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Interpixel Interference Mitigation in Visible Light Communication Using Image Sensor

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ABSTRACT To improve the data rate in a camera-based visible light communication system, multiple LEDs in an LED array are used to transmit multiple bits in one frame. The problem is that LEDs are always captured in the image with some degree of blooming effect. This effect increases the intensity of pixels surrounding the origin LEDs in the image. When multiple LEDs are used, the blooming effect from all LEDs causes the interpixel interference (IPI) problem that greatly degrades the quality of the received signal. This paper analyzes the blooming effect and finds that the IPI problem increases when the number of "ON" LEDs in the array increases. Through the analysis, this paper proposes a differential coding to minimize the number of "ON" LEDs in every transmitted frame and thus minimize the IPI effect. The proposed scheme is then verified through simulations. The results show that a lower bit error rate, which indicates a better signal quality, can be achieved by applying the proposed scheme.

INDEX TERMS VLC, LED, image sensor, differential coding, interference.

I. INTRODUCTION

Demand for telecommunication capacity has been rapidly increasing worldwide, with the available radio spectrum being limited. Therefore, visible light communication (VLC) technology has been considered as a future wireless communication technology. Compared to radio frequency (RF) communication, VLC has several advantages including wide bandwidth, unharmed environment, security, and high reuse capacity.

There are two types of receiver in a VLC system: photodiode and image sensor. Among the two, image sensor is a favorable choice thanks to many reasons. Cameras with the spatial separation capability can distinguish different light sources, and thus eliminate the interference between transmitters as well as the noise from ambient light sources. Camera also facilitates the positioning function. Because of these reasons, VLC using image sensors has attracted a significant amount of attention from many researchers [1]–[6].

In a camera based VLC system, to improve the data rate, an LED array which consists of multiple LED chips would be used instead of a single LED chip. By using LED array, multiple bits can be transmitted in one frame. However, using multiple LEDs also raises a challenge, that is interpixel interference (IPI).

Basically, regardless of the types of camera used as a receiver, LEDs are always captured in the images with some degrees of blooming effect. This effect increases the intensity of pixels surrounding the origin LEDs in the image. When using multiple LEDs, the blooming effect from one LED affects the intensity of pixel surrounding the LEDs and results in the IPI effect. Because of IPI effect, the status of "ON" or "OFF" of LEDs would be more difficult to be determined and thus the BER of the received signal would increase [7]–[12]. In [7], Kasashima *et al.* eliminated the blooming effect by processing the acquired image based on the estimated blooming coefficient. However, the blooming coefficient depends on the many environmental parameters, which are subject to change at all times. In [8]–[10], a mathematical method, namely the second order polynomial fitting, was used to reduce the blooming. This method is suitable for short communication distances. In [12], the blooming effect is reduced by changing the exposure setting of the camera. However, this approach has negative impacts on the signal quality.

In this paper, the IPI effect is mathematically analyzed. Based on the analysis, it is found that the IPI effect is dependent on the number of "ON" LEDs in the array. More specially, the more number of "ON" LEDs in the array, the higher impact of IPI effect on the received signal. To address this problem, a differential coding is proposed to minimize the number of "ON" LEDs in every transmitted frame. The proposed scheme utilizes the differences in the consecutive bit streams to encode the current bit stream. The encoded bit stream would require less number of "ON" LEDs in the array and thus the BER of the received signal can be improved without sacrificing the data rate. The structure of the paper is as follows. Section II provides an overview of the camera based VLC system. In Section III, the concept of the blooming effect is given, and its influence is also analyzed. Section IV introduces the IPI effect mitigation scheme. The simulation results are discussed in Section VI. Finally, a summary is provided in section VII.

II. SYSTEM MODEL AND BLOOMING EFFECT

A. SYSTEM ARCHITECTURE

The system architecture is considered in this paper is illustrated in Fig. 1. A $m \times n$ LED array is used to transmit optical signal which will be received by a high-speed camera. The input data is encoded by the encoder and then given to the LED driver which regulates the power to the LED array. Each LED in the array will blink in a specific way depending on the power regulated by the driver. The blinking of LEDs results in the two statuses: On or Off of LEDs in the LED array image captured by the high-speed camera. Image processing techniques are used to determine the status of LEDs in the array. The On or Off status of each LED in the captured image is then translated into the logical bit 0 or 1 using the decoder.

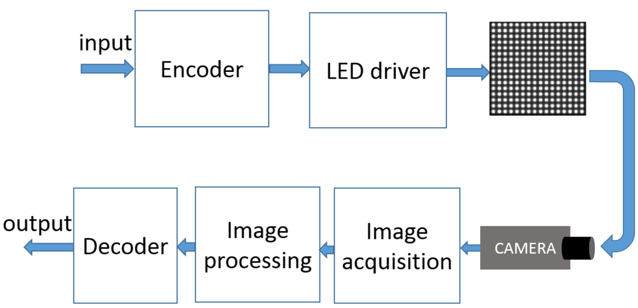

FIGURE 1. System architecture model.

