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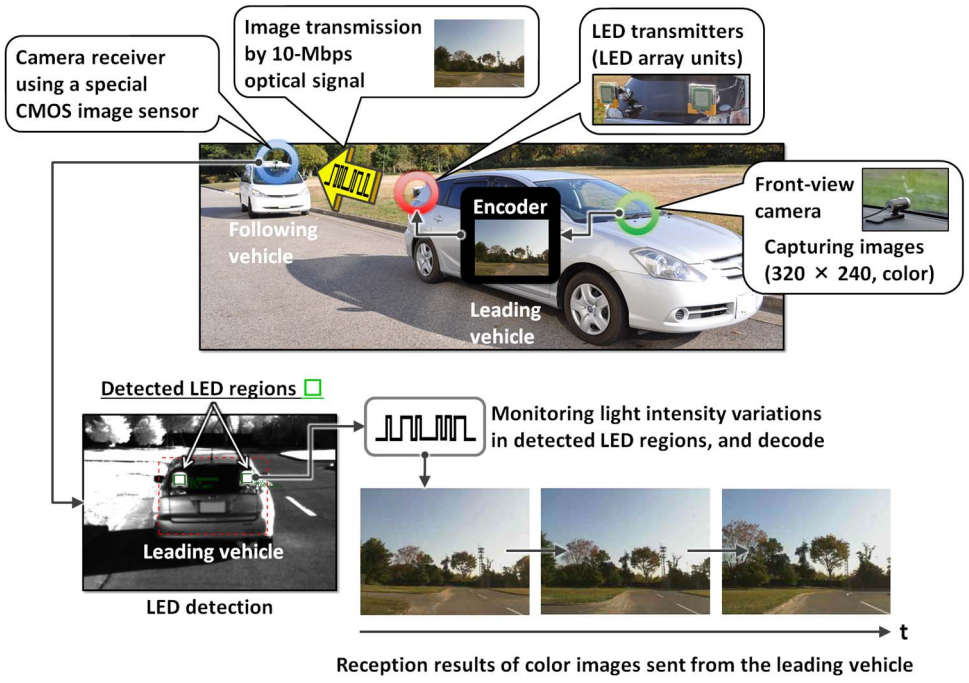

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Optical Vehicle-to-Vehicle Communication System Using LED Transmitter and Camera Receiver

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Abstract: This paper introduces an optical vehicle-to-vehicle (V2V) communication system based on an optical wireless communication technology using an LED transmitter and a camera receiver, which employs a special CMOS image sensor, i.e., an optical communication image sensor (OCI). The OCI has a "communication pixel (CPx)" that can promptly respond to light intensity variations and an output circuit of a "flag image" in which only high-intensity light sources, such as LEDs, have emerged. The OCI that employs these two technologies provides capabilities for a 10-Mb/s optical signal reception and real-time LED detection to the camera receiver. The optical V2V communication system consisting of the LED transmitters mounted on a leading vehicle and the camera receiver mounted on a following vehicle is constructed, and various experiments are conducted under real driving and outdoor lighting conditions. Due to the LED detection method using the flag image, the camera receiver correctly detects LEDs, in real time, in challenging outdoor conditions. Furthermore, between two vehicles, various vehicle internal data (such as speed) and image data (320 $\times$ 240, color) are transmitted successfully, and the 13.0-fps image data reception is achieved while driving outside.

Index Terms: Optical wireless communication (OWC), visible light communication (VLC), LED transmitter, camera receiver, CMOS image sensor, vehicle-to-vehicle communication.

1. Introduction

Recently, light emitting diode (LED) based optical wireless communication (OWC) systems have been developed [1]–[3]. Especially, an OWC technology using visible light LEDs, referred to as visible light communication (VLC), has been receiving much attention [4]–[6]. The LED is suitable as an optical-signal-sending device because light intensity of the LED can be modulated at high speed in comparison with traditional lighting devices, such as incandescent bulbs and fluorescent lamps. Furthermore, LEDs are inexpensive, already used for lightings and signages, and have high energy efficiency and long operating life. Moreover, basic performances of LEDs are being improved constantly while achieving even lower cost. Therefore, the LED-based

OWC system is expected to be a convenient and ubiquitous communication system in the near future. The widespread use of LEDs as light sources has reached into automotive fields. For example, LEDs are used for taillights, brake lights, headlights, and traffic signals. Accordingly, vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V or V2I) communication systems using LED-based OWC technology have been studied [7]–[14].

