Interpixel Interference Cancellation Method for Road-to-Vehicle Visible Light Communication

Tatsuya KASASHIMA*, Takaya YAMAZATO*, Hiraku OKADA*, Toshiaki FUJII*,
Tomohiro YENDO†, and Shintaro ARAI‡,
* Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603, JAPAN
† Nagaoka University of Technology, 1603-1, Kamitomioka, Nagaoka, Niigata 940-2188, JAPAN
‡ Kagawa National College of Technology, 551 Kohda, Takuma-cho, Mitoyo, Kagawa, 769-1192 Japan
E-mail: kasasima@katayama.nuee.nagoya-u.ac.jp

***Abstract*—This paper aims to improve the transmission distance for the road-to-vehicle visible light communication system (R2V-VLC) using LED array and high-speed camera by reducing interference caused at the receiver. As we can transmit multiple data using LED array and high-speed camera, parallel data transmission can be possible. However, due to the diffusion of LED and the finiteness of the pixel size of image sensor, the focused LED will affect not only the actual corresponding pixel but also its surrounding pixels. We call this phenomenon as "interpixel interference (IPI)" and it causes degradation in error rate performance. To mitigate the IPI, we propose IPI cancellation scheme for the R2V-VLC system. As the results of the experiment, we can extend the error-free distance from 40m to 60m by the IPI cancellation.**

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. Needless to say, LEDs are key components of visible light communications (VLC) [1], [2].

In this paper, we use an LED array as the transmitter and a high-speed image sensor as the receiver in visible light communications. If we transmit data in parallel using an LED array consists of many LEDs, then a parallel data transmission is possible. The receiver retrieves the data from the luminance value of the pixel that correspond to each of LED. The advantage of using image sensor is that it can captures images and simultaneously decode data transmitted from the LED array. Many of useful image processing methods, such as position estimation, object recognition and object tracking can be utilized with the data reception by VLC [3]–[5].

Figure 1 shows a conceptual image of the road-to-vehicle visible light communication system (R2V-VLC). Examples of data transmitted from LED array (LED traffic light) 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, and etc. If the vehicle is in the middle of intersection waiting for left turn, we might transmit a video image that a driver might be difficult to see from his vehicle. Hence we use high-speed camera as a reception device the LED array (transmitter) recognition and its tracking are easy because the movement of a vehicle is relatively small compared to the frame rate of high-speed camera.

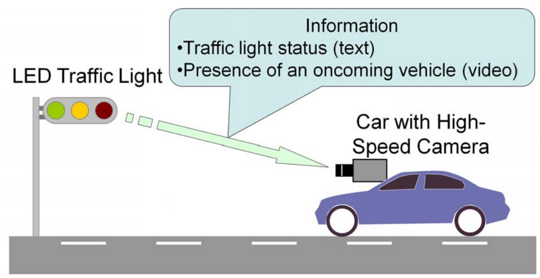


Fig. 1. Road-to-vehicle visible light communication (R2V-VLC) using LED array (LED traffic signal) and high-speed camera.

Possible drawbacks are diffusion of LED and finite pixel size of image sensor. The focused LED will affect not only the actual corresponding pixel but also its surrounding pixels. We call this phenomenon as "interpixel interference (IPI)" and it causes degradation in error rate performance.

In this paper, we tackle to mitigate the effect of IPI. We first present mathematical presentation of IPI and then try to mitigate the effect of IPI by an introduction of IPI cancellation scheme. As the results of the experiment, we can extend the error-free distance from 40m to 60m by the IPI cancellation.

The paper is organized as follows:In section II, we give the system overview of R2V-VLC. In section III, we define IPI, and in section IV, we give the IPI cancellation scheme. In section V, the experimental results are presented and finally in section VI we summarize the paper.