B. TRANSMITTER

Assuming that each LED in the array is used to transmit a single bit, a transmitted bit is denoted by $x_{r,c}(t) = [0, 1]$, where $r = 1, 2, \ldots, m$ and $c = 1, 2, \ldots, n$ are the row and column index, respectively. Assuming that NRZ-OOK modulation technique is used to modulate the optical signal with pulse duration of T, the transmitted optical power is given as:

$$X_{r,c}(t) = x_{r,c} \times u(t). \tag{1}$$

Let P is the power delivered to the LED, the pulse function is given as follows:

$$u(t) = \begin{cases} P, & 0 \leq t \leq T; \\ 0, & Otherwise. \end{cases} \tag{2}$$

C. RECEIVER

The optical power received from a single LED is given as:

$$Y_{R,C}(t) = \theta X_{r,c}(t) + N_{R,C}, \tag{3}$$

where R, C are the pixel coordinates corresponding to the LED position (r, c) in the array, θ is the environmental gain determined by the weather condition, and $N_{R,C}$ is the noise caused by ambient light. It is assumed in this paper that the weather has no impact on the channel and thus $\theta = 1$.

It is assumed that a perfect synchronization between camera and LEDs is achieved. Then, the pixel value of the LED in the image (i.e. the received signal) is calculated from the received optical power and the exposure time as [13]:

$$Y_{PV_{R,C}} = 118 \times 2^{ED(Y_{R,C}, t_H)/\gamma}, \tag{4}$$

where $Y_{PV_{R,C}}$ is the pixel value of the LED in the image, $Y_{R,C}$ is the received optical power, t_H is the exposure time of the camera, $ED(Y_{R,C}, t_H)$ is function of the exposure difference, and γ is the gamma encoding value, which is a given hardware parameter determined by camera manufactures. Note that exposure difference is the difference between two kinds of exposure value. The first kind of exposure value is called indicated exposure value, which represents the required camera exposure setting to yield a middle gray image of LED. In an 8-bit color image, the middle gray image has the pixel value of 118 while the maximum pixel value is 255. The second kind of exposure value is called set exposure value, which represents the current camera exposure setting. Based on the exposure difference, the pixel value of the LED can be calculated.

III. BLOOMING EFFECT AND IPI EFFECT

A. BLOOMING EFFECT

This section describes the influence of the blooming effect on the pixel value. In practice, blooming effect always happens with some degrees in the captured image. The degree of blooming effect is dependent on the quality of the lens and especially the camera exposure setting. An image sensor is basically a two dimensional array of photodiodes (that are pixels) which convert the received photons to an electrical charge. Each photodiode in a sensor has a limitation of how much electrical charge can be held. When the camera setting is overexposure, photodiodes in the area of the sensor corresponding to the LED would receive too many photons and the excess electrical charge in these photodiodes would overflow to surrounding photodiodes and cause the blooming effect. The more overexposure of the camera setting, the higher level of the blooming effect. In addition, the level of the blooming effect also proportionally increases with the size of the LED in the captured image.

The blooming effect is illustrated in Fig. 2. The left and right figures are the two images of the same LED with different blooming effect level. The blooming effect level in the right image is higher because this image was captured with higher level of overexposure. It can be seen through

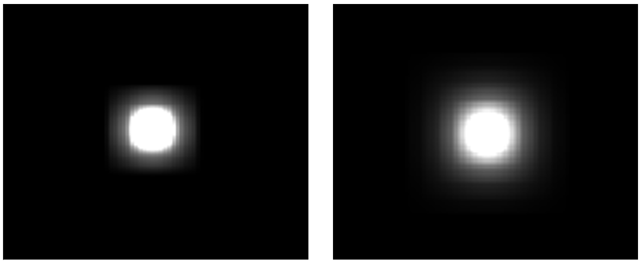

FIGURE 2. Captured images with different blooming effect levels.

Fig. 2 that the blooming effect increases the intensity of pixels surrounding the origin LEDs. Therefore, the region surrounding the LED in the right image is affected by the blooming effect more than that of the left image.

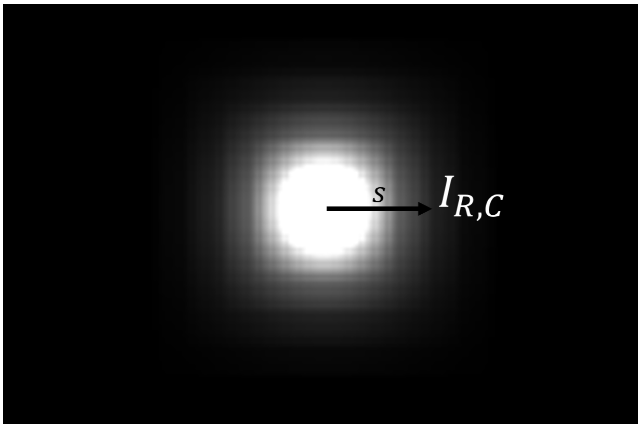

FIGURE 3. Blooming effect on a pixel at a given distance.

