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

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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.

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 $32 \times 32$ LED array and an encoder. Let $LED(r,c)$ be the LED position of $r$ row and $c$ column, where $r, c = 1, 2, \ldots, 32$. The encoder generate a non-negative rectangular pulse of duration $T_i$ and module the LED by changing its luminance. Here $T_i$ is the bit duration and
the data rate of one LED be \( R_b = 1/T_b \). The luminance of \( LED_{(r,c)} \) at time \( t \) is

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

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:

\[
g(t) = \begin{cases} 
1 & (0 \leq t \leq T_b) \\
0 & \text{(otherwise)}.
\end{cases}
\]

### 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 \( r, c \)th LED is

\[ y_{(r,c)}(t) = x_{(r,c)}(t). \]

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

\[
l(t) = \sum_i g_{sh}(t - (i - 1)T_b),
\]

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

\[
g_{sh}(t) = \begin{cases} 
1 & (0 \leq t \leq T_b) \\
0 & \text{(otherwise)}.
\end{cases}
\]

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

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

where \( \delta \) 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.
We assume that 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 \( \alpha_1 \) and \( \alpha_2 \) 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

\[
\begin{align*}
y_{IPI}(r,c)(t) &= x(r,c)(t) + \sum_{(r_1, c_1) \in \alpha_1} h x(r_1, c_1)(t) \\
&+ \sum_{(r_2, c_2) \in \alpha_2} \frac{h}{\sqrt{2}} x(r_2, c_2)(t) + w(r,c)(t).
\end{align*}
\]

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:

\[
\begin{align*}
P_{IPI}(u,v) &= \delta \int_0^{T_b} y_{IPI}(r,c)(t) \cdot l(t) dt \\
&= p(u,v) + \sum_{(u_1, v_1) \in \beta_1} h p(u_1, v_1) \\
&+ \sum_{(u_2, v_2) \in \beta_2} \frac{h}{\sqrt{2}} p(u_2, v_2) + n(u,v),
\end{align*}
\]

where \( \beta_1 \) and \( \beta_2 \) 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

\[
p(u,v) = \delta \int_0^{T_b} y(r,c)(t) \cdot l(t) dt
\]

that is identical to Eq. (6) and \( n(u,v) \) is noise component denoted as the following:

\[
n(u,v) = \delta \int_0^{T_b} w(r,c)(t) \cdot l(t) dt
\]
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 $\hat{p}_{IPI}(u,v)$ is finally fed to decoder to retrieve the original data.

A. IPI Cancellation

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

$$P_{IPI}(u,v) = (P_{IPI}(u-1,v-1), \ldots, P_{IPI}(u,v-1), P_{IPI}(u,v), P_{IPI}(u,v+1), \ldots, P_{IPI}(u+1,v+1))^T.$$  \hspace{1cm} (11)

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

$$P_{IPI}(u,v) = HP_{(u,v)} + N_{(u,v)},$$ \hspace{1cm} (12)

where $P_{(u,v)}$ be the vector representation of the pixel corresponding to $LED_{(r,c)}$ given by Eq. (6). It is becomes

$$P_{(u,v)} = (P_{(u-2,v-2)}, \ldots, P_{(u,v-1)}, P_{(u,v)}, P_{(u,v+1)}, \ldots, P_{(u+2,v+2)})^T,$$ \hspace{1cm} (13)

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

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

$$\hat{p}_{IPI}(u,v) = m^T P_{IPI}(u,v),$$ \hspace{1cm} (14)

where $m$ is defined as the solution of

$$m = \arg \min_{m} \mathbb{E} \{||p_{(u,v)} - m^T P_{IPI}(u,v)||^2\}.$$ \hspace{1cm} (15)

As a result, the weight vector $m$ becomes

$$m = [HH^T + N_0^2 I]^{-1} h,$$ \hspace{1cm} (16)

where $I$ is a unit matrix and $h$ is given by

$$h = (h N_0 / \sqrt{2}, h N_0 / \sqrt{2}, h N_0 / \sqrt{2}, h N_0 / \sqrt{2}, h N_0 / \sqrt{2}, h N_0 / \sqrt{2}, h N_0 / \sqrt{2}, h N_0 / \sqrt{2}, h N_0 / \sqrt{2})^T.$$ \hspace{1cm} (17)

Assuming that the diffusion factor $h$ were known at the receiver, then we can suppress the IPI. We describe the detail of calculation $m$ 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 $32 \times 32$ LEDs allocated in spacing of 15mm between each LED. The half-value angle of each LED is $22.6^\circ$.

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 $N_0^2 \approx 0$ and we rewrite Eq. (16) as

$$m = [HH^T]^{-1}h.$$  

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 $2 \times 2$ LEDs to express one bit data of the high rate. For the low rate data, we assign the same one bit data to $8 \times 8$ LEDs. Compared with a low rate data, a high rate data is severely 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.

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