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Multiple Exposure Coding for Short and Long Dual Transmission in Vehicle Optical Camera Communication

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ABSTRACT In vehicle optical camera communication (VOCC), LED lamps in a vehicle are used to transmit an optical signal that will be received by cameras attached in another vehicle. Although having many advantages, VOCC also has one drawback: in long-distance communication, transmitters are required to have low spatial frequencies to improve signal quality. However, for short-distance communication, the transmitters need to have high spatial frequencies to improve the data rate. To solve this problem, this paper proposes a multiple exposure-based overlay coding which allows both low and high spatial frequency signals to be transmitted in the same transmitter at the same time. Two cameras with exposure times set at different levels are used to receive the two kinds of signal. Consequently, the high signal quality of the long-distance communication and high data rate of the short-distance communication can be achieved simultaneously. The performance of the proposed coding is analyzed mathematically and then verified through simulations.

INDEX TERMS Optical camera communication, visible light, vehicle, overlay coding.

I. INTRODUCTION

Vehicle to Vehicle (V2V) communication is the technology that allows vehicles in transit to communicate to each other over direct or indirect links. Vehicles benefit a lot from this type of communication. For example, vehicles can send information related to position, speed, lane departure, braking, and other emergency warnings to one another to prevent accidents and improve traffic management. It is this technology that will enable autonomous driving cars to be really deployed and will become essential part of any transportation system in the near future [1].

There has been a substantial amount of research trying to use radio frequency (RF) signal for V2V communication over the years but many problems remain unsolved. In recent years, an emerging technique named optical camera communication (OCC) has been developed and promised to replace RF for short range communication. This technique works on the basis that LEDs transmit visible light signal that will be received by cameras with image sensors [2]–[6]. OCC has a great potentiality to be used in V2V communication thanks to many advantages. With the front, tail LED lamps, and especially daytime running light (DRL) available in any vehicle and high quality dashboard cameras which are increasingly present in vehicles, transmitting and receiving OCC signal between vehicles can be done with the implementation of some additional hardware such as LED driver circuit and camera synchronization unit. Besides the availability of hardware, the spectrum for OCC is always free to use and thus an international standard for V2V communication using OCC can be made to leverage the concern related to interference between vehicle and non-vehicle communication. The interference between vehicles, which is the major problem when using RF communication, can also be solved thanks to the line of sight (LOS) transmission of OCC and the spatial separation capability of the cameras used as receivers in OCC. The uses of cameras in OCC also bring another great advantage of OCC: the inherent capability of determining the position of the signal sources [7], which is the essential information for safety application and especially sophisticated application like cooperative driving vehicle.

That being said, OCC is not without drawbacks for using in V2V communication. One of the most noticeable drawbacks is related to the great dependency of the spatial frequency of

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the transmitter on the communication range in OCC. More specifically, to have the LEDs distinguishable in the image, the LED panel must have a certain degree of spatial frequency depending on the communication distance. At short distances, LEDs can be distinguished easily and hence a high spatial frequency would be used for the LED panel to improve the data rate. However, at long distances, the LED panel must have a low spatial frequency to improve the bit error rate.

To solve the dilemma in the spatial frequency of LED panel in vehicle optical camera communication (VOCC), Nishimoto *et al.* [8] proposed a simple overlay coding which allows the high and low spatial frequency signals used for the short and long distance communication to be overlaid and simultaneously transmitted from the same LED panel. However, because the two data streams are overlaid directly without any special mechanism, the received signal consists of 4 levels, which makes it difficult for the detection. This paper proposes a multiple exposure based overlay coding in which two cameras with the exposure time set at different levels are used to receive and separate the two kinds of signals. The benefit of the proposed coding is that both the high signal quality of the long distance communication and the high data rate of the short distance communication can be achieved at the same time. Also, because of the use of two levels of exposure time, the received signal consists of only 2 levels, which makes the detection much easier and ensures a low bit error rate. In this paper, the system performance achieved by the proposed coding is analyzed mathematically and the effects of different parameters on the system performance are revealed. These analyses are then verified through simulation.

II. SYSTEM ARCHITECTURE AND FUNDAMENTALS

A. ARCHITECTURE OF A BASIC VOCC SYSTEM

The architecture of a basic VOCC system is illustrated in Fig. 1. An LED tail lamp or an LED DRL on a vehicle transmits modulated visible light signal to a vehicle behind it. The LED tail lamp and LED DRL are LED panels composed of several LEDs of which one or more convey one bit depending on the coding applied to the original data. Through a modulation scheme, which is usually on-off keying, the encoded digital data is transmitted as visible light signal that will be received as images of the LED panel captured by the camera in the vehicle behind. From these images, the original data can be obtained through demodulation and decoding process.

B. CODING AND THE SPATIAL FREQUENCY OF LED PANEL

The original digital data is a stream of binary bits. To transmit these bits using an LED panel, a coding scheme is required to specify which LEDs in the panel would be used to represent which bits in the bit stream. Basically, a binary bit can be conveyed using a single LED in the panel. However, in many cases, instead of a single LED, a number of LEDs would be used to represent a single binary bit. The reason for this is to facilitate the demodulation and decoding process which will be applied to the received signal.

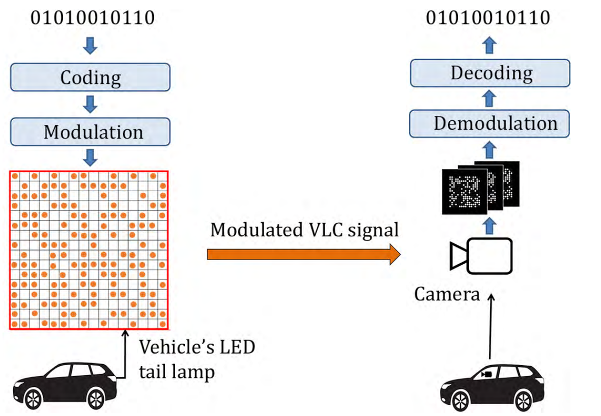


FIGURE 1. Architecture of a basic VOCC system.

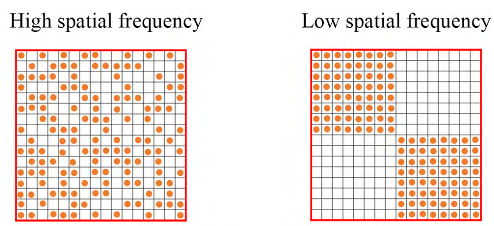


FIGURE 2. High and low spatial frequency LED panels.

Depending on the coding, the transmitted signal would have different spatial frequencies as illustrated in Fig. 2. Note that spatial frequency is the frequency in spatial domain, not in time domain. In time domain, high frequency means more bits are transmitted within a given time period. In spatial domain, given a specific space corresponding to the area of a specific LED panel, higher spatial frequency means more bits are conveyed within that space. The left LED panel in Fig. 2 has 256 bits transmitted inside. On the other hand, the right LED panel in Fig. 2 has only 4 bits transmitted inside. Therefore, the spatial frequency in the left LED panel is higher than that of the right LED panel.

In general, with high spatial frequency signal, one or a small number of LEDs are used to convey a single binary bit and the result is that many bits could be transmitted at a time. Although this makes a high data rate achievable, this also introduces difficulties to the demodulation process applied to the captured image of the LED panel. Consequently, the original data might be obtained with more errors. On the other hand, with low spatial frequency, many of LEDs are used to convey a single binary bit. While this decreases the data rate, the demodulation process can be performed easily and hence the original data can be obtained with fewer errors.

C. MODULATION AND DEMODULATION

After the original data is encoded, each LED in the panel is assigned to convey a specific binary value of either 0 or 1. Then, a modulation scheme is required to represent this binary value through visible light. Usually, on-off keying modulation where the binary bit is represented by the state of being turned On or Off of the LEDs is used. The state of

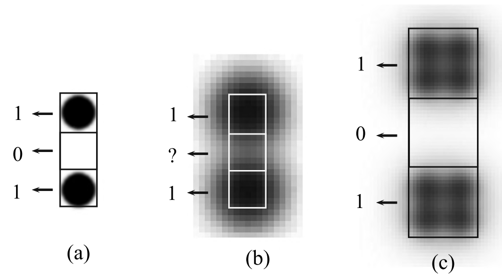


FIGURE 3. **Effect of spatial frequency of LED panels on demodulation accuracy. (a) Short distance high frequency. (b) Long distance high frequency. (c) Long distance low frequency.**

being turned On or Off of an LED would result in the presence and absence of that LED in the captured image of the LED panel.