More importantly, Fig. 2 implies that the impact of the blooming effect on a pixel decreases as the inter-distance between that specific pixel and the origin LED in the image increases. Given a pixel which has the distance s to the LED center as illustrated in Fig. 3, the interpixel interference caused by the LED at this pixel is given as:

$$I_{R,C}(t) = \frac{\sigma}{s} Y_{R,C}(t), \tag{5}$$

where σ is the blooming coefficient.

B. INTERPIXEL INTERFERENCE EFFECT

To increase the data rate for the communication, multiple LEDs are installed in the array to transmit multiple bits per frame. The presence of multiple LEDs in the captured image combined with the blooming effect results in the phenomenon called interpixel interference (IPI). Let I_α, I_β indicate the interpixel interference caused by adjacent LEDs at $\alpha \in (R-1, C-1), (R-1, C+1), (R+1, C-1), (R+1, C+1)$, and $\beta \in (R-1, C), (R, C-1), (R, C+1), (R+1, C)$, respectively as shown in Fig. 4. The IPI effect E_{IPI}, defined as the total interpixel interference caused by all surrounding LEDs at a given pixel, is calculated as:

$$E_{IPI} = \frac{\sigma}{\sqrt{2}s}\sum_{\alpha} I_\alpha + \frac{\sigma}{s}\sum_{\beta} I_\beta. \tag{6}$$

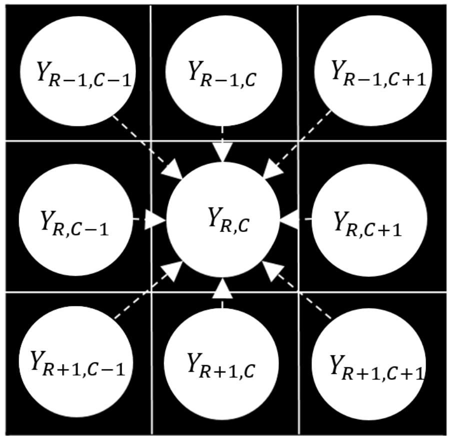

FIGURE 4. Interpixel interference.

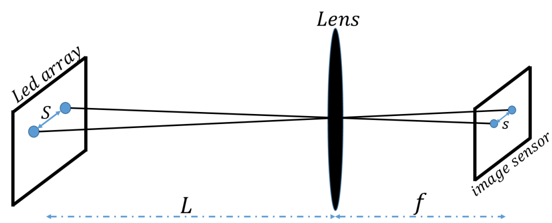

FIGURE 5. Light-of-sight channel model of VLC system using image sensor and LED.

The simple channel model is shown in Fig. 5. The relationship between the distance between LEDs in the image sensor s and the distance between LEDs in the LED array S is given as follow:

$$\frac{S}{s} = \frac{L}{f}, \tag{7}$$

where S, s are the distances between two LEDs in the LED array and in the image sensor, respectively, and L, f are the communication distance and focal length of the camera, respectively. From Eq. (6) and Eq. (7), the IPI effect is given as:

$$E_{IPI} = \frac{\sigma L}{\sqrt{2}Sf}\sum_{\alpha} I_\alpha + \frac{\sigma L}{Sf}\sum_{\beta} I_\beta. \tag{8}$$

Through Eq. (8), it can be seen that the IPI effect is determined by four factors: the blooming coefficient σ, the distance S between LEDs, the communication distance L, and the number of "ON" LEDs in the array. More specifically, the IPI effect increases when the blooming coefficient, communication distance, and the number of "ON" LEDs increase while it decreases when the distance between LEDs increases. The Fig. 6(a) and 6(b) demonstrate the impact of blooming effect on the BER corresponding to different blooming effect levels and different intervals between LEDs in the array. The distance between the LED array and the camera and the focal length of the lens are assumed to be 50m and 35mm, respectively.

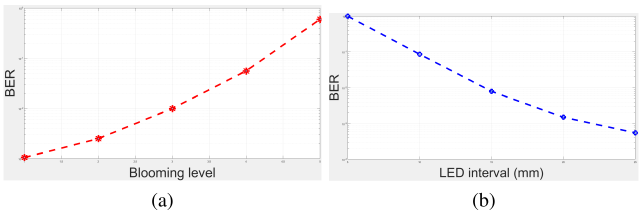

FIGURE 6. BER evaluation at communication range of 50m by changing (a) the blooming level (b) LED interval.