On the other hand, a camera is expected to be the receiver for automotive OWC systems [15]–[19]. Cameras have already been used for safety and comfort applications in the automotive field. Therefore, using the camera as the optical signal receiver is reasonable and straightforward. Moreover, the camera receiver provides the non-interference communication capability to OWC systems due to the excellent spatial separation capability of the image sensor mounted in the camera [20]. Thus, the OWC technology using a camera (image sensor) achieves non-crosstalk communication with multi-LEDs without a complicated protocol and processing, prevents optical signals from being mixed with noise such as directly incident sunlight, and enables simple link designs. This capability is not found in other wireless communication technologies and will significantly contributes for realizing the automotive OWC system that has to communicate with multi-nodes under outdoor environments.

Various potentials, capabilities, and advantages of the camera-based OWC system have already been reported [21]–[23]. However, only a few reports have implemented the camera-based OWC system in a real automotive system and conducted experiments under real driving and outdoor lighting conditions [16], [19], [24]. To achieve a useful camera-based OWC system for automotive applications, barriers must be overcome: one is data rate improvement and another is accurate and quick LED detection. The data rates per pixel of previous camera receivers are in the tens of kb/s or less [20], [25]–[27]. For transmitting various vehicle internal data (e.g., speed and braking states) and large multi-media data (e.g., audio, image, and video), even higher data rates more than a few Mb/s/pixel are expected. Additionally, the receiver system has to find the LED transmitters in captured images via image processing techniques. However, it is very hard to correctly and promptly detect LED transmitters from images under outdoor lighting environments with a low computing cost.

This paper introduces an OWC technology based optical V2V communication system linked by an LED transmitter and a camera receiver. In the camera receiver, a special CMOS image sensor, i.e., an optical communication image sensor (OCI) [28], is employed. The OCI has a non-conventional pixel, a "communication pixel (CPx)," which is specialized for high-speed optical signal reception. Additionally, it has an output circuit for a non-conventional image, a "1-bit flag image," which only reacts to high-intensity light sources such as LEDs and thus facilitates the LED detection. The OCI which employs two key technologies provides capabilities for a Mb/s-class optical signal reception and a prompt and accurate LED detection to a camera receiver.

In this paper, first, the OCI is explained, and the LED transmitter and camera receiver using the OCI are described. Subsequently, the optical V2V communication system using the LED transmitter and camera receiver is introduced and tested in various experiments under challenging outdoor lighting environments while driving. Through the experiments, the performance of the LED detection method by using the 1-bit flag image is confirmed. Finally, transmissions of various vehicle internal data and color image data are demonstrated.

2. Overview of Optical V2V Communication System

Fig. 1 illustrates the optical V2V communication system. In this figure, a leading vehicle (LV) has LED transmitters that use vehicle LED light sources such as tail lights, brake lights, and head lights. A following vehicle (FV) has the camera receiver. The LV collects its own various internal data (such as speed) and sends these data to the FV by optical signals. At the same time, the camera receiver on the FV captures the images and looks for the LED regions in the captured images via image processing techniques. In Fig. 1, the LED regions are enclosed by green rectangles. Subsequently, the receiver system monitors the light intensity variations in the detected LED regions and receives the optical signals.