In the demodulation, the image of the LED panel is processed and the states of being present and absent of each LED are determined to obtain the transmitted binary data. Usually, the states of absence and presence of a LED are detected based on the intensity of the pixels corresponding to that LED in the captured image. In the ideal case, the capture image is sharp, and this detection can be done easily. However, in reality, images are always captured with some degree of blurring. There are many causes for the image blur: inevitable flaws in the lens, errors in focusing, and noises in the sensor. While image blur always degrades the accuracy of the demodulation, the effect is actually dependent on the size of LEDs and the inter-distance between LEDs in the image. These two factors are in turn determined by the communication distance and the spatial frequency of the signal transmitted by LED panel.

Given an LED panel, at a short distance, each LED in the panel would appear large and the inter-distance between LEDs would also be large in the captured image. In this case, the blur area only takes a small part in the outer edge of the LEDs as illustrated in Fig. 3(a) and thus does not affect the area of adjacent LEDs in the image. Therefore, the absence and presence of a LED in the panel can be easily determined based on the intensity of the pixels belonging to that LED in the image. However, at a long distance, the LED and the inter-distance would be small in the captured image of the LED panel. The blurring of one LED would greatly interferes in the intensity of the pixels belonging to the adjacent LEDs in the image, thus makes the state of presence and absence of these LED difficult to be determined as illustrated in Fig. 3(b). To enhance the distinguishability of each LED in the image of the LED panel captured at long distance, a low spatial frequency of the signal is used as illustrated in Fig. 3(c). Due to the low spatial frequency, the distance between LEDs in the image becomes larger and thus the demodulation process could be performed with higher accuracy.

D. OCC SIGNAL RECORDING IN CAMERA

The mechanism of LED image acquisition, which is also the mechanism of how the OCC signal is recorded, is shown

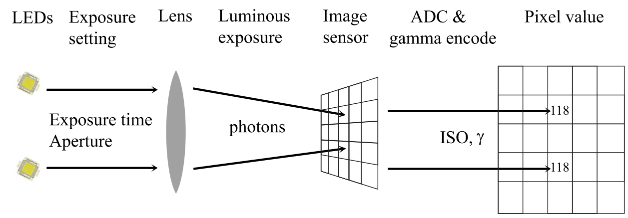


FIGURE 4. **The mechanism of image acquisition.**

in Fig. 4. The light emitted from each LED in the panel goes through the lens and falls into a specific region in the image sensor. Because of the spatial separation capability of the lens, the light from different LEDs would arrive at different regions on the sensor. Depending on the intensity of the LEDs and the exposure setting, which includes the setting related the lens aperture and the exposure time of the camera, a certain luminous exposure, which represents the number of photons per unit of area, would be received at these regions in the image sensor. The energy from these photons is then converted to a voltage. After the analog to digital converting and gamma encoding, the voltage will be represented by a pixel value which has the value ranging from 0 to 255.

As mentioned earlier, the states of absence or presence of the LEDs is determined based on the pixel value, which is given as follow [9], [10]:

$$PV = 118 \times 2^{ED/\gamma}. \tag{1}$$

In Eq. 1, γ is the gamma value used for gamma encoding. ED is the exposure difference between the indicated exposure EV_{ind}, which is determined by the intensity of the light source including LED and background light, and the set exposure EV_{set}, which is determined by the setting of the camera:

$$ED = EV_{ind} - EV_{set}. \tag{2}$$

Since the light that arrives at the image sensor comes from both LED and background light, the indicated exposure EV_{ind} is calculated from the indicated exposure of the LED EV_{LED} and the indicated exposure of the background light EV_{BG}:

$$EV_{ind} = \log_2(2^{EV_{LED}} + 2^{EV_{BG}}). \tag{3}$$

The indicated exposure value EV_{LED} corresponding to the light radiated from LED is given as:

$$EV_{LED} = \log_2 \frac{L_v \times S}{K}, \tag{4}$$

where L_v is the luminance in cd/m^2 of the light radiated from LED, S is the ISO speed set in the camera, and K is the reflected light meter calibration constant. The indicated exposure value EV_{BG} corresponding to the background ambient light bouncing off the LED surface is given as:

$$EV_{BG} = \log_2 \frac{E_v \times S}{C}, \tag{5}$$

where E_v is the illuminance in *lux* of the ambient light coming to the LED and C is the incident light meter calibration

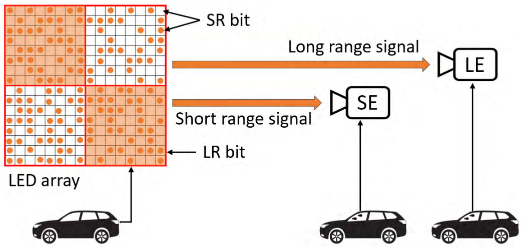


FIGURE 5. System architecture.

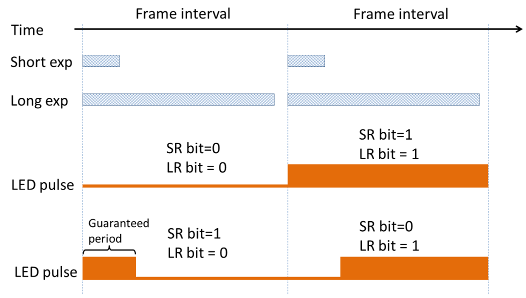


FIGURE 6. Overlay coding mechanism.

constant. The set exposure of the camera is used to represent a combination of lens aperture and exposure time as:

$$EV = \log_2 \frac{N^2}{t}, \tag{6}$$

where N is the aperture (f-number) of the lens and t is the exposure time in seconds. Note that because of the property of the gamma encoding, the condition for Eq. 1 to be valid is that the exposure difference is smaller than a specific value:

$$ED < \gamma \times \log_2 \frac{256}{118} \approx 2.5. \tag{7}$$

III. PROPOSED OVERLAY CODING AND PERFORMANCE ANALYSIS

A. PROPOSED OVERLAY CODING

The idea of overlay coding comes naturally from the fact that the short and long range communication signal must be transmitted in different spatial frequencies. So, the question is how the two kind of signals can be transmitted in the same LED panel. The answer for this question can be obtained by looking at the way the signal is demodulated. Regardless of how the two signals are transmitted, the only way to distinguish the two received signals is through the difference of pixel intensity. Therefore, the two signals must be transmitted in a way that the pixel intensities of the same LED in the captured images corresponding to the two signals are different. As explained previously, the pixel intensity is dependent on the exposure time of the camera. Therefore, the pixel intensity of the same LED can be differentiated when captured by two cameras with the exposure time set at different levels. From this idea, the overlay coding is proposed as described in Fig. 5 and 6.

The system architecture of the proposed overlay coding is illustrated in Fig. 5. The whole LED panel is used to transmit short range (SR) and long range (LR) bits simultaneously. Two cameras with the exposure time set at different levels are placed in every vehicle to receive the SR and LR signals transmitted from other vehicles simultaneously. In the SR signal, a SR bit is conveyed using a single LED in the panel. The close vehicle would use the camera with a short exposure (SE) time setting to capture the image of the LED panel. The captured image of the LED panel corresponding to this SR signal would have a high spatial frequency.

To reduce the spatial frequency of the LR signal, one LR bit is conveyed using multiple LEDs in the panel. In the proposed coding shown in Fig. 5, a quarter of the panel, which is a block of 8 × 8 LEDs, is used to convey a single LR bit. The far vehicle would use the camera with a long exposure (LE) time setting to capture the image of the LED panel. The captured image of the LED panel corresponding to this LR signal would have a low spatial frequency.

Since the value of a SR bit and a LR bit conveyed by the same LED can be different, the pixel intensity of that LED in the images captured by the SE and LE cameras must be different. To this end, there must be an agreement between the modulation of the light transmitted from each LED and the exposure time set in the two cameras. This kind of agreement is described in Fig. 6.

The mechanism of the proposed overlay coding shown in Fig. 6 is based on the fact that the exposure time can be much shorter than the frame interval of the camera. Therefore, the exposure time of the SE camera can be set to a value that is much shorter than that of the LE camera as illustrated in Fig. 6. Since both the SR bit and LR bit conveyed by an LED might have two possible values: 0 and 1, there are 4 cases corresponding to 4 combinations of the SR and LR bits that an LED needs to convey in one frame interval. Each LED would be modulated in a specific way depending to these cases.

As shown in Fig. 6, there is a short period called guaranteed period at the beginning of each frame interval. The LED is turned On or Off to represent the value of 1 or 0 of the SR bits, respectively. Note that the guaranteed period must be longer than the exposure time of the SE camera. In the remaining time of the frame interval, the LED is turned On or Off to convey the value of 1 or 0 of the LR bit. Since the exposure time of the SE camera is shorter than the guaranteed period, the state of the LED in the period after the guaranteed period would not affect the SR signal.

Specifically, when the values of both SR and LR bits are 0, the LED is turned Off during the entire frame interval. In contrast, when the values of both SR and LR bits are 1, the LED is turned On during the entire frame interval. When the value of the SR bit is 1 and that of the LR bit is 0, the LED is turned On during the guaranteed period and then turned Off in the remaining period. When the value of the SR bit is 0 and that of the LR bit is 1, the LED is turned Off in the guaranteed period and then turned On in the remaining period.

