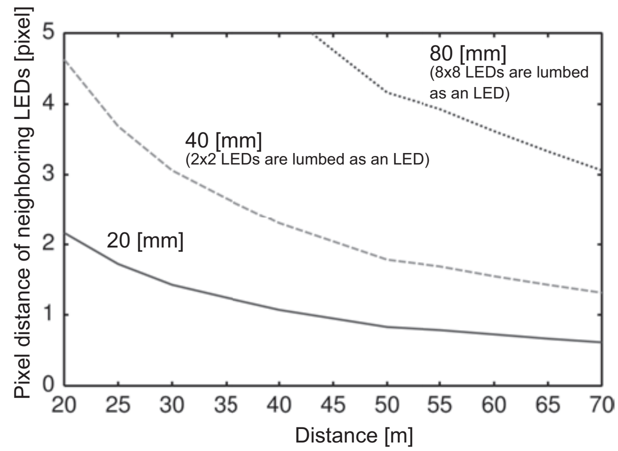

Fig. 3. Pixel-distance of neighboring LEDs versus transmitter-receiver distance, where the LED spacing is 20 [mm].

etc.) used in real life[3]. Also, it is difficult to design the error-free ranges of the high-priority data and low-priority data. To solve the limitation problem, we propose a more flexible way of designing the application of LEDs depending on the transmitters.

In this section, we explain our proposed overlay coding scheme. We start with the discussion on the error-free range and the distance of two neighboring LEDs measured as pixels in a captured image. This pixel-distance of neighboring LEDs can be a guideline to distinguish LEDs.

A. Pixel-distance of neighboring LEDs

Let us define the pixel-distance as the number of pixels of two neighboring LEDs in a captured image.

Figure 3 shows the pixel-distance of neighboring LEDs versus the transmitter-receiver distance. The LED spacing is 20mm 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 the figure, we observe that if we assign each LED different data, then 20m may be the range that we may achieve the error-free transmission as the pixel-distance of 2 is obtained at 20m. In contrast, if we assign 2×2 LEDs the same data and consider

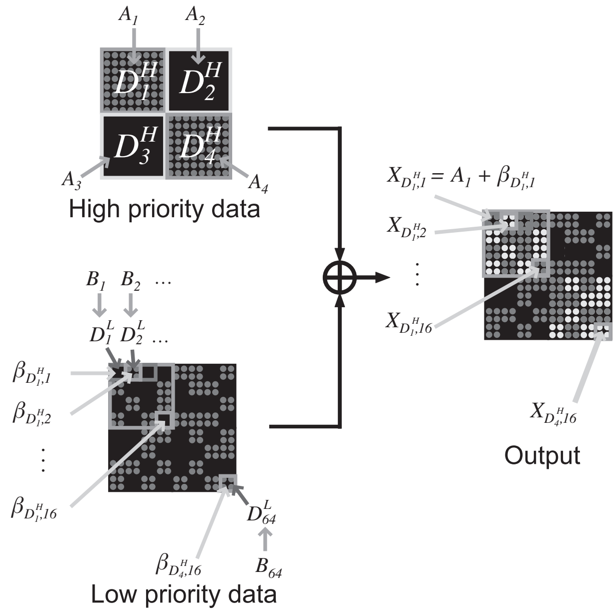

Fig. 4. Illustrated figure of the coding process.

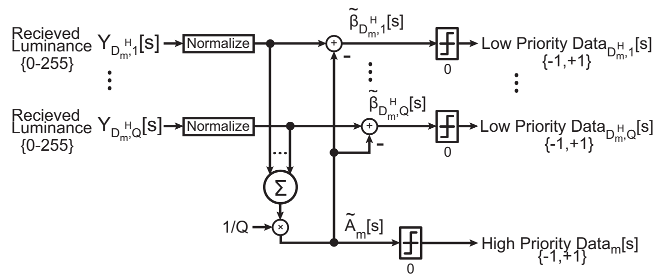

Fig. 5. Decoding scheme.

it as an LED then we achieve the pixel-distance of 2 up to 45m.

From the discussion above, we propose the overlay coding scheme.

B. Overlay coding

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

1) Coding: Figure 4 is the illustrated figure of the coding process. In the proposed scheme, we divide the data into two priorities, high priority and low priority, and transmit them. We then assign high priority data to a flexible number of LEDs. We set the number so that the pixel-distance of neighboring LEDs is more than 2 in the desired error-free range of high priority data.