II. System Overview

A. Transmitter

Transmitter consists of 32×32 LED array and an encoder. Let $LED_{(r,c)}$ be the LED position of r row and c column, where r, c = 1, 2, . . . , 32. The encoder generate a non-negative rectangular pulse of duration T_b and module the LED by changing its luminance. Here T_b is the bit duration and

978-1-4673-6337-2/13/$31.00 ©2013 IEEE

the date rate of one LED be $R_b = 1/T_b$. The luminance of $LED_{(r,c)}$ at time t is

$$x_{(r,c)}(t) = \sum_k s_{(r,c,k)} \cdot A \cdot g(t - (k-1)T_b), \tag{1}$$

where k is the index number and $s_{(r,c,k)} (0 \leq s_{(r,c,k)} \leq 1)$ is a coefficient to determine the intensity of $LED_{(r,c)}$. A pulse function $g(t)$ is given below:

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

B. Receiver

The receiver consists of the high-speed camera, image processing unit and decoder. The transmitted signal arrives at the receiver through the optical channel. The high-speed camera has the CMOS image sensor, and each pixel outputs a photo-current corresponding to the received light intensity. If the optical channel effect can be neglected, the signal at the r, cth LED is

$$y_{(r,c)}(t) = x_{(r,c)}(t). \tag{3}$$

Let us assume that the receiver is exactly synchronized with the transmitter. Let the image sampling period be T_b. The image light exposure function can be represented as

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

where i = 1, 2, . . . is the exposure duration number and $g_{sh}(t)$ is a pulse denoted as the following:

$$g_{sh}(t) = \begin{cases} 1 & (0 \leq t \leq T_b) \\ 0 & (otherwise). \end{cases} \tag{5}$$

The sample output of the pixel corresponding to $LED_{(r,c)}$ in the ith exposure intervals is

$$p_{(u,v,i)} = \delta \int_{(i-1)T_b}^{iT_b} y_{(r,c)}(t) \cdot l(t) dt, \tag{6}$$

where δ is a constant to describe the light-current transform efficiency. Here, $p_{(u,v,i)}$ is the luminance value of the pixel at the position u, v and time index i. Without loss of generality, we drop i in following discussion.

III. Diffuseness of LED and Interpixel Interference

A. Diffusion of LED

Let us consider a simplified system model depicted in Fig. 2. If we suppose that VLC channel is ideal, and an image sensor consists of infinite large pixels at the receiver, then the light coming from the transmit LED can be considered as a point-lightning source and only one corresponding pixel will outputs its luminance value. However, due to the diffuseness of LED and the finiteness of the pixel size of image sensor, the focused LED will affect not only the actual corresponding pixel but also its surrounding pixels.

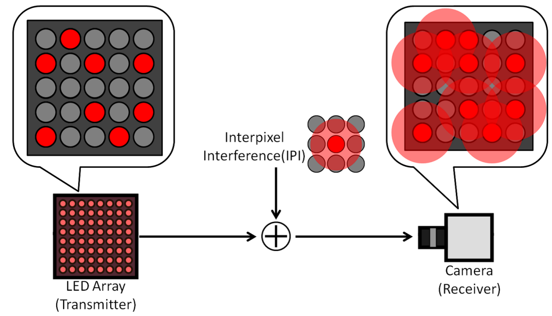
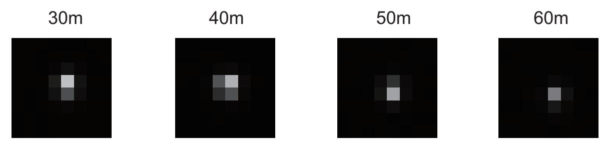


Fig. 2. A a simplified system model for an explanation. Here, the transmitted LED pattern (left) is captured by an image sensor (right) . Each of 5×5 LEDs transmits data by On-Off Keying. The captured image consists of 5×5 pixels and each of transmit LEDs are captured by the respective pixel.The focused LED affects not only to the actual corresponding pixel but also to its surrounding pixels, causing IPI.