Like to other communication systems, OCC also requires the synchronization between transmitter and receivers. In this paper, the synchronization between LED and cameras is assumed to be achieved through one of many existing video camera wireless synchronization mechanisms [11], [12].

B. PERFORMANCE ANALYSIS

There are two primary aspects of the performance of a communication system: data rate and signal quality. The first performance aspect - data rate in a VOCC system can be calculated easily by multiplying the number of bits transmitted in each frame with the frame rate of the camera and thus will not be focused in the performance analysis. However, the second performance aspect - signal quality of the VOCC system varies depending on the setting of the proposed overlay coding. Therefore, this section will focus on analyzing the quality of the short range and long range signal. Since the accuracy of the demodulation of the received signal relies on the pixel intensity of the LED in the captured image, the signal quality in VOCC can be defined as the difference in the pixel intensity of the LED when it conveys the bit 0 and 1. Based on equations which determine the pixel intensity of the image, the relationship between the signal quality of the short and long range communication data and system parameters can be revealed.

1) SIGNAL QUALITY OF THE SHORT RANGE COMMUNICATION

The signal quality of the short range communication is defined as the difference in the intensity of the LED in the image captured by the SE camera when the SR bit 1 and 0 are transmitted. Let t_S denote the exposure time of the SE camera. When the SR bit 1 is transmitted, the SE camera receives the light from the LED and background in the entire t_S period. Through Eq. (1-7) and Fig. 6, the exposure difference of the combined light source received by the SE camera when bit 1 is transmitted, denoted as ED_{S1}, is given as:

$$ED_{S1} = \log_2 2^{EV_{LED}+2^{EV_{BG}}} - EV_{setS}, \tag{8}$$

where EV_{setS} is the set exposure value of the SE camera:

$$EV_{setS} = \log_2 \frac{N^2}{t_S}. \tag{9}$$

Therefore, the pixel value of the LED in the image captured by the SE camera when the SR bit 1 is transmitted, denoted as PV_{S1}, is given as:

$$PV_{S1} = 118\Big(\frac{S \times t_S}{K \times N^2}(L_v + E_v\frac{R}{\pi})\Big)^{1/\gamma}. \tag{10}$$

When the SR bit 0 is transmitted, the SE camera only receives the background light during the exposure period t_S. Therefore, the exposure difference of the light received by the SE when the SR bit 0 is transmitted, denoted as ED_{S0}, is given as:

$$ED_{S0} = ED_{BG} - EV_{setS}. \tag{11}$$

Therefore, the pixel value of the LED in the image captured by the SE camera when the SR bit 0 is transmitted, denoted as PV_{S0}, is given as:

$$PV_{S0} = 118\Big(\frac{S \times t_S}{K \times N^2} \times E_v\frac{R}{\pi}\Big)^{1/\gamma}. \tag{12}$$

From Eq. (10) and (12), the contrast between the SR bit 1 and 0, denoted as Ct_S, is given as:

$$\begin{aligned} Ct_S &= PV_{S1} - PV_{S0} \\ &= 118\left(\left(L_v+E_v\frac{R}{\pi}\right)^{1/\gamma} - \left(E_v\frac{R}{\pi}\right)^{1/\gamma}\right)\left(\frac{S \times t_S}{K \times N^2}\right)^{1/\gamma}. \end{aligned} \tag{13}$$

To examine the effect of the short exposure time t_S on the contrast of the SR signal, the derivative of the contrast with respect to t_S is calculated as:

$$\begin{aligned} \frac{\partial Ct_S}{\partial t_S} &= \frac{118}{\gamma}\left(\left(L_v + E_v\frac{R}{\pi}\right)^{1/\gamma} - \left(E_v\frac{R}{\pi}\right)^{1/\gamma}\right) \\ &\quad \times \left(\frac{S}{K \times N^2}\right)^{1/\gamma} {t_S}^{1/\gamma - 1}. \end{aligned} \tag{14}$$

Since $\frac{\partial Ct_S}{\partial t_S} > 0$, the contrast would increase as the short exposure t_S of the SE camera increases. The extinction ratio ER_S, which is the ratio between the pixel value of the SR bit 1 and 0, is given as:

$$ER_S = \frac{PV_{S1}}{PV_{S0}} = \left(1 + \frac{L_v}{E_v}\frac{\pi}{R}\right)^{1/\gamma}. \tag{15}$$

Since $\frac{\partial ER_S}{\partial t_S} = 0$, the extinction ratio of the SR signal would not be affected by the change of the short exposure time t_S.

2) SIGNAL QUALITY OF THE LONG RANGE COMMUNICATION

The signal quality of the long range communication is defined as the difference in the intensity of the LED in the image captured by the LE camera when the LR bit 1 and 0 are transmitted. Let t_L denote the exposure time of the SE camera. When the LR bit 1 is transmitted, the LE camera receives the light from the LED and background in two different ways depending on the value of the SR bit which is transmitted through that LED simultaneously. More specifically, when the values of both the LR and SR bits are 1, the LE camera receives the light from the background and the LED during the entire t_L period. Therefore, the pixel value of the LED in the image captured by the LE camera in this case, denoted as $PV_{L1_{S1}}$, is given as:

$$PV_{L1_{S1}} = 118\Big(\frac{S \times t_L}{K \times N^2}(L_v + E_v\frac{R}{\pi})\Big)^{1/\gamma}. \tag{16}$$

Let t_g denote the guaranteed period shown in Fig. 6. For simplicity, assume that $t_g = t_S$. When the value of the LR bit is 1 and that of the SR bit is 0, the LE camera receives the light from the background in the entire t_L period. However, the light from LED comes to the LE camera only within a period equal to $t_L - t_S$. Therefore, the pixel value of the LED in the image captured by the LE camera when the value of the LR and SR bit are 1 and 0, respectively, is given as:

$$PV_{L1_{S1}} = 118\Big(\frac{S \times t_L}{K \times N^2}(L_v \frac{t_L - t_S}{t_L} + E_v \frac{R}{\pi})\Big)^{1/\gamma}. \quad (17)$$

When the values of both the LR and SR bits are 0, the LE camera does not receive any light from the LED but only the background light during the t_L period. Thus, the pixel value of the LED in the image captured by the LE camera when the value of both the LR and SR bits are 0, denoted as $PV_{L1_{S0}}$, is given as:

$$PV_{L0_{S0}} = 118\Big(\frac{S \times t_L}{K \times N^2} \times E_v \frac{R}{\pi}\Big)^{1/\gamma}. \quad (18)$$

When the value of the LR bit is 0 and that of the SR bit is 1, the LE camera receives the light from the background in the entire t_L period, but receives the light from the LED in t_s period. Therefore, the pixel value of the LED in the image captured by the LE camera when the value of the LR bit is 0 and the value of the SR bit is 1, denoted as $PV_{L0_{S1}}$, is given as:

$$PV_{L0_{S1}} = 118\Big(\frac{S \times t_L}{K \times N^2}(L_v \frac{t_S}{t_L} + E_v \frac{R}{\pi})\Big)^{1/\gamma}. \quad (19)$$

The contrast between the LR bit 1 and 0 is given as:

$$\begin{aligned} Ct_L &= \frac{1}{2}\left(PV_{L1_{S0}} + PV_{L1_{S1}} - PV_{L0_{S0}} - PV_{L0_{S1}}\right) \\ &= 59\Big(\frac{S \times t_L}{K \times N^2}\Big)^{1/\gamma}\Bigg(\Big(L_v \frac{t_L - t_s}{t_L} + E_v \frac{R}{\pi}\Big)^{1/\gamma} \\ &\quad + \Big(L_v + E_v \frac{R}{\pi}\Big)^{1/\gamma} - \Big(E_v \frac{R}{\pi}\Big)^{1/\gamma} \\ &\quad - \Big(L_v \frac{t_S}{t_L} + E_v \frac{R}{\pi}\Big)^{1/\gamma}\Bigg). \end{aligned} \quad (20)$$

Usually, the value of the long exposure time t_L is close to the frame interval. Therefore, the only parameters that might affect the contrast of the LR signal is the value of the short exposure time t_S. The derivative of the contrast with respect to t_S is given as:

$$\begin{aligned} \frac{\partial Ct_L}{\partial t_S} &= \frac{-59}{\gamma}\Bigg(\Big(L_v (t_L - t_S) + E_v \frac{R}{\pi} t_L\Big)^{1/\gamma - 1} \\ &\quad + \Big(L_v t_S + E_v \frac{R}{\pi} t_L\Big)^{1/\gamma - 1}\Bigg) L_v \Big(\frac{S}{K \times N^2}\Big)^{1/\gamma}. \end{aligned} \quad (21)$$

Since $\frac{\partial Ct_L}{\partial t_S} < 0$, the contrast would decreases as the short exposure time t_S of the SE camera increases. The extinction ratio ER_L, which is the ratio between the pixel value of the LR bit 1 and 0, is given as:

$$\begin{aligned} ER_L &= \frac{PV_{L1_{S0}} + PV_{L1_{S1}}}{PV_{L0_{S0}} + PV_{L0_{S1}}} \\ &= \frac{\Big(L_v \frac{t_L - t_g}{t_L} + E_v \frac{R}{\pi}\Big)^{1/\gamma} + \left(L_v + E_v \frac{R}{\pi}\right)^{1/\gamma}}{\left(E_v \frac{R}{\pi}\right)^{1/\gamma} + \Big(L_v \frac{t_g}{t_L} + E_v \frac{R}{\pi}\Big)^{1/\gamma}} \end{aligned} \quad (22)$$

TABLE 1. Simulation environment.