Let D_m^H be the area of the LEDs that represents the high-priority data and let D_n^L be the area of the LEDs that represents low-priority data, where the number of D_m^H and D_n^L are M and N, respectively, for $(m = 1, 2, \cdots, M, n = 1, 2, \cdots, N)$. We allocate the same data {-1,+1} to D_m^H and so for D_n^L. For example, in the case of $M = 1$, the number of LED included in the area of D_1^H is $256 (= 16 \times 16)$. All LEDs are given the same high-priority data and we transmit a single data at a time. Also, in the case of $M = 4$, the number of LED included in the area of D_1^H is $64 = (8 \times 8)$ and we transmit four data at a time. If we denote R_b as the transmission bit rate of a single LED, then MR_b is the data rate of high priority data and NR_b is that of low priority data, respectively.

Let us now focus on individual LED, say $LED_{u,v}$ in sth symbol. Let $A_m[s]$ be the high-priority data and $a_{u,v}[s]$ be the high-priority data signal that is assigned to $LED_{u,v}$. We assign $A_m[s]$ to D_m^H. Similarly, Let $B_n[s]$ be the low-priority data and $b_{u,v}[s]$ be low-priority data signal that is assigned to $LED_{u,v}$. We assign $B_n[s]$ to D_n^L. Then we obtain the following equation for the data assignment.

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

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

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

In this paper, we allocate one bit {-1,+1} to the high-priority and one bit {-1,+1} to low-priority, respectively. So the overlaid signal takes value of {-2,0,+2}. These data are expressed by 3 grades of luminance.

The transmitter's LEDs generate a nonnegative pulse with a duration of T_s, where T_s is the bit duration. As shown in Fig.6, we achieve 3 grades of luminance by changing the width of the pulse.

Fig. 7 shows the actual transmission data frame of one data. As we must follow the sampling theorem, the same data are transmitted twice. We further add the inverted signals that are mainly used for LED array detection and tracking. For the detail discussion on these, please refer to [4] and [5]. Because of these, we achieve the data rate of overlay coding as $(M + N)/4T_s$.

2) 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 obtain the luminance $Y_{D_m^H,q}[s]$ from each image, we normalize the luminance values by using the mean $E_{D_m^H,q}$ and the variance $V_{D_m^H,q}$ of the extracted luminance $Y_{D_m^H,q}[s]$. (Reference to eq.(3)–(5).)

$$E_{D_m^H,q} = \frac{\sum_{s=0}^{S-1} Y_{D_m^H,q}[s]}{S} \tag{3}$$

$$V_{D_m^H,q} = \frac{\sum_{s=0}^{S-1} (Y_{D_m^H,q}[s] - E_{D_m^H,q})^2}{S} \tag{4}$$

$$\widehat{Y}_{D^H_m,q}[s] = \frac{Y_{D^H_m,q}[s] - E_{D^H_m,q}}{\sqrt{V_{D^H_m,q}}} \quad (5)$$

We decode using the normalized luminance value of $\widehat{Y}_{D^H_m,q}[s]$.

Figure 5 shows block diagram of the decode scheme. We focus on the qth LED in the area of the high-priority D^H_m at sth symbol. We first calculate an average of the normalized luminance in the area of D^H_m, and that is represented by below equation.

$$\frac{\sum_q \widehat{Y}_{D^H_m,q}[s]}{Q} = \tilde{A}_m[s] + \frac{\sum_q \tilde{\beta}_{D^H_m,q}[s]}{Q} \quad (6)$$

In the eq. (6), the first term represents the high-priority data in the area of D^H_m, the second term represents the average of the low-priority data in the area of D^H_m. We then obtain the high-priority data as follows.

$$\tilde{A}_m[s] = \frac{\sum_q \widehat{Y}_{D^H_m,q}[s]}{Q} - \frac{\sum_q \tilde{\beta}_{D^H_m,q}[s]}{Q} \quad (7)$$

The second term of right-hand side of eq. (7) converge to zero because the transmitted low-priority data is binomial distribution with -1 and $+1$. Therefore, we can obtain the high-priority data by below equation.

$$\tilde{A}_m[s] \simeq \frac{\sum_q \widehat{Y}_{D^H_m,q}[s]}{Q} \quad (8)$$

Since the transmitted data is overlaid, the low-priority data can be calculated by using the high-priority data.

$$\tilde{\beta}_{D^H_m,q}[s] = \widehat{Y}_{D^H_m,q}[s] - \tilde{A}_m[s] \quad (9)$$

We perform threshold processing to the high-priority data $\tilde{A}_m$ and the low-priority data $\tilde{\beta}_{D^H_m,q}$. We decode the data as $+1$ if it is plus, and decode as -1 it is minus.

C. Advantage and Disadvantage of using Overlay Coding

In this section, we discuss the advantage and the disadvantage of using the proposed scheme (the overlay coding), compared with using the conventional scheme (the two-dimensional fast Haar wavelet transform).