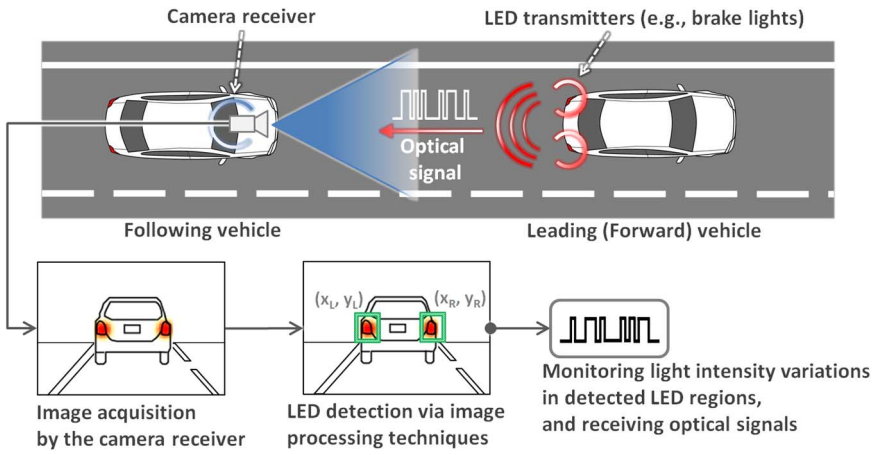


Fig. 1. Illustration of the optical V2V communication system.

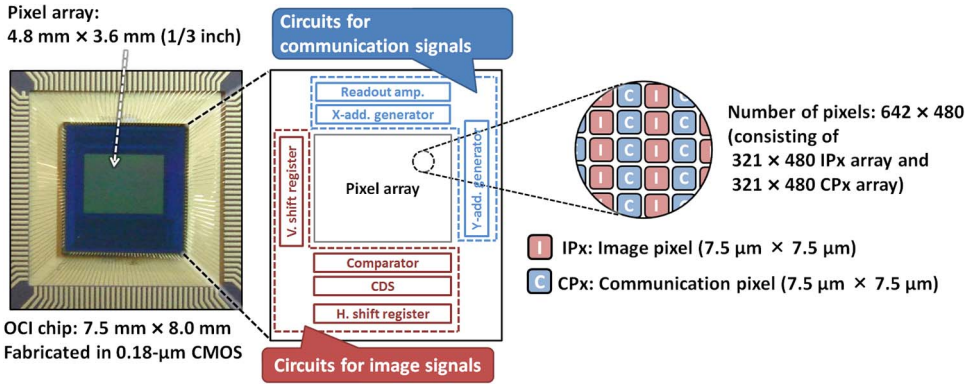


Fig. 2. Photograph and structure of the OCI.

In the future, images captured by the camera receiver will be used for not only LED detection, but also safety and comfort applications, such as lane detection and pedestrian detection. In other words, the camera for the OWC system and the camera for the image processing system will be combined, and a single camera will be used for both functions. Hence, the cost increase will be little because most camera components can be shared, and no extra space is needed for the camera receiver. Moreover, since this system can fuse two results, i.e., the results of data communication and the results of image processing, new applications could emerge.

As commonly known, the OWC is a line-of-sight (LOS) communication. Since optical signals propagate in a straight line, OWC links are easily blocked by objects which the light cannot penetrate, such as buildings, walls, thick gas, and thick fog. In addition, its communication range is limited in areas overlapping the light radiation angle of the LED transmitter and the view angle (angle of view, AOV) of the camera receiver. Conversely, this drawback frees the communication system from the multi-path fading problem and simplifies link designs. Additionally, signal leakages to unwanted nodes are low and the receiver is not affected by unnecessary signals outside of the AOV. Furthermore, the optical channel does not need to consider common electromagnetic noises and are license-free the world over.

3. Optical Communication Image Sensor (OCI)

In this paper, a special CMOS image sensor, the OCI, is employed in the camera receiver. Fig. 2 shows a photograph and the structure of the OCI. The OCI is fabricated by 0.18-μm

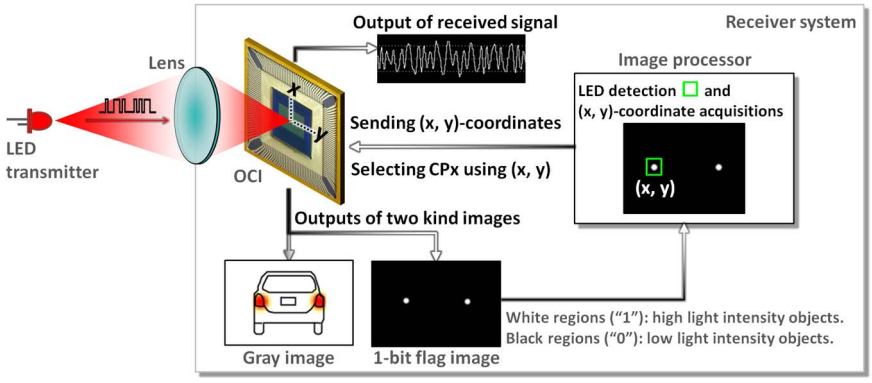


Fig. 3. Entire operation of the OCI.