By considering the IPI effect, the received signal is given as:

$$\hat{Y}_{R,C}(t) = Y_{R,C}(t) + E_{IPI}. \tag{9}$$

Pixel value of received signal under IPI effect is given as:

$$Y_{PV_{R,C}} = 118 \times 2^{ED(\hat{Y}_{R,C},t_H)/\gamma}. \tag{10}$$

IV. PROPOSED DIFFERENTIAL CODING

A. PRINCIPLE OF THE PROPOSED DIFFERENTIAL CODING

From Eq. (8), it can be seen that in order to reduce the IPI effect, the presences of I_α and I_β must be reduced as many as possible. As a result, the main idea of the proposed differential coding to deal with the IPI effect is to reduce the number of the "ON" LEDs in one frame. Assuming that the binary bit 1 is represented by a "ON" LED, a bit stream would be encoded by the proposed differential coding to reduce the number of bit 1s and thus the transmitted frame would have fewer number of "ON" LEDs. The mechanism of the proposed differential coding is shown in Fig. 7. The current bit stream is compared with a previous bit stream to calculate the hamming distance (HD) between the two bit streams using XOR operation. Depending on the HD value, the encoded bit stream which has fewer number of bit 1s will be transmitted.

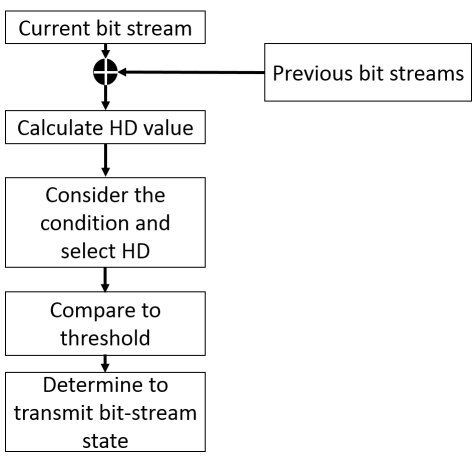

FIGURE 7. Flowchart of the proposed scheme.

B. SIMPLE VERSION OF THE PROPOSED DIFFERENTIAL CODING

The input bit streams are arranged into a $m \times n$ matrix before applying differential coding. First, the hamming distance (HD) between the current bit stream $x_{r,c}(t)$ at current time t and the previous bit stream $x_{r,c}(t-1)$ is computed as:

$$HD = sum(a_{r,c}(1)), \tag{11}$$

where $a_{r,c}(1)$ is the result of XOR operation given as:

$$a_{r,c}(1) = x_{r,c}(t) \oplus x_{r,c}(t-1), \tag{12}$$

where $\oplus$ denote the XOR operation.

HD value is the number of different bits between the current bit stream and the previous bit stream. The calculated HD value is then compared to a threshold, which equals to half of the number of bits in the bit stream. Depending on the result of the comparison, the encoded bit stream which will be transmitted is given as:

$$\hat{x}_{r,c}(t) = \begin{cases} a_{r,c}(t), & \text{for } HD < \dfrac{m \times n}{2}, \\ \overline{a_{r,c}(t)}, & Otherwise. \end{cases} \tag{13}$$

The meaning of Eq. (13) is that when the number of different bits between the current bit stream and the previous bit stream is less than half of the number of bits in the bit stream, only the difference, which is defined as the set of different bits, are transmitted. When the number of identical bits between the two bit streams is less than half of the number of bits in the bit stream, only the similarity, which is defined as the set of identical bits, are transmitted. Consequently, the number of bit 1s in the transmitted bit stream is always less than 50% of the total number of bits in the bit stream.

Although the simple version of the proposed coding guarantees that the encoded bit streams always has less number of bit 1s compared to the original bit streams, the effectiveness of this version is just as high as the simpler flipping coding. In the flipping coding, the number of bit 1s and the number of bit 0 in the bit stream are compared to each other. If there is less bit 1, the bit stream is transmitted as it is. If there is more bit 1, the bit stream if flipped before transmitted to ensure that the number of bit 1s in the transmitted bit is less than 50% of the total number of bits.

The reason for using the proposed differential coding instead of the simpler flipping coding is that the effectiveness of the differential coding can be improved significantly by using more previous reference frames. This mechanism will be described in the following section.

C. PROPOSED DIFFERENTIAL CODING WITH MULTIPLE PREVIOUS REFERENCE FRAMES

To reduce the number of "ON" LEDs in current frames, the current bit stream is compared to not only the bit stream in the very previous frame but also multiple bit streams in previous reference frames to calculate HD values. Let HD_i denote the hamming distance between the current bit stream and the bit stream in the $i-th$ previous frame. The value of HD_i is given as:

$$HD_i = sum(a_{r,c}(i)), \tag{14}$$

where $a_{r,c}(i)$ is the result of the XOR operation between the current bit stream $x_{r,c}(t)$ and the bit stream $x_{r,c}(t-i)$ in the *i-th* previous reference frame:

$$a_{r,c}(i) = x_{r,c}(t) \oplus x_{r,c}(t-i), \tag{15}$$

where $\oplus$ denote the XOR operation.