Parameter	Value
Camera shutter mechanism	Global shutter
Sensor physical size	$36 \times 24\,(mm^2)$
Sensor resolution	1280×720 (pixels)
Lens focal length	50(mm)
Frame per second	500(fps)
LED array area	$25 \times 25\,(cm^2)$
Number of LED chips in an LED array	16×16 (LEDs)
Inter-distance between LED chips	5.6 (mm)
Luminance of LED	500 to 16000 (cd/m^2)
Ambient light illuminance	0 to 10000 (lux)
Number of bit transmitted in one SR frame	256 (bits)
Number of bit transmitted in one LR frame	4 (bits)
Gross SR data rate	128 (kbps)
Gross LR data rate	2 (kbps)

$$\begin{aligned} \frac{\partial ER_L}{\partial t_S} &= -\frac{L_v}{\gamma}\Bigg(\Big(L_v (t_L - t_S) + E_v \frac{R}{\pi} t_L\Big)^{1/\gamma - 1} \\ &\quad \times \Bigg(\Big(E_v \frac{R}{\pi}\Big)^{\frac{1}{\gamma}} + \Big(L_v t_S + E_v \frac{R}{\pi} t_L\Big)^{\frac{1}{\gamma}}\Bigg) \\ &\quad + \Big(L_v t_S + E_v \frac{R}{\pi} t_L\Big)^{\frac{1}{\gamma} - 1} \\ &\quad \times \Bigg(\Big(L_v (t_L - t_S) + E_v \frac{R}{\pi} t_L\Big)^{1/\gamma} \\ &\quad + \Big(L_v + E_v \frac{R}{\pi}\Big)^{1/\gamma}\Bigg)\Bigg). \end{aligned} \quad (23)$$

Since $\frac{\partial ER_L}{\partial t_S} < 0$, the extinction ratio of the LR bit would decreases as the short exposure time t_S increases.

IV. SIMULATION

A. SIMULATION ENVIRONMENT

1) LED ARRAY AND CAMERAS

The system is simulated in Matlab. The simulation parameters are shown in Table 1. In the simulation, a global shutter camera is assumed to be used. The frame rate of both the SE and LE cameras in the simulation are assumed to be 500 fps. The time gap for data readout between two frames is assumed to be 50% of the time interval between frames. The LED array is assumed to consist of 16 × 16 LEDs. The luminance of each LED is assumed to range from 500 to 16000 cd/m^2 and the illuminance of background light is assumed to range from 0 to 10000 lux. The focal length of the lens is 50 mm.

Regarding the LED luminance, LEDs might have very high luminance (200 Mcd/m^2) [13]. Therefore, the maximum LED luminance of 16000 cd/m^2 assumed in this simulation is possible with current technology. Regarding the suitability of this luminance on vehicle, it is true that this luminance is too high for vehicle tail light. The reason is because the main use of tail light is for illuminating in the night, which does not require that much of luminance. However, for Daytime Running Light (DRL), which is used in vehicle during daylight condition to increase the conspicuity of the vehicle, the maximum LED luminance of 16000 cd/m^2 is reasonable. For example, the United Nations Economic Commission for Europe (UNECE) R87 regulation specifies an apparent surface of DRL between 25 and 200 cm^2 and a luminous intensity between 400 and 1200 cd. This apparent surface and intensity permit the maximum luminance of DRL up to 480000 cd/m^2 [14].

Regarding the camera synchronization, current technology allows a very high accuracy of the synchronization for cameras. For example, in 3D video application, multiple cameras at different angles are triggered by external signals to start the recording of a moving object at the same time. The Photron FASTCAM Mini UX100 camera can be triggered by external signals with the delay time approximate to 118 nanoseconds. This camera even allows the synchronization at the frame rate up to 1350fps with varying frame intervals. Given that many wireless camera synchronization mechanisms have been proposed [11], [12] and very high level of synchronization has been achieved in commercial products, it is assumed that the synchronization error at the frame rate of 500fps with regular frame interval of the cameras in the simulation can be ignored.

Note that because the exposure times of the cameras assumed in the simulation are very short, the image motion blur caused by the speed of vehicles can be ignored.

2) CODING APPLIED FOR SHORT AND LONG RANGE SIGNAL AND DATA RATE

The coding applied for the SR signal uses one LED in the panel to convey one SR bit. Since there are 16 × 16 LED in the array, there will be 256 SR bits that are transmitted in every frame. The LED at row r, column c in the array would be used to convey the value of the $(16 \times r + c) - th$ bit in the original SR bit stream. Each SR bit 1 is represented by the presence of the LED and each SR bit 0 is represented by the absence of the LED.

The coding applied for the LR signal use each quarter of the panel, which is an array of 8 × 8 LEDs, to convey one LR bit. Therefore, 4 LR bits are transmitted in every LR frame. The value of 1 and 0 of the first, second, third, and fourth bits in the LR bit stream would be represented by the presence and absence of LEDs in the top-left, top-right, bottom-left, and bottom-right quarter of the panel, respectively.

The data rate is calculated by multiplying the number of bits transmitted in one frame with the frame rate of the camera. Therefore, the data rate of SR signal is $256 \times 500 = 128kbps$ and the data rate of LR signal is $4 \times 500 = 2kbps$.

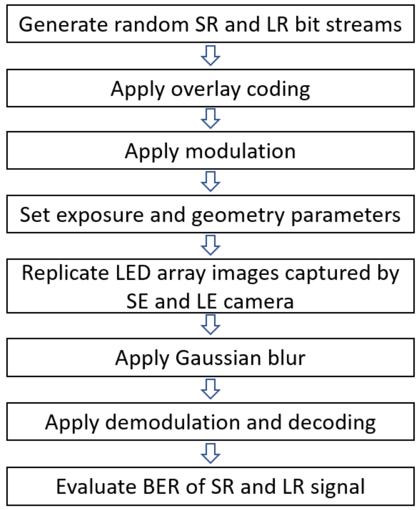


FIGURE 7. **Simulation procedure.**

3) ERROR DETECTION AND CORRECTION CODES

As in any communication system, error detection and correction codes are also necessary in VOCC to reduce the bit error rate, especially in bad channel conditions. These types of codes have been heavily studied in the field of information theory and existing codes such as checksum, cyclic redundancy check, automatic repeat request, Reed-Solomon, etc. [15], can be applied directly to the input and output SR and LR bit streams to reduce the bit error rate. However, these error detection and correction codes are not applied in the simulation for the sake of showing the raw performance of the proposed overlay coding.

B. SIMULATION PROCEDURE

The simulation procedure is illustrated in Fig. 7. Firstly, the two bit streams of the SR and LR data are randomly generated. After that, the proposed overlay coding is applied to these bit streams. Then, OOK modulation is applied to the encoded data. Through the modulation, each LED in the panel has a specific pattern of turning On and Off depending on the SR and LR bit it conveys. Then exposure parameters, which include the intensity of the LED and background light and the exposure setting of the SE and LE cameras, and the geometry parameters, which include distance and angle between cameras and LED array are assumed. Based on the modulation of each LED and exposure and geometry parameters, the LED array images captured by the SE and LE cameras can be replicated. The coordinate of every pixels of LEDs in the image is obtained through pinhole camera model [16] shown in Fig. 8. The values of LED pixels and background pixel are obtained using Eq. (1)-(7). Gaussian blur is applied to the simulated LED panel images to replicate the natural blur effect that would appear in practice. Then, the simulated images are demodulated and decoded to obtain the SR and LR bit streams. After that, the contrasts between the bit 0 and 1 and the BER of the two signals are calculated

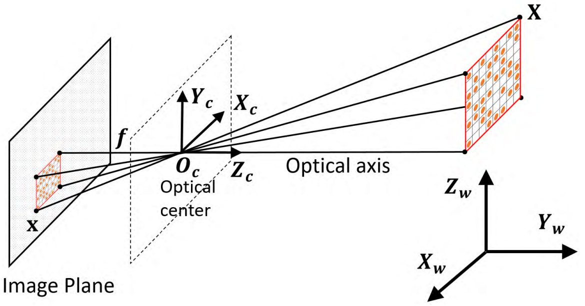


FIGURE 8. Pinhole camera model for LED array image replication.

to evaluate the performance of the proposed overlay coding at different settings of the system.