CMOS image sensor technology. To achieve receptions of high-speed optical signals, the CPx is invented. The CPx, designed by pinned-PD technology, provides substantially improved response speed to light intensity variations, and it has already demonstrated 20 Mb/s optical signal reception per pixel. As shown in this figure, the OCI pixel array consists of the CPx and the image pixel (IPx) arrays which are set in alternate shifts. The IPx array captures images to detect the LED transmitters, and the CPx array receives optical signals. This hybrid pixel array is integrated in the OCI with peripheral circuits that drive both pixel arrays and process captured image signals and received optical signals.

Fig. 3 shows the entire operation of the OCI. First, the OCI outputs two kinds of images captured by the IPx array. One kind is a conventional gray image, and the other is a 1-bit flag image for quick LED detection. The flag image is taken in a very short exposure time compared with that of the gray image and is binarized by comparator circuits in the peripheral circuits for image signals. Therefore, low light intensity objects are perfectly eliminated. In contrast, high light intensity objects, such as LEDs, remain as "1" in the flag image. When this flag image is used for LED detection, the calculation time and the misdetection rate are greatly reduced because most unnecessary objects are removed. After the flag image is delivered to an image processor on an external unit, the LED regions are detected and the central coordinates of the LED regions are obtained via basic image processing techniques. Next, the obtained (x, y)-coordinates are inputted to the X- and Y- address generators of the OCI. Then, the CPx corresponding to the inputted (x, y)-coordinates are selected by the address generators, and the selected CPx is activated. Finally, the optical signal received by the selected CPx is outputted through readout amplifiers in the peripheral circuits for communication signals. This entire operation is repeated continuously, and so high-speed optical signals are received while the LED transmitter is tracked.

4. LED Transmitter and Camera Receiver Systems

Fig. 4 shows photographs and a block diagram of an LED transmitter system. This transmitter system consists of an LED array unit and a controller including a PC. The controller collects various data for sending, and it packetizes and encodes the send data. The LED array unit has LED drivers and 10 $\times$ 10 LEDs, and its optical power is up to 4 W. In this system, 870-nm near-infrared (NIR) LEDs capable of being modulated at high speed (fc: 55 MHz) are used tentatively.

Fig. 5 shows a photograph and a block diagram of a camera receiver system including a PC. A 12.5-mm lens is attached to receiver system and the AOV is 22 (H) deg. $\times$ 16 (V) deg. Since optical filters are not used on the lens, a receivable light wavelength range is from the visible to NIR light. The PC sets various parameters to the camera receiver and has application software to display received data, flag images, and gray images. In the receiver system, the gray image signals and the flag image signals outputted from the OCI are constructed on the frame

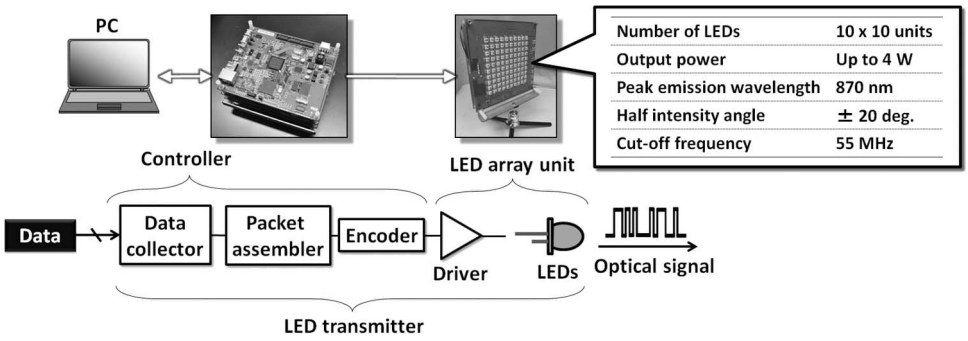


Fig. 4. Photographs and block diagram of the LED transmitter system.