The advantage of using the proposed scheme is that there is no limitation of both the number and the disposition of LEDs. Furthermore, from the discussion in section III-A and section III-B1, to achieve error-free performance, we can freely change the size of the LEDs that are assigned the same data in each priority in the case of encoding. This is also the advantage of using the proposed scheme. Therefore, using the overlay coding, we can realize the most suitable hierarchical coding to the utilizing situation.

Since the conventional scheme adopt the orthogonal transform coding, each priority data does not influence each other. Therefore we can decode each priority data individually using the conventional scheme. On the other hand, the proposed scheme adopt the non-orthogonal coding scheme. The proposed scheme is formed of the addition of high-priority data and low-priority data as eq. (2). From this point of view, the disadvantage of using overlay coding is that each priority-data interferes and influences each other.

In the decoding, it is required to remove the influences that both the high-priority data influence on the low-priority data and the low-priority data influence on the high-priority data. When Q is large enough, eq. (7) can be approximated by eq. (8). In this case, we can remove the influence which low-priority data influence on high-priority data. However, in practice, it is difficult to remove the influence of interference in using proposed scheme. In order to observe the influence of interference, we perform experiment using the conventional scheme and the proposed scheme.

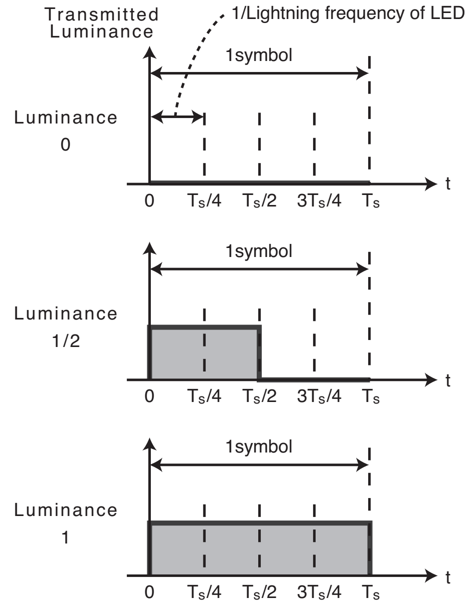

Fig. 6. Luminance:Pattern of lighting.

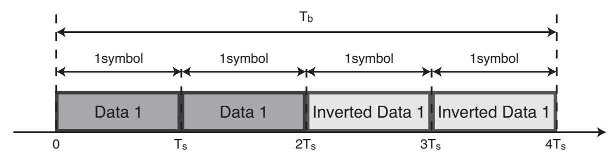

Fig. 7. Actual transmission data frame of one data.

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

IV. 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 bit error rate (BER). Table I shows the

TABLE III
DIVISION OF LED ARRAY AND DATA RATE.

	wavelet transform		Overlay coding							
			Pattern1 (H1_L256)		Pattern2 (H1_L64)		Pattern3 (H4_L256)		Pattern4 (H4_L64)	
Priority	high	low	high	low	high	low	high	low	high	low
The number of LED corresponded 1bit	1	1	256	1	256	4	64	1	64	4
The number of bits per 1symbol	64bit	64bit	1bit (M=1)	256bit (N=256)	1bit (M=1)	64bit (N=64)	4bit (M=4)	256bit (N=256)	4bit (M=4)	64bit (N=64)
Data rate	16kbps	16kbps	0.25kbps	64kbps	0.25kbps	16kbps	1kbps	64kbps	1kbps	16kbps

TABLE II
EXPERIMENTAL PARAMETER.

Lightning frequency of LED	4kHz
Shutter speed	1000fps
Focal length of a lens	35mm
Focus of a lens	infinity
Lens diaphragm	11
Filter of a lens	ND4L filter
Resolution	128×128pixel
Communication distance	20m-70m at intervals of 5m
Condition of experiment	static

specifications of the high-speed camera. And table II and table III shows 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

Fig. 9 and Fig. 10 show the BER performances of the high-priority and that of low-priority of the two hierarchical coding methods using our proposed overlay coding and the conventional wavelet transform, respectively.

For the BER of high-priority of our proposed overlay coding, we achieve error-free transmission for all distance 20m-70m. Compared with the conventional scheme, we confirm that our scheme outperforms the conventional scheme. In the low-priority, BER of our scheme is less than 10^{-1} for the distance up to 40m. We note that we can correct errors till the BER reaches 10^{-1} by a turbo code with a code rate of one-third. Compared with conventional scheme, with pattern 2 (H1_L64) and pattern 4 (H4_L64) we can lengthen the communication distance.