C. EXAMINED SYSTEM PARAMETERS AND SIMULATION SCENARIOS

The major factor that affect the BER of the signal are contrast between bit 0 and 1. The contrast in turn is affected by many system parameters including exposure time of SR camera, LED luminance, background light illuminance, and image blurriness. Besides, the performance of the bit detection algorithm used for detecting bit 0 and 1 in the LED array is also affected by the distortion of the LED array image, which is dependent on the angle between camera and LED.

In this paper, simulations are firstly conducted to examine the effect of four system parameters: exposure time of SR camera, LED luminance, background light illuminance, and image blurriness. In these simulations, two vehicles are assumed to have parallel moving direction as shown in Fig. 9. It is assumed that the optical axis of the camera, which is perpendicular to the image sensor, is parallel to the moving direction of the vehicle. The normal vector of the LED array is also parallel to the moving direction of the vehicle. Therefore, in Fig. 9, the image sensor is parallel to the LED array.

When the image sensor and LED array is parallel, the perspective distortion of the LED array in the image caused by relative horizontal and vertical positions of LED array is negligible. In other words, the size and shape of LED arrays at different horizontal and vertical positions in the image would be the same as shown in Fig. 10. Consequently, the BERs of the SR and LR signal in this case are dependent on only the contrast between bits 0 and 1, which is determined by exposure time of SR camera, LED luminance, background light illuminance, image blurriness.

The effect of the distortion of LED array image on the BER will be examine later. Simulations will be conducted with varying angles between camera and LED array.

Figure 11 shows the simulated images of the LED panel captured by the SE and LE cameras at the distance of 10 m and 70 m, respectively, when the image sensor is parallel to LED array. Note that because of the long distance, the image of LED array in the LR frame is much smaller than that of the SR frame and hence for the clear representation, the image

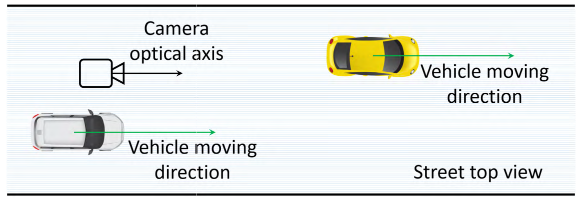


FIGURE 9. Image sensor is parallel to LED array.

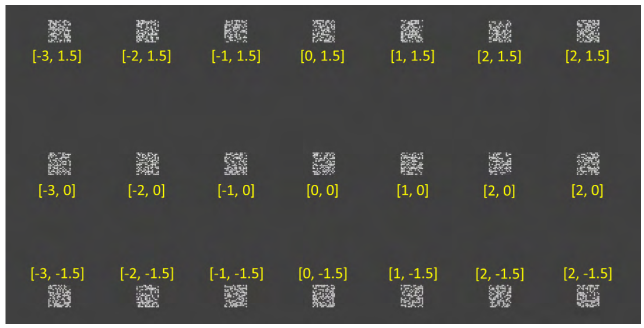


FIGURE 10. Simulated image of LED arrays at different horizontal and vertical positions.

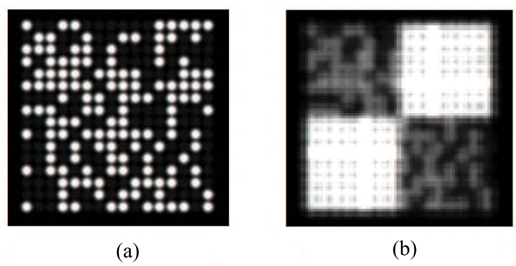


FIGURE 11. Received short and long frame. (a) Short distance frame. (b) Long distance frame.

of LED array in the LR frame shown in Fig. 11(b) has been magnified for 700%. This figure also shows that when the distance is far, the effect of the blur in the image is intensified.

D. SIMULATION RESULT

1) EFFECT OF EXPOSURE TIME OF SR CAMERA

The signal quality of the SR and LR data corresponding to different level of the short exposure time t_S of the SR camera are shown in Fig. 12. In this simulation, the ISO of both cameras are set to 100, the long exposure time is 1/1000 second, which equals to half of the frame interval. The short exposure time increases from 1/32000 to 1/1000 second. The guaranteed period is assumed to equal the short exposure time. The luminance of the LED is 8000 cd/m^2 and the illuminance of background light is assumed to be 1000 lux, which is equivalent to the lighting condition in a cloudy day. The contrasts between bit 0 and 1 of both SR and LR signal are shown in Fig. 12(a). It can be seen that the simulation result confirms the theoretical analysis presented before. As the short exposure time increases, the contrast of the SR signal increases while that of the LR signal decreases.

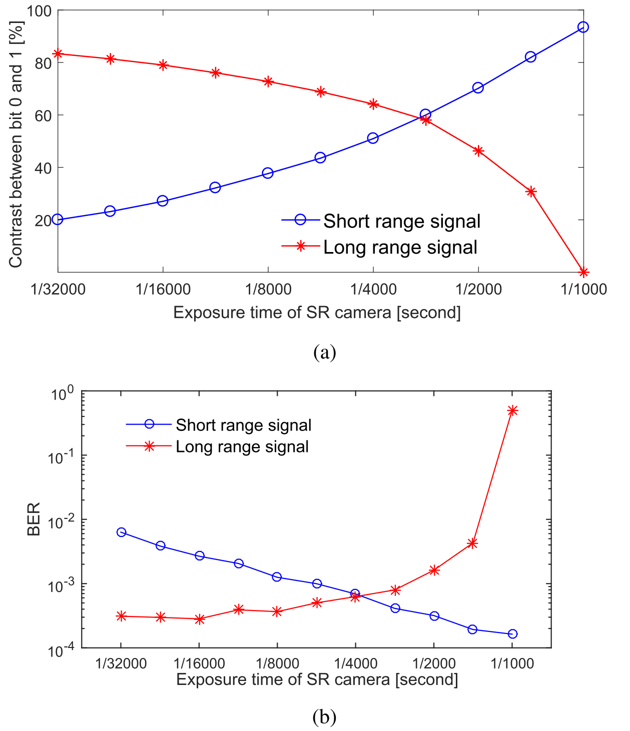


FIGURE 12. Signal quality corresponding to different exposure time of SR camera. (a) Contrast between bit 0 and 1 corresponding to different exposure time of SR camera. (b) BER corresponding to different exposure time of SR came.

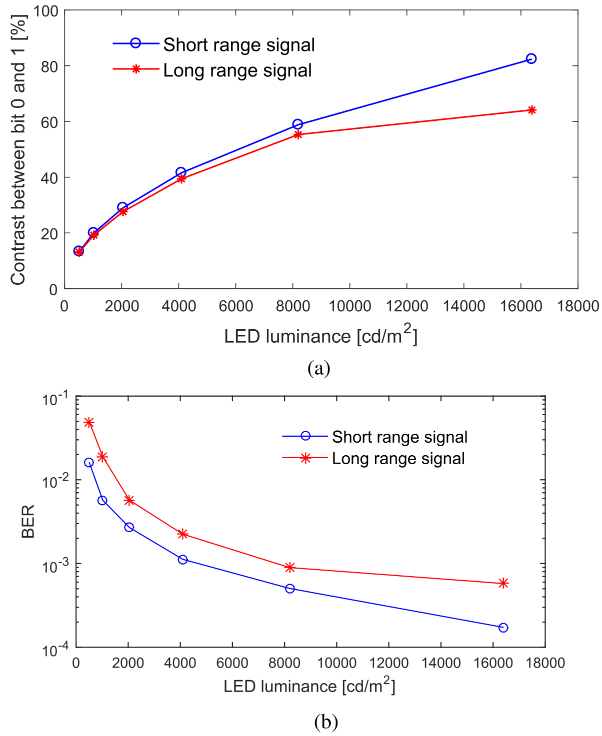


FIGURE 13. Signal quality corresponding to different LED luminance. (a) Contrast between bit 0 and 1 corresponding to different LED luminance. (b) BER corresponding to different LED luminance.

The reason for the increase in the contrast of the SR signal is obvious. The pixels belonging to an LED in the image sensor only receives the light from the background when that LED transmits the SR bit 0. However, when that LED transmits the SR bit 1, these pixels receive the light from both LED and background. Therefore, when the exposure time of the SR camera increases, the difference in the amount of light received by these pixels in the two cases of bit 0 and 1 also increases, thus making the contrast increase.