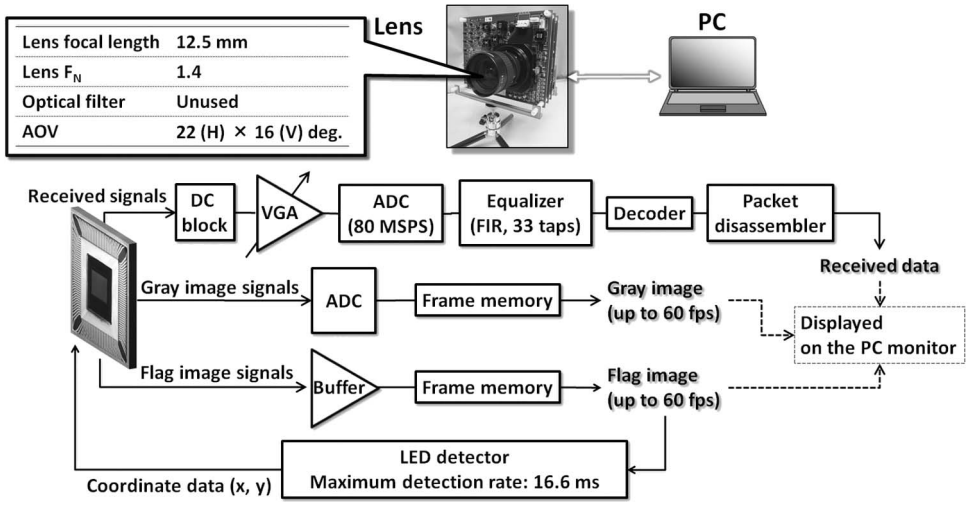
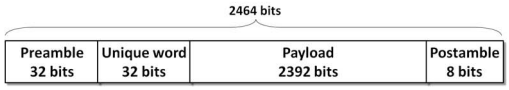


Fig. 5. Photograph and block diagram of the camera receiver system.

memories, and each image is completed in a period of up to 16.6 ms (at up to 60 fps). In this system, the gray image is used for display purposes. The completed flag image is delivered to the LED detector, and LED regions are detected by using a typical connected-component labeling method in a period of up to 16.6 ms. The x- and y-coordinate data of detected LEDs are carried back to the OCI, after which the CPx corresponding to the (x, y)-coordinates is activated, as explained in the previous section. Optical signals received by the activated CPx are digitized by the 80-MSPS ADC and equalized by a 33-tap finite impulse response (FIR) filter. Finally, equalized signals are decoded, and data are picked from the packets.

Fig. 6 shows the packet structure and communication specifications. A packet consists of a 32-bit preamble, 32-bit unique word, 2392-bit payload, and 8-bit postamble. The data rate is 10 Mb/s, which is half the rate of an already reported rate (20 Mb/s), to ensure the reliability and stability of the communication quality. The encoding method is Manchester coding. The packet send cycle is up to 0.5 ms and will suitably be changed depending on types of experiments. As countermeasures against errors, the BCH code and block interleaving are used. In this system, BCH codes capable of correcting up to 1-bit and 3-bit errors are prepared, and either one of 1-bit and 3-bit error corrections will be chosen by results of field experiments in Section 6. When the 1-bit or 3-bit error correction is used, the factual payload size is reduced to approximately 2164 bits and 1708 bits, respectively. This format is tentatively designed for confirming the performance of this system and non-standard format.

When many light sources, such as LEDs and the sun, appear in an image as shown in Fig. 7, the camera receiver system labels each light source, e.g., “A,” “B,” “C,” “D” and “E.”



Encoding method	Manchester code
Data rate	10 Mb/s
Packet send cycle	Up to 0.5 ms
Error countermeasures	Block interleaving BCH code > for 1-bit error correction > for 3-bit error correction

Fig. 6. Packet structure and communication specifications.

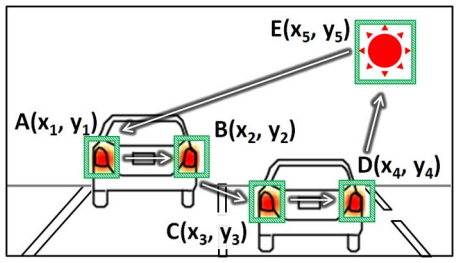


Fig. 7. Selection sequences of detected light sources.