Note that from each XOR result $a_{r,c}(i)$, a difference $a_{r,c}(i)$ and a similarity $\overline{a_{r,c}(i)}$ are obtained. By comparing the number of bit 1s in obtained differences and similarities, either a specific difference or a specific similarity which has the lowest number of bit 1s is transmitted.

Assume that the XOR result $a_{r,c}(i_L)$ between the current bit stream and the previous $i_L - th$ bit stream has the lowest HD value, which is denoted as HD_L. The number of bit 1s in the difference $a_{r,c}(i_L)$ is HD_L. Therefore, among all differences, $a_{r,c}(i_L)$ has the lowest number of bit 1s.

Assume that the XOR result $a_{r,c}(i_H)$ between the current bit stream and the previous $i_H - th$ bit stream has the highest HD value, which is denoted as HD_H. The number of bit 1s in the similarity $\overline{a_{r,c}(i_H)}$ is $m \times n - HD_H$. Therefore, among all similarities, $\overline{a_{r,c}(i_H)}$ has the lowest number of bit 1s.

From the above observations, the lowest number of bit 1s among all differences is HD_L and the lowest number of bit 1s among all similarities is $m \times n - HD_H$. Therefore, the transmitted bit stream which has the lowest number of bit 1s is determined as:

$$\hat{x}_{r,c}(t) = \begin{cases} a_{r,c}(i_L), & \text{for } HD_L < m \times n - HD_H, \\ \overline{a_{r,c}(i_H)} & \text{for } HD_L \geq m \times n - HD_H. \end{cases} \tag{16}$$

From Eq. (16), when $HD_L < m \times n - HD_H$, the difference $a_{r,c}(i_L)$ will be transmitted. When $HD_L \geq m \times n - HD_H$, the similarity $\overline{a_{r,c}(i_H)}$ will be transmitted. This mechanism guarantees the minimum number of bit 1s being transmitted in every frame to reduce the IPI effect.

Note that when the number of reference frames is more than 1, the information which indicates the index i of the previous reference frame and the status of the transmitted bit stream, which is the similarity or the difference, needs to be transmitted along with the data in the current frame for decoding.

D. DATA FRAME STRUCTURE

The information payload is illustrated in Fig. 8. Specifically, this includes 39 preambles and 1000 frames of data. The preamble utilizes the Barker sequence to make it easy to detect and track the LED array movement. In addition, the preamble includes the white and black frames which are transmitted. After acquiring frames, the pixel values are then averaged as a threshold to determine status "ON" or "OFF" of the LEDs. The status of LED is then translated to the bit value of "0" or "1". Moreover, the preambles is transmitted periodically so that the threshold can be updated with the environmental changes.

E. RECEIVER DECISION

The bit value of each LED in the received image is determined by comparing the received pixel value to a threshold I_{th}, which is obtained through processing the Barker sequence.

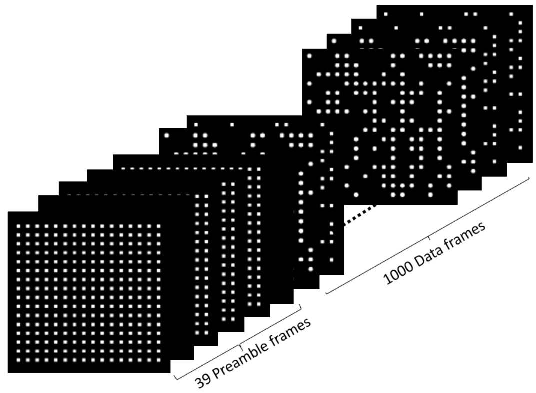

FIGURE 8. The frame structure of data.

The value of the decoded bit $\dot{x}_{r,c}$ is given as followed:

$$\dot{x}_{r,c} = \begin{cases} 1, & \text{if } Y_{PV_{R,C}} \geq I_{th}, \\ 0, & \text{if } Y_{PV_{R,C}} < I_{th}, \end{cases} \tag{17}$$

where $Y_{PV_{R,C}}$ is the received pixel value of each LED and $I_{th}$is the threshold calculated as the average gray-scale value of the "ON" LED during the preamble frame:

$$I_{th} = \frac{1}{27 \times m \times n} \sum_{k \in W} \sum_{R=1}^{m} \sum_{C=1}^{n} Y^k_{PV_{R,C}}, \tag{18}$$

where $n \times m$ is matrix size, $W = \{1, 2, 3, 4, 5, 8, 9, 11, 13, 14, 15, 16, 17, 18, 21, 22, 24, 26, 27, 28, 29, 30, 31, 34, 35, 37, 39\}$ is the set of white frames inside the Barker sequence, and $Y^k_{PV_{R,C}}$ is the received pixel value of LED on k^{th} white frame in W.