The insight that Fig. 12(a) provides is that there is trade-off between the quality of the SR and LR signal. The exposure time of the SR camera should be chosen to satisfy the requirement about the contrast of both SR and LR signal. Usually, the contrast of 50% or above is considered sufficient for the demodulation can be performed with little error. It can be seen in Fig. 12(a) that there are values for the exposure of the SR camera that yield the contrast of the SR and LR signal of more than 50 %. Therefore, it can be believed that the proposed overlay coding can offer the high signal quality of both SR and LR signal.

The contrast of the LR signal decreases as the exposure time of the SR camera increases can be explained by reminding Fig. 6. In the case that an LED transmits the SR bit of 1 and the LR bit of 0, the pixels belonging to that LED receive more light as the exposure time of the SR camera increases, thus making the values of these pixels increase and become indistinguishable from the pixels of another LED that transmits the LR bit of 1. Similarly, in the case that an LED transmits the SR bit of 0 and the LR bit of 1, the values of the pixels belonging to that LED would decreases and become indistinguishable from another LED that transmits the LR bit of 0.

Given the same transmitted signal, the BER of the received signal is dependent on the demodulation technique used in the system. More specifically, the BER of the VOCC is dependent on the image processing technique used to detect the LEDs in the received images. In the simulation, a simple intensity-based algorithm is used to detect the LEDs in the simulated images. The BERs of the SR and LR signal are shown in Fig. 12 (b). It can be seen that the BER of the SR signal decreases while that of the LR signal increases when the exposure time of the SR camera increases. With the exposure time of the SR camera ranging from 1/8000 second to 1/2000 second, the BER of both SR and LR signal are below 10^{-3}, which indicates a good signal quality for the communication.

2) EFFECT OF LED LUMINANCE

The signal quality of both SR and LR signal corresponding to different levels of the LED luminance ranging from 500 to 16000 cd/m^2 is shown in Fig. 13. The contrasts between bit 0 and 1 of the SR and LR signal are shown in Fig. 13(a). It can be seen in this figure that as the LED luminance increases, the contrast of both the SR and LR signal increases. This is because when LED luminance increases, the pixel value of the ON LED, which represents bit 1, would increase accordingly while the pixel value of the OFF LED, which represents bit 0, does not change. Therefore, when LED luminance increases, the contrast between ON and OFF LED would also increase. The BERs of the received signals are shown in Fig. 13 (b). As expected, the BER decreases when the LED luminance increase. The BER of both SR and LR signal are below 10^{-3} when the LED luminance exceeds 6000 cd/m^2.

3) EFFECT OF BACKGROUND LIGHT ILLUMINANCE

The signal quality of both SR and LR signal corresponding to different levels of the background illuminance ranging from 0 to 10000 *lux* is shown in Fig. 14. The contrasts between bit 0 and 1 of the SR and LR signal are shown in Fig. 14(a). It can be seen that as the background illuminance increases, the contrast of both SR and LR signal would decrease. This is because as the background illuminance increases, both the pixel values of the ON and OFF LEDs would increase. However, since the LED light is stronger than the background light, the pixel value of the ON LED is mostly determined by the LED luminance, not by the background light. When the background light increases, the pixel value of the ON LED only slightly increases. Because the increase of the pixel value the OFF LED is greater than that of the ON LED, the gap between the pixel values of ON and OFF LED become smaller. In other words, when background light illuminance increases, the contrast between ON and OFF LED would decrease. Because of the decrease of contrast, the BERs of both SR and LR signal increase when the background illuminance increases as shown in Fig. 14(b). However, the BER of the LR signal still remains in the order of 10^{-3} even when the background illuminance reaches 10000 lux, which is the level of illuminance in a bright daylight environment.

In Fig. 9 and 10, the contrast changes greatly (e.g. increase from 20% to 95%) at different values of SR camera exposure time and LED luminance. Therefore, a significant change in the BER can be observed. In Fig. 11, the contrast only changes slightly (e.g. decrease from 58 to 48%) at different values of background illuminance. This is because the background light is weaker than the LED luminance and thus the increase of the OFF LED pixel value when the background light increases is less than increase of the ON LED pixel value when the LED luminance increases. Consequently, when the background light increases, the contrast between ON and OFF LED would not change as greatly as when LED luminance increases. Also, because of the small change in the contrast, only a small change in the BER is observed. This result suggests that the impact of background illuminance on signal quality is less than that of the SR camera exposure time and LED luminance.

4) OVERALL VIEW OF THE EFFECT OF LED LUMINANCE AND BACKGROUND LIGHT ILLUMINANCE

The overall view of the contrast and BER of SR and LR signal corresponding to different levels of LED luminance and background illuminance is shown in Fig. 15. In this simulation, the LED luminance ranges from 500 to 16000cd/m^2, the background light illuminance ranges from 300 to 10000*lux*. Figures 13 and 14 show the directions of the changes of contrast and BER of SR and LR signal when either LED luminance or background illuminance is fixed and the other parameter is changing. It can be seen through Fig. 15 that the trends of contrast and BER of both SR and LR signal observed in Fig. 13 and 14 remain the same at all levels of LED luminance and background illuminance.

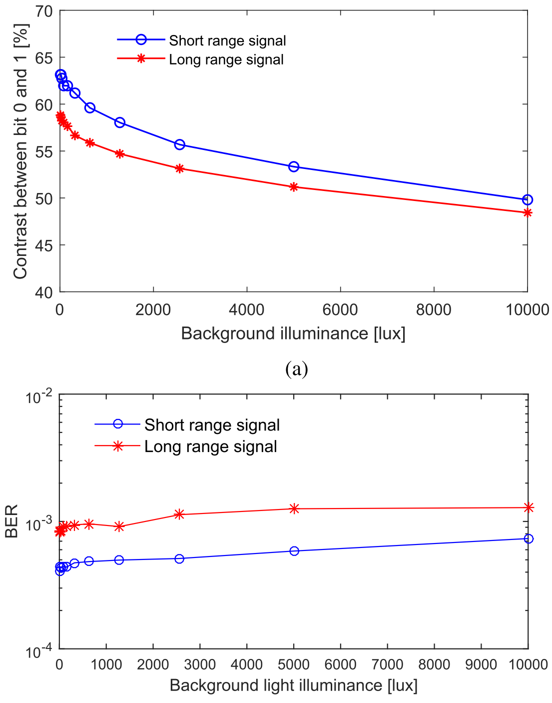


FIGURE 14. Signal quality corresponding to different background illuminance. (a) Contrast between bit 0 and 1 corresponding to different background illuminance. (b) BER corresponding to different background illuminance.

5) EFFECT OF IMAGE BLURRINESS

Blurriness is an inevitable phenomenon of image capturing caused by blooming effect and various types of optical aberration. The nature of image blurriness is the convolving of the incoming image with blurry diffraction patterns such as Airy disk pattern in the case of blooming effect as illustrated in Fig. 16. These blurry diffraction patterns can be approximated using a Gaussian function [17].

In this paper, blurriness is replicated by convolving the incoming image with a Gaussian function. The degree of blurriness is determined by the value of the standard deviation σ of the Gaussian filter. LED array images replicated with the values of σ of 0.5, 1, and 1.5pixels are shown in Fig. 17.

The BERs of SR and LR signal corresponding to different levels of blurriness are shown in Fig. 18. In the simulation for this figure, the LED luminance is randomly set between 4000 and 8000cd/m^2, the background illuminance is randomly set between 1000 and 2000lux. The results in Fig. 18 show that the signal quality decreases as the blurriness

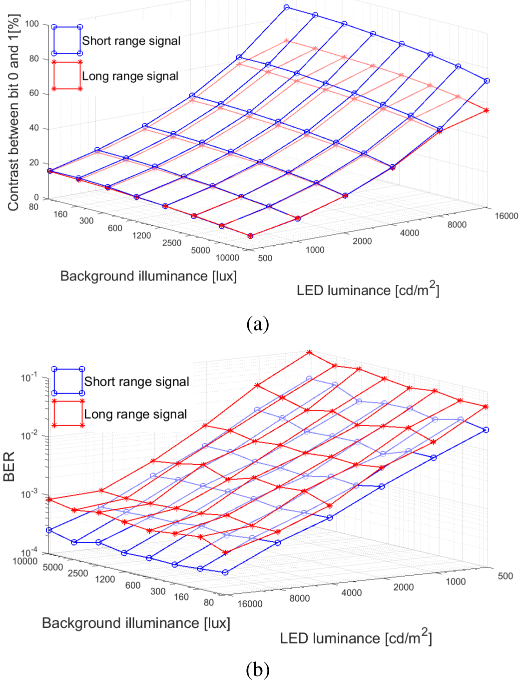


FIGURE 15. Signal quality corresponding to different LED luminance and background illuminance. (a) Contrast between bit 0 and 1 corresponding to different LED luminance and background illuminance. (b) BER corresponding to different LED luminance and background illuminance.