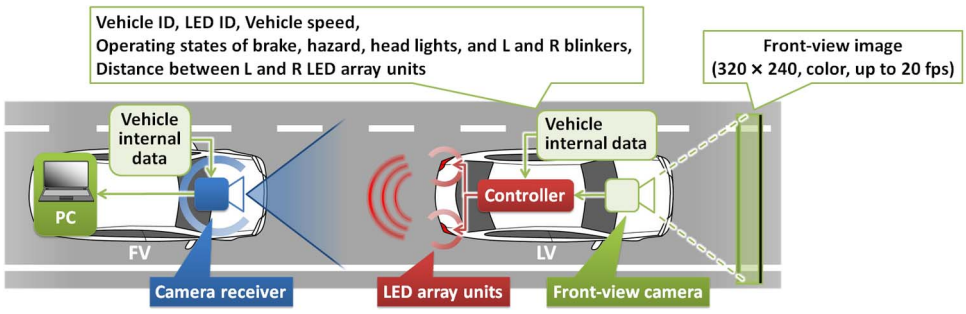


Fig. 8. Block diagram of the optical V2V communication system.

Subsequently, the receiver system selects a labeled target and receives optical signals one-by-one. For example, when the data of $A(x_1, y_1)$ is successfully received, the camera receiver selects $B(x_2, y_2)$ as the next target. When the data reception of the final target is finished, the camera receiver selects the first labeled target again. This loop operation is repeated until the next target positions are obtained from the next flag image. When the next target positions are obtained, each new target is labeled again by the same routine. If a preamble of a packet is not captured from a selected target during arbitrary set times, that target will be skipped and the next-labeled target will be selected. Therefore, targets that do not have data, such as the sun and street lights, are skipped in a given time.

5. Optical V2V Communication System

Fig. 8 shows a block diagram of the optical V2V communication system using the LED transmitters and camera receiver.

The leading vehicle (LV) has two LED array units, a controller including the PC, and a front-view camera for taking view images from the front of the LV, i.e., front-view images. The controller collects various vehicle internal data and the front-view image (320 $\times$ 240, color), and the LED array units send these data. The vehicle internal data consists of a vehicle ID, an LED ID for identifying left and right sides, vehicle speed, operating states of various devices (brake, hazard, head lights, and left and right blinkers), and the distance data between the left and right side LED array units. The two LED array units send the same data except for the LED ID data.

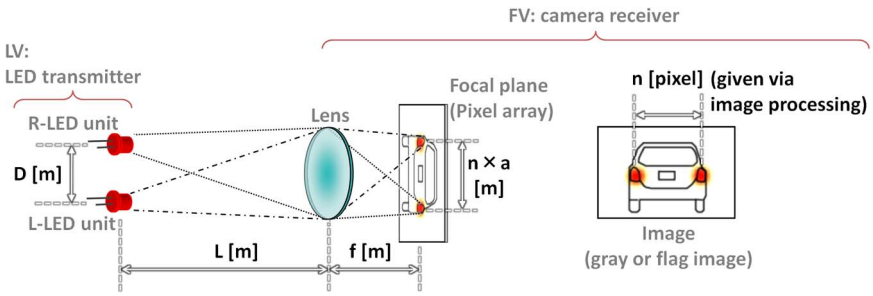


Fig. 9. Measurement method of inter-vehicle distance.

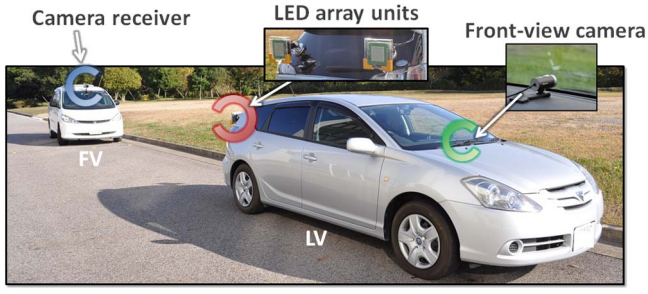


Fig. 10. Prototype optical V2V communication system.