Based on the obtained information which indicates the transmitted bit stream is the difference or similarity, the state of $\widetilde{a}_{r,c}$ is given as:

$$\widetilde{a}_{r,c}(t) = \begin{cases} \dot{x}_{r,c}(t), & \text{if difference}, \\ \overline{\dot{x}_{r,c}(t)}, & \text{if similarity}. \end{cases} \tag{19}$$

Assuming that the index of compared-frame was known at the receiver side, the output data can be obtained by XOR operations again:

$$\widetilde{x}_{r,c}(t) = \widetilde{a}_{r,c}(t) \oplus \widetilde{x}_{r,c}(t-i). \tag{20}$$

The cumulative error must be considered in case of using differential coding. At the receiver side, after decoding the received image and obtaining the output bit stream, the HD value is calculated again to compare with the transmitted HD value. Any difference between the two HD values indicates errors in the transmission, and the current frame needs to be transmitted again.

V. SIMULATION

A. SIMULATION ENVIRONMENT AND REPLICATION METHOD

1) SIMULATION ENVIRONMENT

The simulation was conducted using MATLAB version R2017a. All simulation parameters are listed

TABLE 1. High-speed camera parameter.

Sensor	Complementary Metal-Oxide-Semiconductor(CMOS)
Resolution	1280x960
Pixel size	$36 \times 10^{-5} \times 24 \times 10^{-5} m^2$
Readout time	0.015sec
Exposure time	1/3000sec
Focal length	35mm
ISO	100

TABLE 2. Transmitter parameter.

LED array	16x16
LED interval	15mm
Gross data rate	256kbps
Net data rate	246.391kbps
Error correction code	Convolution code
Luminous intensity	6000mdc
Modulation	NRZ-OOK

in Table 1 and Table 2. Differential coding is applied to examine the proposed IPI effect mitigation. In the manuscript, an LED array with 256 LED chips is used. Each LED can transmit one bit in a frame. The frame rate of the camera is 1000 fps. Given the synchronization between the camera and LED can be achieved through existing video camera wireless synchronization mechanisms [14], [15], the gross data rate of the system is 256 kbps. By excluding 39 preambles, the net data rate of the system is $^{1000}/_{1039} \times 256 = 246.391$ kbps. The communication distance ranges from 20m to 70m. In every frame, a bit stream of 256 bits is randomly generated. The uniform random is used to generate each bit. To verify the effectiveness of the proposed scheme, the performances of three variations of the system are compared. These three variations include the original system without any scheme, the system with flipping scheme, and the system with the proposed differential coding scheme.

2) SIMULATION REPLICATION METHOD

The simulation replication is illustrated in Fig. 9. At transmitter side, an original 256-bits stream have generated randomly. Then, this bit stream will be encoded using the proposed coding scheme. The encoding process would require previous bit streams, which are stored in the memory of the transmitter. The encoded bit stream is then modulated by OOK modulation with certain transmitted optical power of the LEDs. Then, the original 256-bit stream will be stored in the memory of the transmitter as a previous bit stream for encoding the next bit streams.

At the receiver side, based on the pinhole camera model [16], the process of image capturing of the LED array is replicated to generate an image of LED array. The blooming effect on this generated LED array image is replicated using Gaussian blur function. The blooming effect level is controlled by changing the blooming coefficient σ. After that, in the demodulation step, the generated image with blooming effect of LED array is processed to obtain a bit stream. This bit stream is then decoded using the proposed coding scheme

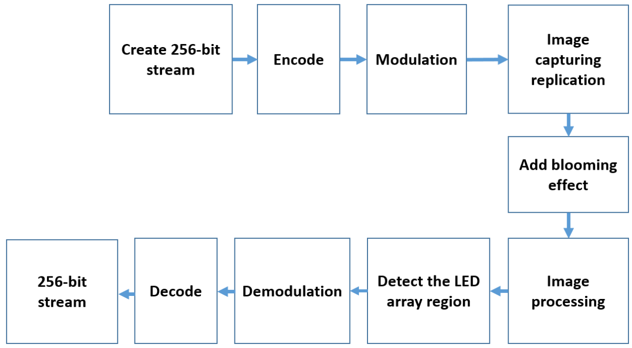

FIGURE 9. Simulation replication.

to obtain the original bit stream. This original bit stream is then stored in the memory of the receiver for decoding the next bit streams.

Initially, there is no previous bit stream at the transmitter and receiver. Therefore, the very first 256-bits stream is transmitted without encoding and also received without decoding.

B. SIMULATION RESULTS AND DISCUSSION

1) NUMBER OF PREVIOUS REFERENCE FRAMES

The value of HD which is under 30% is considered good enough for reducing the IPI effect. It is obvious that the more number of reference frames, the higher probability to get a HD value under 30%. Figure 10 shows the probability of getting a HD value under 30% corresponding to different number of reference frames. With 15 reference frames, the probability to get a HD value under 30% is 95%. A number of reference frames greater than 15 only results in a small increase in the probability. Therefore, the differential coding with 15 reference frames is used in the simulation to achieve a good performance in terms of IPI effect reduction while maintaining the computational cost in a reasonable level.