30m:

1	3	4	3	2
2	6	18	6	2
3	28	201	20	3
4	19	76	16	4
3	5	9	5	3

40m:

3	3	2	2	1
4	10	12	4	2
7	81	184	13	3
5	45	77	10	2
3	4	6	3	1

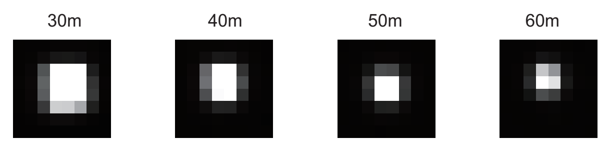
50m:

4	4	7	4	3
4	15	48	12	3
4	21	168	14	3
3	6	16	5	3
3	3	2	4	2

60m:

4	4	3	4	4
3	4	12	7	4
5	9	122	19	3
4	7	24	10	4
3	4	6	5	4

Fig. 3. Captured image of one LED (shown in above) and the luminance values of the pixel of the respective LED and its around pixels (shown in bottom).



30m:

14	24	25	22	8
82	230	235	232	29
96	233	236	242	50
90	239	230	240	55
56	214	213	175	30

40m:

5	15	26	24	12
10	100	231	230	50
11	111	222	224	73
10	76	229	237	48
6	16	34	33	12

50m:

7	10	10	6	4
21	73	69	21	6
54	233	221	56	8
44	226	218	53	7
12	31	32	13	4

60m:

8	22	18	7	4
30	207	151	18	5
44	223	212	25	6
20	74	60	13	4
4	6	7	4	4

Fig. 4. Captured image of nine LEDs aligned in 3×3 array (shown in above) and their luminance values (shown in bottom).

Figure 3 shows actual capture images of an LED taken for the transmitter-receiver distance, from 30 to 60m taken at every 10m. As we describe in detail in Sec.V A, resolution of the high-speed image sensor is 128×128 and images are shoot at the frame rate of 1,000fps. The upper side of images is the captured image for the case of an LED is ON. Below each of the images, we show the luminance value of the respective pixel of the LED and the luminance values around the pixel.

From the figure, we confirm that the diffusion of LED is limited to the surrounding pixels of the respective pixel of the LED, and they take rather small luminance value compared to the luminance of the LED. We also see that as the distance become longer, diffusion of LED become smaller. Unfortunately, because the LED is not captured at the center of the pixel due to the finiteness of the pixel size, the diffusions are not symmetrically distributed. Such can also be confirmed as the maximum luminance value at each distance varies where

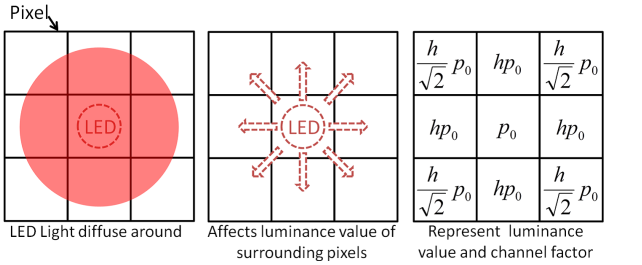


Fig. 5. LED diffusion, its influence to neighboring pixels, and the channel factors.

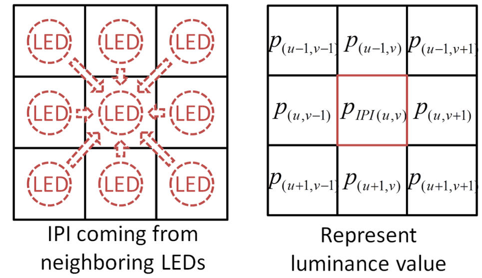


Fig. 6. Interpixel interference (IPI) and its affect to the neighboring LEDs.

it supposed to decrease as the distance gets long in an ideal case.

To see the diffusion of LED to neighboring LEDs, next in Fig. 3 we show capture images of 3×3 LEDs taken for the transmitter-receiver distance, from 30 to 60m taken at every 10m. In this case, we lump nine LEDs together in 3×3 array and all LEDs are ON. The diffusion of an LED affects to its neighboring LEDs.

From the figure, we confirm the increase of luminance values of the respective pixels of the LEDs due to the diffusion coming from their neighboring LEDs. We also see that the diffusion is rather large, and they are not symmetrically distributed.