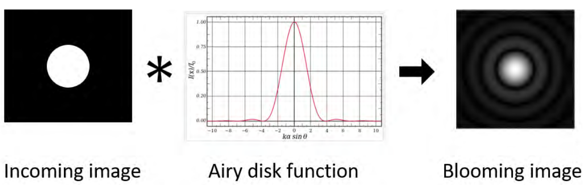


FIGURE 16. Blurriness caused by blooming effect.

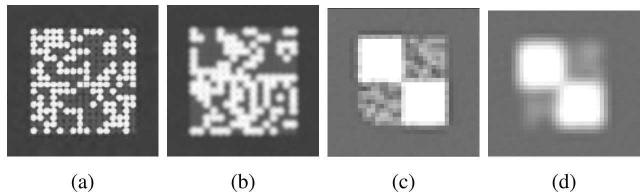


FIGURE 17. Replicated LED image at different degree of blurriness. (a) $\sigma = 0.5$. (b) $\sigma = 1.5$. (c) $\sigma = 0.5$. (d) $\sigma = 1.5$.

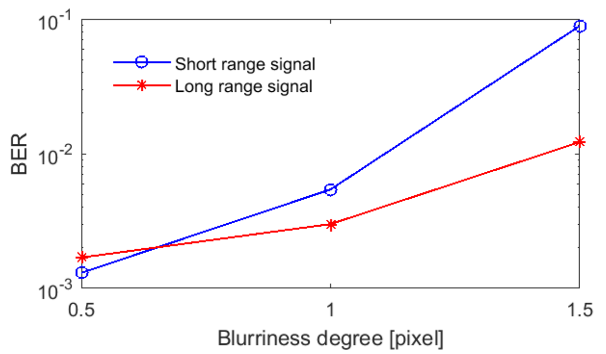


FIGURE 18. BER of SR and LR signal corresponding to different levels of blurriness.

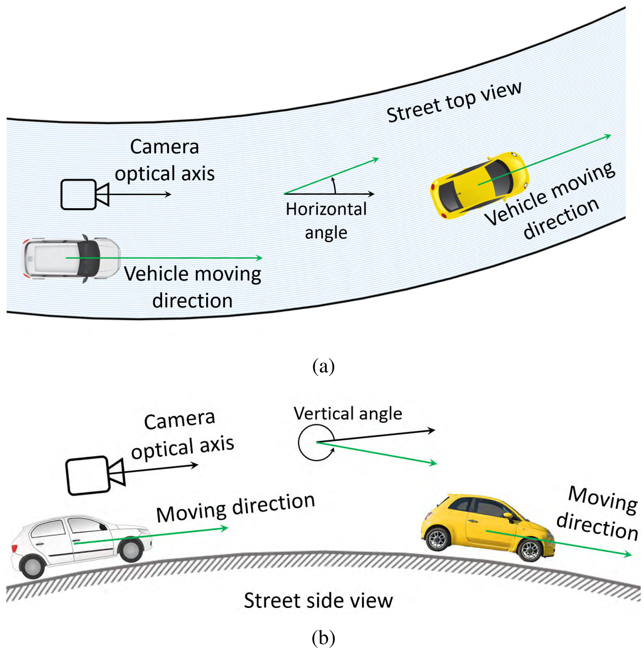


FIGURE 19. Horizontal and vertical angles between camera and LED array. (a) Horizontal angle. (b) Vertical angle.

increases. However, the effect of blurriness on the SR signal is stronger than that on the LR signal as the BER of the SR signal increase more rapidly when the blurriness increases. This is because blurriness causes the LED light to be spread out to adjacent LEDs, thus reduce the contrast between bit 0 and 1. As can be seen in Fig. 17(b) and 17(d), the SR and LR signals are all affected by the blurriness. However, since SR signal has high spatial frequency, bit 0s and 1s of SR signal are less separated from each other and thus is more vulnerable to detection error compared to LR signal.

6) EFFECTS OF CAMERA ANGLE

a: DEFINITION OF CAMERA ANGLE

When the image sensor and LED array is not parallel, the perspective distortion of LED array in the image is noticeable and will affect the BER of SR and LR signal. The property and degree of the perspective distortion are determined by the camera angle, which is defined as the combination of horizontal and vertical angles between the optical axis of the camera and the normal vector of the LED array as shown in Fig. 19.

In practice, the moving directions of two vehicles might be different when one vehicle is turning to another lane or just moving along a curvature of the street. In this case, a non-zero horizontal angle between the optical axis of the camera and the moving direction of the vehicle containing the LED array

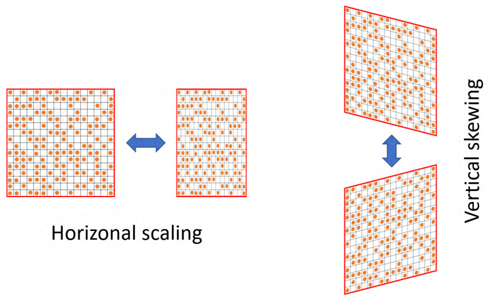


FIGURE 20. **Distortion caused by horizontal angle.**

is formed as illustrated in Fig. 19(a). On the other hand, a non-zero vertical angle is formed when two vehicles are moving in a curved surface such as a bridge as illustrated in Fig. 19(b).

Note that both horizontal and vertical angles are measured counterclockwise from the camera optical axis. Therefore, the horizontal angle in Fig. 19(a) has a positive value and the vertical angle in Fig. 19(b) has a negative value.

b: EFFECT OF HORIZONTAL ANGLE

The distortion of the LED array image caused by the horizontal angle between camera and LED array is the combination of two effects: horizontal scaling and vertical skewing as described in Fig. 20.

At short distance, the degree of horizontal scaling is determined by both the horizontal angle and the horizontal position. The larger the angle is, the higher the horizontal scaling degree is. Also, at a specific horizontal angle, the degree of horizontal scaling would decrease or increase as the horizontal position changes from left to right depending on the value of the horizontal angle is positive or negative, respectively. On the other hand, the degree of vertical skewing is determined only by the vertical position of the LED array. The horizontal scaling and vertical skewing of LED arrays in a SR frame corresponding to a horizontal angle of 60 degrees are illustrated Fig. 21(a).

The effects of horizontal and vertical positions on the scaling and skewing degrees vanish at long distance. This means that in LR frames, the degrees of scaling and skewing of LED arrays at different horizontal and vertical position are the same. Figure 21(b) shows a cropped replicated image of various LED arrays at different horizontal and vertical positions. It can be seen that the shapes of all LED array in the image are the same. This is because there is only horizontal scaling effect, which is caused by the horizontal angle, on these LED array.

To examine the effect of the horizontal angle between camera and LED array on the BER of SR and LR signal, at a given horizontal angle, 1000 LED array images are replicated for each kind of signal. The horizontal and vertical positions of LED array in each image are set randomly. The LED luminance, background light illuminance are set randomly in ranges from 4000 to 800cd/m^2 and from 1000 to 2000lux, respectively. The exposure time of the SR camera is set to 1/8000s. The simulation result is shown in Fig. 22. It can be seen that the BER of both SR and LR signals increase as the horizontal angle increases. However, the effect of horizontal angle on SR signal is greater than that on LR signal. This is because the SR signal has higher spatial frequency and thus is more affected by the scaling effect caused by the horizontal angle. In Fig. 21(a), the rightmost LED arrays are horizontally scaled down to a degree where bit 0 and 1 in the array are totally undetectable. On the other hand, in Fig. 21(a), the LED arrays in LR frame are also horizontally scaled down but still detectable.

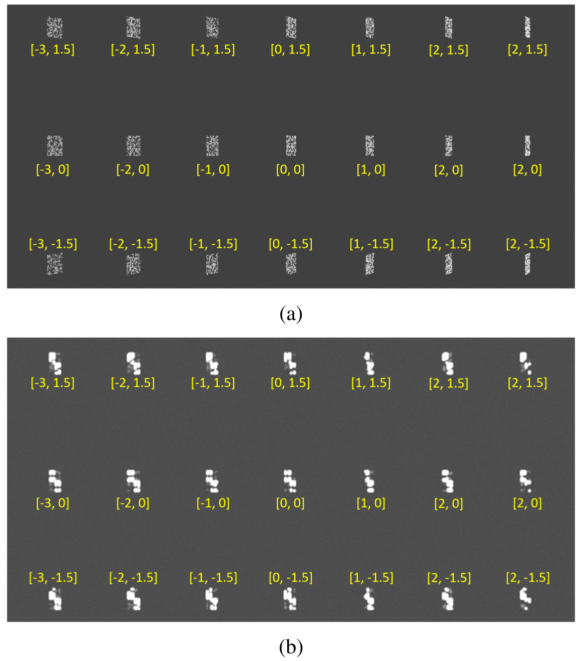


FIGURE 21. **Distortion caused by camera horizontal angles on LED array image. (a) Distortion of short range frame. (b) Distortion of long range frame.**

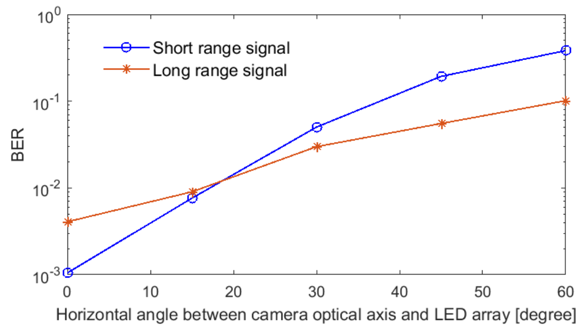


FIGURE 22. **BER at different horizontal angle.**

c: EFFECT OF VERTICAL ANGLE

The distortion of LED array in the image caused by vertical angle is the combination of horizontal skewing and vertical scaling as illustrated in Fig. 23.