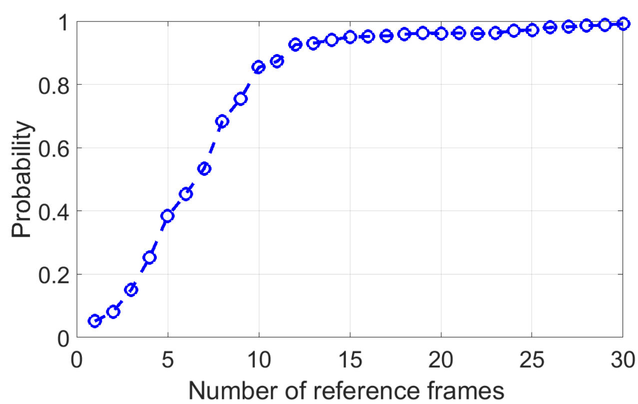

FIGURE 10. The probability of getting a HD value under 30% corresponding to different numbers of reference frames.

From Eq. (8), besides the number of "ON" LEDs in the panel, the IPI effect is dependent on three parameters:

the adjacent LED intensity, blooming coefficient, and LED interval. Although the number of "ON" LEDs in the panel is reduced thanks to the proposed scheme, the system performance with the proposed scheme applied is still affected by three other parameters. Therefore, the performance of the proposed scheme is investigated with different values of these parameters. When the effect of a specific parameter is examined, the value of that parameter will vary within a specific range while the values of other two parameters are fixed. The default values for the LED interval, blooming coefficient, and communication distance are 15mm, 3, and 50m, respectively.

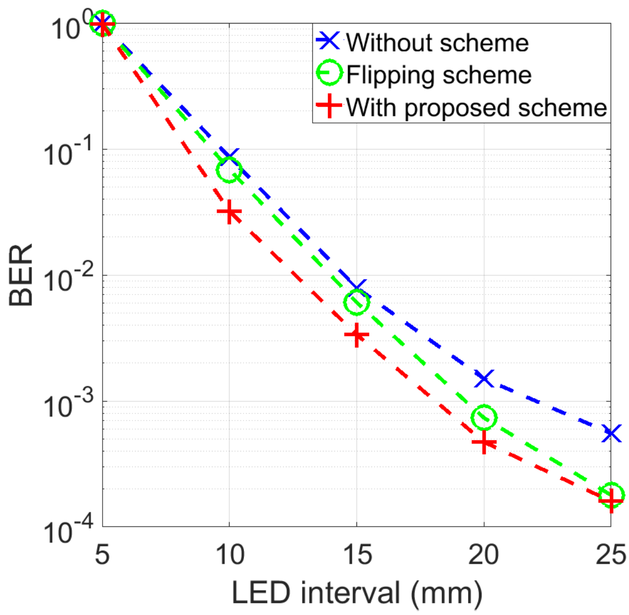

FIGURE 11. **BER performance corresponding to different LED intervals.**

2) THE IMPACT OF LED INTERVAL

Figure 11 shows the BER corresponding to the interval between LEDs in the array ranging from 5 to 25 millimeters. The BER of the signal with and without the proposed scheme all decrease as the LED interval increases. This is because the impact of IPI effect decreases as the LED interval increases. The result shown in this figure also proved that the BER of the received signal is always lower when the proposed scheme is applied. Also, it can be seen that the BER decreases when the simple flipping scheme is applied but the effectiveness of the flipping scheme is lower than that of the proposed scheme.

In practice, there is always a limit to which the size of the transmitter can be. Also, a more compact transmitter would be desirable in most systems. Therefore, increasing the interval between LEDs would not be the solution to deal with IPI effect. By applying the proposed scheme, the system can achieve a good signal quality while keeping the transmitter at a reasonable size.

3) THE IMPACT OF BLOOMING EFFECT LEVEL

The BERs of the received signals corresponding to different blooming effect level are shown in Fig. 12. In this simulation, the blooming effect is replicated using the Gaussian Blur function in Matlab. This function has two inputs: the original LED image and a scalar value σ. The blooming effect level is controlled by changing the value of σ.