B. Simplified LED diffusion model

From the observation of the LED diffusion, we obtain the following tendency:

- LED diffusion is limited to the surrounding pixels of the respective pixel of the LED
- LED diffusion takes rather small value compared to the luminance of the LED
- The distribution of the LED diffusion is not symmetrical

These suggests difficulty of deriving a complete mathematical representation of the diffusion and also difficulty of estimation of the diffusion. We, therefore, consider a simple mathematical representation of the diffusion by assuming that a) we limit the LED diffusion only to the surrounding pixels and b) LED diffusion are the same if the distance is the same and they are equally distributed.

Figure 5 shows the simplified LED diffusion model and its influence to neighboring pixels. Let h be the diffusion factor and p_0 be the luminance value of the pixel as shown Fig. 5. We assume that h is the same for all eight surrounding pixels. Since the distance to diagonal pixel is $\sqrt{2}$ longer than that to adjacent pixel, we multiply the diffusion factor of the diagonal pixels by $1/\sqrt{2}$. Note that this diffusion factor is caused not by a channel disturbance as in a RF channel but by the diffuseness of LED and the reduction in pixel size.

C. Interpixel Interference (IPI)

Figure 6 shows the focused LED at the center and the LED diffusions are coming from its neighboring LEDs. Let us define the interference as "interpixel interference (IPI)". As we mentioned before, the cause of the IPI is not like the inter-symbol interference (ISI) in RF channel, but we treat IPI as the ISI to represent the mathematical model.

If we define α_1 and α_2 as sets of diffusion factors of LED given by $\alpha_1 \subset (r-1,c),(r,c-1),(r,c+1),(r+1,c)$ and $\alpha_2 \subset (r-1,c-1),(r-1,c+1),(r+1,c-1),(r+1,c+1)$.

Then using the diffusion factors we rewrite Eq. (3) as

$$\begin{aligned} y_{IPI(r,c)}(t) &= x_{(r,c)}(t) + \sum_{(r_1,c_1)\in\alpha_1} hx_{(r_1,c_1)}(t) \\ &+ \sum_{(r_2,c_2)\in\alpha_2} \frac{h}{\sqrt{2}} x_{(r_2,c_2)}(t) + w_{(r,c)}(t). \end{aligned} \tag{7}$$

Here, the second and third terms of Eq. (7) are IPI components and $w_{(r,c)}(t)$ is shot noise from ambient light. When the ambient light has high intensity, the shot noise from the ambient light can be modeled as a white Gaussian noise.

We assume $w_{(r,c)}(t)$ as a white Gaussian noise process with a double-sided power spectral density $N_0/2$.

By substituting Eq. (7) into Eq. (6), we obtain the following:

$$\begin{aligned} p_{IPI(u,v)} &= \delta \int_0^{T_b} y_{IPI(r,c)}(t)\cdot l(t)dt \\ &= p_{(u,v)} + \sum_{(u_1,v_1)\in\beta_1} hp_{(u_1,v_1)} \\ &+ \sum_{(u_2,v_2)\in\beta_2} \frac{h}{\sqrt{2}} p_{(u_2,v_2)} + n_{(u,v)}, \end{aligned} \tag{8}$$

where β_1 and β_2 as sets of diffusion factors of pixel given by $\beta_1 \subset (u-1,v),(u,v-1),(u,v+1),(u+1,v)$ and $\beta_2 \subset (u-1,v-1),(u-1,v+1),(u+1,v-1),(u+1,v+1)$.

$p_{(u,v)}$ is given as

$$p_{(u,v)} = \delta \int_0^{T_b} y_{(r,c)}(t)\cdot l(t)dt \tag{9}$$

that is identical to Eq. (6) and $n_{(u,v)}$ is noise component denoted as the following:

$$n_{(u,v)} = \delta \int_0^{T_b} w_{(r,c)}(t)\cdot l(t)dt \tag{10}$$

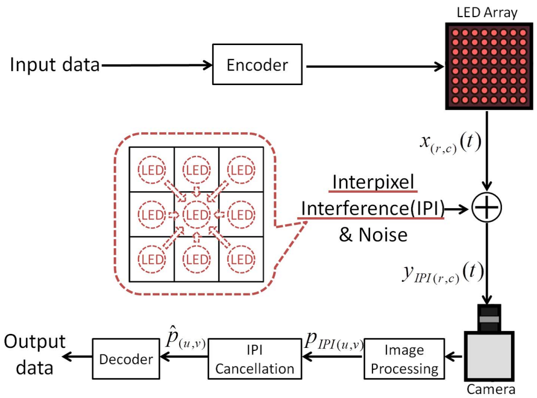


Fig. 7. The block diagram of the proposed IPI cancellation scheme.

TABLE I
EXPERIMENTAL PARAMETER.

	High rate data	Low rate data
Number of LED corresponded 1bit	2×2 LEDs	8×8 LEDs
Data Rate R_b	64kbps	2kbps
Error control code	Turbo code	Convolutional code
Code rate	1/2 (punctured)	1/2
Lightning frequency of LED	4kHz	
Camera model	FASTCAM-1280PCI made by Photron	
CMOS resolution	128x128	
Lens model	Ai Zoom Nikkor made by Nikon	
Selected shutter speed	1000fps	
Filter of a lens	Neutral Density 4 filter (ND4L filter)	
Focal length of a lens	35mm	
Focus of a lens	infinity	
Lens diaphragm	11	
Communication distance	30m-60m at intervals of 5m	

IV. IPI CANCELLATION SCHEME

Figure 7 shows a block diagram of the IPI cancellation scheme.

The CMOS image sensor outputs image. The output is fed to the image processing block. The image processing block that determines the pixel position of each of LED, u, v, outputs its luminance value, $p_{IPI(u,v)}$.

We treat the IPI as same as ISI in RF channel. The IPI cancellation block computes the IPI components and reduce them by a minimum mean square error (MMSE) criterion filter. The output $\hat{p}_{(u,v)}$ is finally fed to decoder to retrieve the original data.

A. IPI Cancellation

Let $\mathbf{P}_{IPI(u,v)}$ be the received pixel vector that interests u, vth pixel. The vector is sampled over IPI length whose length is nine. It is given by

$$\mathbf{P}_{IPI(u,v)} = (p_{IPI(u-1,v-1)}, \cdots, p_{IPI(u,v-1)}, p_{IPI(u,v)}, p_{IPI(u,v+1)}, \cdots, p_{IPI(u+1,v+1)})^T. \quad (11)$$

If we adopt MMSE criterion [6], then from Eq. (8), $\mathbf{P}_{IPI(u,v)}$ can be expressed by

$$\mathbf{P}_{IPI(u,v)} = \mathbf{H}\mathbf{P}_{(u,v)} + \mathbf{N}_{(u,v)}. \quad (12)$$

Where $\mathbf{P}_{(u,v)}$ be the vector representation of the pixel corresponding to $LED_{(r,c)}$ given by Eq. (6). It is becomes

$$\mathbf{P}_{(u,v)} = (p_{(u-2,v-2)}, \cdots, p_{(u,v-1)}, p_{(u,v)}, p_{(u,v+1)}, \cdots, p_{(u+2,v+2)})^T, \quad (13)$$

whose length is 25. $\mathbf{N}_{(u,v)}$ is noise vector and $\mathbf{H}$ is the diffusion factor matrix, whose size is 9×25.

If we describe the output of the MMSE criterion filter as $\hat{p}_{(u,v)}$, then we can write it as

$$\hat{p}_{(u,v)} = \mathbf{m}^T \mathbf{P}_{IPI(u,v)}, \quad (14)$$

where $\mathbf{m}$ is defined as the solution of

$$\mathbf{m} = \arg\min_{\mathbf{m}} \mathbb{E}\{||p_{(u,v)} - \mathbf{m}^T \mathbf{P}_{IPI(u,v)}||^2\}. \quad (15)$$

Fig. 8. Experimental eauipment (receiver): On-board High-speed camera.