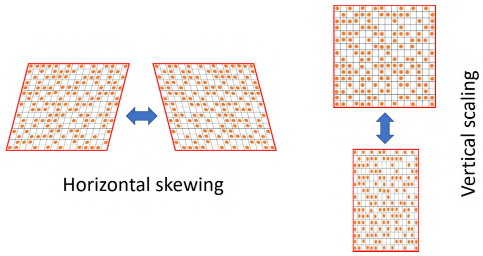
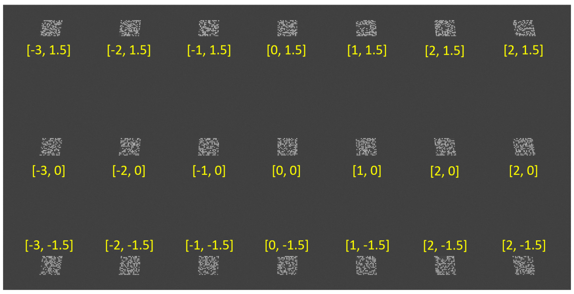
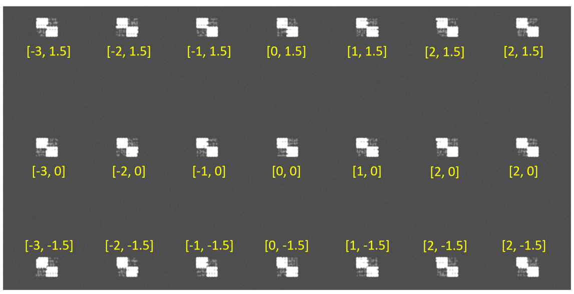


FIGURE 23. Distortion caused by vertical angle.



(a)



(b)

FIGURE 24. Distortion caused by camera vertical angles on LED array image. (a) Distortion of short range frame. (b) Distortion of long range frame.

At short distance, the degree of horizontal skewing is determined by the horizontal position of LED array. The degree of vertical scaling is determined by both vertical angle and vertical position. The larger the vertical angle is, the larger the vertical scaling degree is. Also, depending on the vertical angle is negative or positive, the degree of vertical scaling would degree or increase as the vertical position of LED array change from top to bottom. On the other hand, the degree of horizontal skewing is determined by the horizontal position of the LED array. The horizontal skewing and vertical scaling of LED arrays in a SR frame corresponding to a horizontal angle of 60 degrees are illustrated Fig. 24(a).

At long distance, the effect of horizontal and vertical positions on the skewing and scaling diminishes as can be seen in Fig. 24(b). In this figure, the shape of LED arrays at different position are the same since there is only the vertical scaling effect caused by the vertical angle on these LED arrays.

The BERs of SR and LR signals at different vertical angles are shown in Fig. 25. The settings for this simulation are the same to the one shown in Fig. 22. It can be seen that

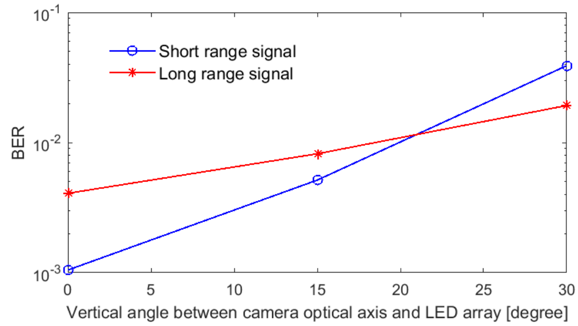


FIGURE 25. BER at different horizontal angle.

the BERs of SR and LR signals increase as the vertical angle between camera and LED array increases. And like the effect of horizontal angle, the effect of vertical angle on the BER of SR signal is greater than that on LR signal. The reason is also because of the higher spatial frequency of the SR signal.

V. CONCLUSION

This paper proposes a multiple exposure based overlay coding used in vehicle optical camera communication systems. The benefit of the proposed coding is to allow transmitters, which are LED panel of tail lamps in vehicles, to transmit both short and long range communication signals with different spatial frequencies simultaneously. The result is that a high data rate of the short range communication and a high signal quality of the long range communication signal can be achieved at the same time. The performance of the proposed overlay coding is mathematically analyzed and then verified through Matlab simulations. The simulation results suggest that the proposed coding can provides the high signal quality of both SR and LR communication signals and thus can be applied in reality.

REFERENCES

[1] R. M. Mare, C. L. Marte, and C. E. Cugnasca, "Visible light communication applied to intelligent transport systems: An overview," *IEEE Latin Amer. Trans.*, vol. 14, no. 7, pp. 3199–3207, Jul. 2016.

[2] I. Takai, T. Harada, M. Andoh, K. Yasutomi, K. Kagawa, and S. Kawahito, "Optical vehicle-to-vehicle communication system using LED transmitter and camera receiver," *IEEE Photon. J.*, vol. 6, no. 5, Oct. 2014, Art. no. 7902513.

[3] P. A. P. Ferraz and I. S. Santos, "Visible light communication applied on vehicle-to-vehicle networks," in *Proc. Int. Conf. Mechatron., Electron. Automot. Eng. (ICMEAE)*, Nov. 2015, pp. 231–235.

[4] T. Yamazato *et al.*, "Vehicle motion and pixel illumination modeling for image sensor based visible light communication," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1793–1805, Sep. 2015.

[5] N. Saha, M. S. Ifthekhar, N. T. Le, and Y. M. Jang, "Survey on optical camera communications: Challenges and opportunities," *IET Optoelectron.*, vol. 9, no. 5, pp. 172–183, 2015.

[6] T. Yamazato *et al.*, "Image-sensor-based visible light communication for automotive applications," *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 88–97, Jul. 2014.

[7] T.-H. Do and M. Yoo, "Visible light communication based vehicle positioning using LED street light and rolling shutter CMOS sensors," *Opt. Commun.*, vol. 407, pp. 112–126, Jan. 2018.

[8] S. Nishimoto *et al.*, "Overlay coding for road-to-vehicle visible light communication using LED array and high-speed camera," in *Proc. 14th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2011, pp. 1704–1709.
[9] T.-H. Do and M. Yoo, "Performance analysis of visible light communication using CMOS sensors," *Sensors*, vol. 16, no. 3, p. 309, 2016.
[10] R. E. Jacobson, "camera exposure determination," in *The Manual of Photography: Photographic and Digital Imaging*, 9th ed. Waltham, MA, USA: Focal Press, 2000.
[11] A. M. Pinto, A. P. Moreira, and P. G. Costa "WirelessSyncroVision: Wireless synchronization for industrial stereoscopic systems," *Int. J. Adv. Manuf. Technol.*, vol. 82, nos. 5–8, pp. 909–919, 2016.
[12] L. Hou, S. Kagami, and K. Hashimoto "Frame synchronization of high-speed vision sensors with respect to temporally encoded illumination in highly dynamic environments," *Sensors*, vol. 13, no. 4, pp. 4102–4121, 2013.
[13] J. Bhardwaj *et al.*, "Progress in high-luminance LED technology for solid-state lighting," *Phys. Status Solidi A*, vol. 214, no. 8, 2017, Art. no. 1600826.
[14] "Valeo lighting systems From light to advanced vision technologies valeoscope technical handbook," Valeo, Paris, France, Tech. Rep. 998542.
[15] F. J. MacWilliams and N. J. A. Sloane, *The Theory of Error-Correcting Codes*. Amsterdam, The Netherlands: Elsevier, 1977.
[16] R. Hartley, A. Zisserman, *Multiple View Geometry in Computer Vision*, 2nd ed. Cambridge, U.K.: Cambridge Univ. Press, 2003.
[17] B. Zhang, J. Zerubia, and J.-C. Olivo-Marin, "Gaussian approximations of fluorescence microscope point-spread function models," *Appl. Opt.*, vol. 46, no. 10, pp. 1819–1829, 2007.

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