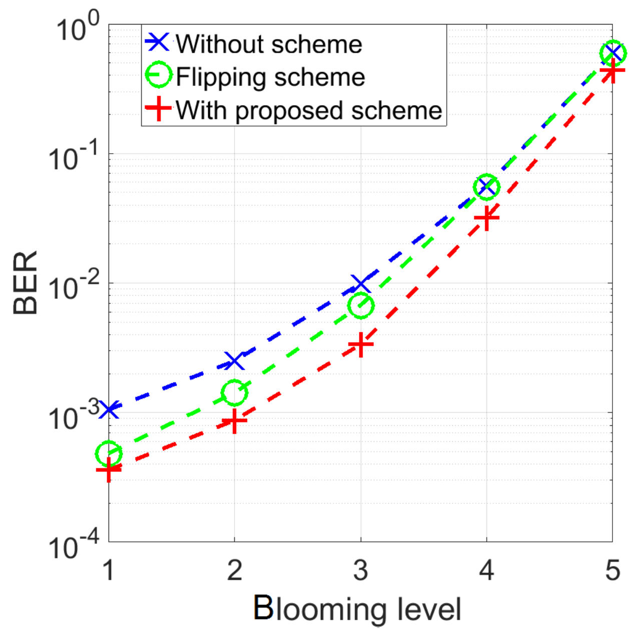

FIGURE 12. **BER performance corresponding to different blooming levels.**

The BERs of the received signals with and without the proposed scheme all increase as the blooming effect level increases. Also, at all levels of blooming effect, the BER of the received signal with the proposed scheme applied is always lower than that without the proposed scheme. It can also be seen that the effectiveness of the flipping scheme is lower than that of the proposed scheme at all blooming effect levels. Even though the BER can be reduced with lower blooming effect level, the blooming effect level is indeed not easy to control. In case the blooming effect level goes out of control, the proposed scheme can help the system keep the lower BER.

Regarding the comparison between the proposed scheme and the existing scheme [7], these two schemes have completely different directions to solve the blooming effect. After receiving the LED image, the existing scheme reduces the blooming effect by shrinking the blooming region around the detected LEDs. However, the inter-pixel interference caused by blooming effect is problematic only when there are many "ON" LEDs in the LED array. Therefore, the proposed scheme reduces the blooming effect by reducing the number of "ON" before the LED array is transmitted. In other words, the proposed scheme and the existing scheme work at different stages in the system. The former works at the transmitting stage while the later at the receiving stage. Therefore, both schemes can be considered complements of each other. After applying the proposed scheme at the transmitter side, the existing scheme can be applied at the receiver side to further reduce the blooming effect. In terms of performance, although the existing scheme gets better result than proposed scheme in normal level of blooming effect, the proposed scheme would outperform the existing scheme in high blooming effect levels.

4) THE IMPACT OF COMMUNICATION DISTANCE

The BERs of the signals received at different communication distances are shown in Fig. 13. In this simulation, the communication distance ranges from 20m to 70m. In principle, when the communication distance increases, the IPI effect increases as discussed previously and thus explains the increase of BER. At close distance (from 20m to 40m), the BERs of the signal with and without the proposed scheme are very low. After the communication distance exceeds 40m, the BERs of the received signal greatly increase as the communication distance increases. Also, applying the proposed scheme always results in the lowest BER of the received signal compared to the case of without any scheme and with the flipping scheme.

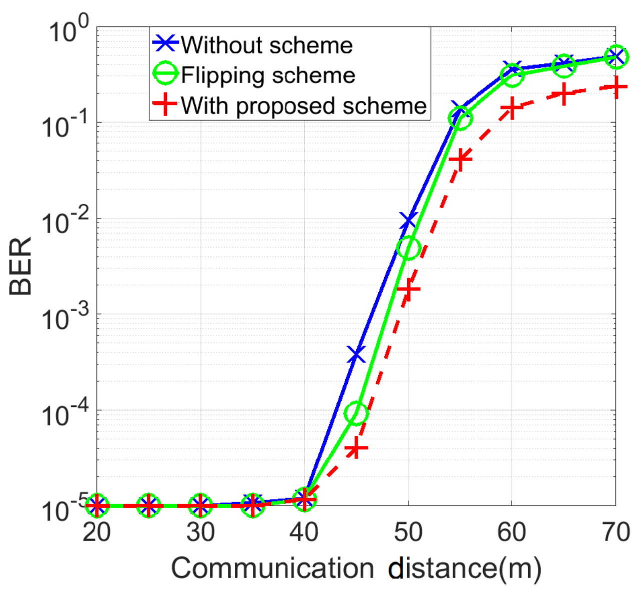

FIGURE 13. BER at different communication range.

In practice, the communication coverage of a system is usually defined in terms of the maximum range at which the BER is still lower than a specific threshold. Since the proposed scheme helps reducing the BER at all communication distance, it can be stated that the communication coverage of camera based VLC system can be extended by applying the proposed scheme.

VI. CONCLUSION

IPI effect is a challenging issue for camera based VLC. This phenomenon is a result of many elements, including a high intensity of the LEDs, the image sensor design, and the communication environment. This paper analyzed the factors that directly determines IPI effect. Through the analysis, the differential coding is proposed to reduce the IPI effect to achieve a better signal quality. Basically, the IPI effect increases when the number of "ON" LEDs in the array increases. The proposed scheme calculates the hamming distance between the current frame and previous reference frames. After obtaining the hamming distance, the input data is encoded in a way that the number of "ON" LEDs is minimized and thus the IPI effect is also minimized. The proposed scheme is then verified through simulations. The simulation results show that the proposed scheme can effectively reduce the IPI effect and improve the quality of the received signal. In the maximum case, applying the proposed scheme reduces the BER of the received signal to 30% as compared to that without the proposed scheme. In average, the performance gain of proposed scheme is 15%.

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