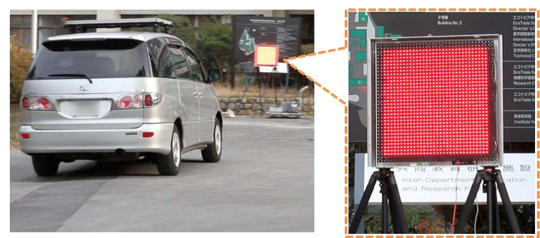


Fig. 9. Experimetal equipment (transmitter): LED array.

As a result, the weight vector $\mathbf{m}$ becomes

$$\mathbf{m} = [\mathbf{H}\mathbf{H}^T + \frac{N_0}{2}\mathbf{I}]^{-1}\mathbf{h}, \quad (16)$$

where $\mathbf{I}$ is a unit matrix and $\mathbf{h}$ is given by

$$\mathbf{h} = (\frac{h}{\sqrt{2}}, h, \frac{h}{\sqrt{2}}, h, 1, h, \frac{h}{\sqrt{2}}, h, \frac{h}{\sqrt{2}})^T.$$

Assuming that the diffusion factor h were known at the receiver, then we can suppress the IPI. We describe the detail of calculation $\mathbf{m}$ in the next chapter.

V. EXPERIMENTAL RESULTS

A. Experimental Setup

We conducted experiments to confirm the effectiveness of the proposed IPI cancellation method. Figures 8 and 9 show field trial instruments; the LED array transmitter and the high-speed camera. We set the high-speed camera on the dashboard of a vehicle. The transmitter LED array consists of 32×32 LEDs allocated in spacing of 15mm between each LED. The half-value angle of each LED is 22.6°.

Unfortunately, we have not obtained a method to estimate the channel factor h in a driving condition, we conducted the experiments on a static condition for distances from 30m to 60m, taken every 5m.

Table I summarizes the experimental parameters. In this experiment, we use ND4L filter as filter of a lens. The ND4L filter reduce the intensity of light to 1/4 of the original. By using ND4L filter, shot noise from ambient light becomes very small value. Thus, noise power spectral density becomes $\frac{N_0}{2} \approx 0$ and we rewrite Eq. (16) as

$$\mathbf{m} = [\mathbf{H}\mathbf{H}^T]^{-1}\mathbf{h}. \quad (17)$$

In following BER performance of IPI cancellation, we apply Eq. (17) as MMSE criterion filter described Eq. (14).

In this experiment, we also apply the overlay coding. The overlay coding allocates high rate data to the high spatial-frequency components, and low rate data to low spatial-frequency components [7]. Please refer to [7] for the detail.

We assign 2×2 LEDs to express one bit data of the high rate. For the low rate data, we assign the same one bit data to 8×8 LEDs. Compared with a low rate data, a high rate data is severally affected by IPI and degrade performance [7]. Thus, we evaluate the results of experiments by bit error rate (BER) of high rate data.

B. Experimental Results

1) Effect of channel factor: We can not determine optimal channel factor h by actual measurement. We, therefore, obtain h by turning on only one LED and measured its around luminance values as shown in Fig.3. Unfortunately, it is difficult to set an LED at a center of a pixel. In most cases, a captured LED diffuses across several pixels. Thus, we carried out several measurement varying the channel factor h and determine the optimal channel factor.

Figure 10 shows the BER performance of high rate data varying the channel factor h from 0.03 to 0.15. Note that in this figure, $h = 0.10 - 0.08$ achieves the same BER performance and they are the best in achieving the longest error free distance. While for $h < 0.08$ or $h > 0.10$, we observe degradation in BER.

2) Error-free distance comparison: Figure 11 shows the BER performances of the high rate data of the IPI cancellation along with the BER of the conventional scheme; without IPI cancellation. We set the channel factor to $h = 0.08$. Without the IPI cancellation, we confirm some errors for communication distance over 45m. We also confirm that once error occurs it severely affect the BER performance. With the IPI cancellation scheme, we can achieve the error-free data transmission for a distance up to 60m. We, therefore, confirm that the error-free range is 20m lengthened by applying the IPI cancellation.