Finally, we compare our proposed schemes having the same data rate for the low-priority. The difference is Q in eq.(7). If Q is less, then we observe some degradation due to the fact that the average of low-priority data of the normalized luminance $\sum_q \widehat{\beta}_{D^H_m,q}[s]/Q$ do not converge to zero. In this case, the interference that low-priority data influence on high-priority data is occurred. However it may be effective to use proposed scheme. By using a turbo code with a code rate of one-third, we can correct errors for the BER less than 10^{-1}. As we confirm the Fig. 10, the BER of the proposed scheme in the distance less than 30m achieves less than 10^{-3}. Therefore we see no drawback caused by the less Q in eq. (7).

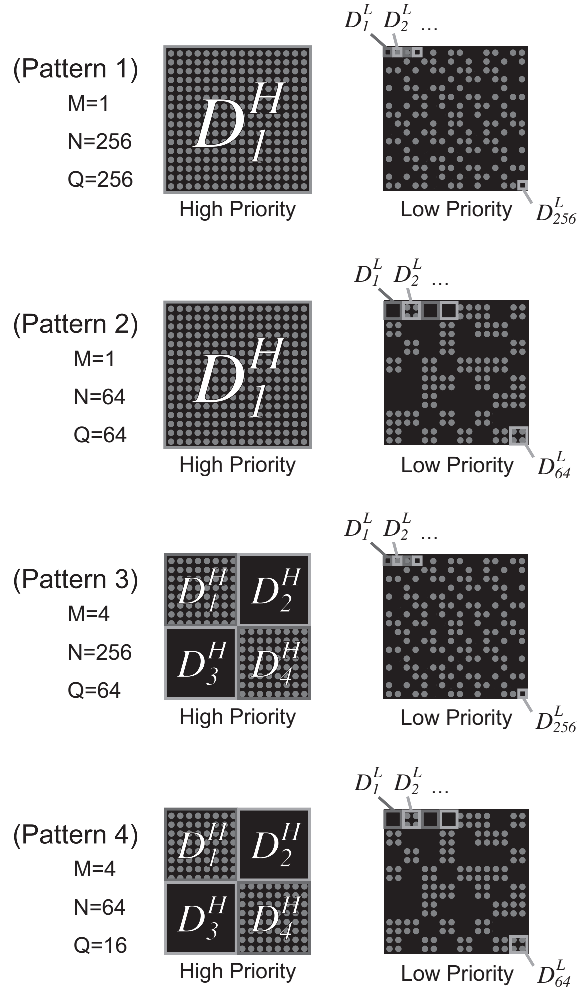

Fig. 8. Division of LED array.

V. CONCLUSION

In this paper, we proposed a new coding method called "overlay coding" to realize a hierarchical coding for visible light communications, through which a high-priority data can be received even if a receiver is far from a transmitter. The experimental result shows that, as far as high-priority data is concerned, the distance for receiving error-free data is extended from 30m to 70m in the overlay coding (compared to the conventional method). And almost an even performance of the bit error rate (BER) is obtained in the transmission of

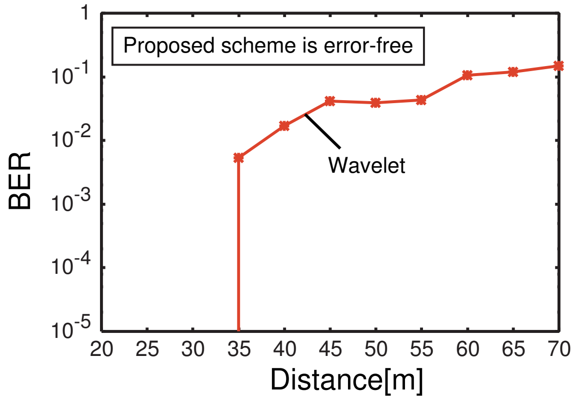

Fig. 9. BER performance of high priority.

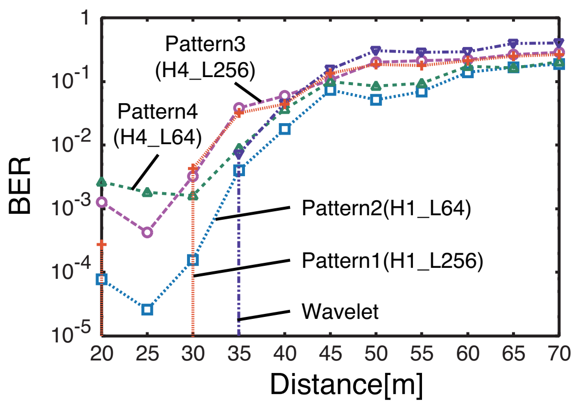

Fig. 10. BER performance of low priority.

low-priority data.

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