VI. Conclusions

In this paper, we proposed the IPI cancellation scheme for the R2V-VLC system. As the results of the experiment, we extend the error-free distance from 40m to 60m by the IPI cancellation.

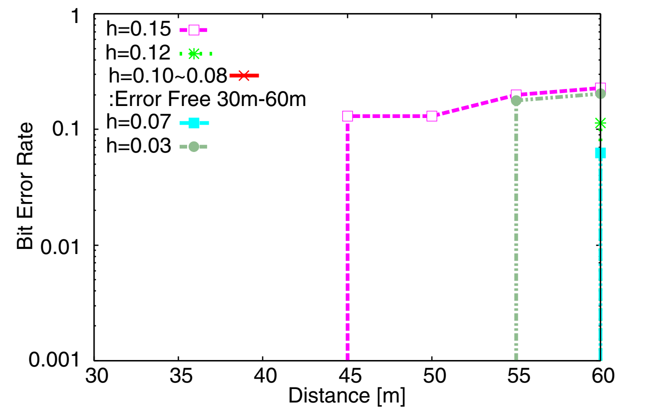


Fig. 10. BER performance of IPI cancellation scheme varying the channel factor h from 0.03 to 0.15.

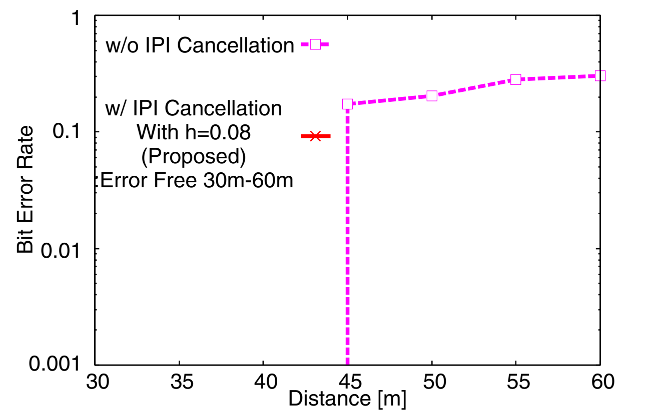


Fig. 11. BER performances of the high rate data with/without IPI cancellation.

Acknowledgment

This work is supported in part by KAKENHI (11007361). The authors would like to thank Prof. Masaaki Katayama and Dr. Kentaro Kobayashi have been illuminating this research.

References

[1] M. Akanegawa, Y. Tanaka, and M. Nakagawa, "Basic Study on Traffic Information System Using LED Traffic Lights", IEEE Trans. on Intelligent Transportation System, vol. 2, no. 4, pp. 197-203, Dec. 2001.

[2] T. Yamazato, S. Haruyama, "[Tutorial] Visible Light Communications", IEEE International Conference on Communications, Jun. 2011.

[3] G. Pang, C. Chan, and T.Kwan, "Positioning beacon system using digital camera and LEDs", IEEE Trans. Vehicular Technology, vol. 52, no. 2, pp, 406-419, Mar. 2003

[4] Y. Shiraki, T. Nagura, T. Yamazato, S. Arai, T. Yendo, T. Fujii, H. Okada, "Robust Receiver Design for Road-to-Vehicle Communication System Using LED Array and High-Speed Camera", 18th World Congress on Intelligent Transport Systems, Oct. 2011.

[5] H.C. N. Premachandra, T. Yendo, T. Yamazato, T. Fujii, M. Tanimoto, Y. Kimura, "Detecting and A LED Traffic Light for Visible Light Communication System", Proc of International Workshop on Advanced Image Technology, Jan. 2009.

[6] J. G. Proakis, M. Salehi, (2008) *Digital Communications*, McGrawHill.

[7] S. Nishimoto, T. Nagura, T. Yamazato, T. Yendo, T. Fujii, H. Okada and S. Arai, "Overlay Coding for Road-to-Vehicle Visible Light Communication using LED Array and High-Speed Camera", International IEEE Conference on Intelligent Transportation Systems, pp. 1704-1709, Oct. 2011.