The front-view image is compressed to a JPEG format image. The front-view camera can output images at up to 20 fps. However, the send-frame-rate of the front-view image is automatically adjusted, depending on the exposure time of the front-view camera and data size of JPEG image. According to preliminary experiments, the average send-frame-rates of the front-view image are approximately 15 fps under daytime lighting conditions and approximately 10 fps under nighttime lighting conditions. A single front-view image is sent by several packets because its size is bigger than the payload size of the packet.

The following vehicle (FV) has the camera receiver and the PC. The camera receiver receives the optical signals and collects the FV vehicle internal data. Received and collected data are delivered to the PC, and the delivered data is analyzed and displayed on the PC monitor.

Additionally, on the FV, new data is computed by using received data and flag images. The relative speed between vehicles is calculated from the difference between the LV speed and the FV speed. The inter-vehicle distance L is calculated by using the distance data between the left and right LED array units, as shown in Fig. 9 and given by:

$$L = \frac{f}{a} \cdot \frac{D}{n}$$

where L is the inter-vehicle distance, D is the distance between the left and right LED array units, f is the lens focal length, n is the distance (i.e., number of pixels) between the left and right LED array units on the image, and a is the IPx size. D is sent from the LV, and f and a are known values, such as 7.5 μm and 12.5 mm in this system. The value of n is easily given via simple image processing techniques. In this way, using both the received data and the captured image, this system provides not only a communication function, but also a ranging function.

Fig. 10 shows a photograph of the prototype optical V2V communication system. The LED array units are attached to the left and right sides of the LV rear window. The front-view camera is set on the LV dashboard. The camera receiver is attached to the FV roof.

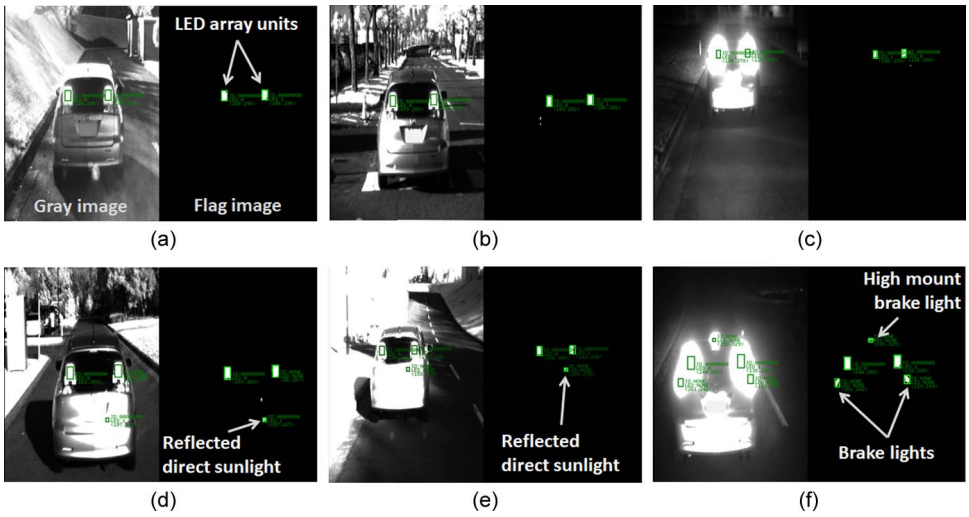


Fig. 11. Detection results of LED array units by using the flag image. (a), (b) Daytime lighting conditions. (c) Nighttime lighting condition. (d), (e) Daytime lighting conditions under which reflection regions of the direct sunlight on the LV body exist. (f) Nighttime lighting condition under which brake lights of the LV are on.

6. Experiments

In this section, various experimental results are presented. All experiments are conducted while driving outside. Outdoor lighting conditions change constantly and considerably, and so are uncontrollable. The experimental hours are form daytime to nighttime. The maximum vehicle speed is 25 km/h. The speed of each vehicle and the inter-vehicle distance are freely adjusted by each driver, and thus are not constant. The experimental road is paved with asphalt and occasionally has an uneven surface. (License numbers of vehicles in all result images are masked.)

6.1. Experimental Results of LED Detection

Fig. 11 shows the detection results of the LED array units by using the flag image under various outdoor lighting conditions. The left and right sides of each result image are the gray image and flag image, respectively. Detection results are presented by green rectangles in both images. In this experiment, small regions under nine pixels in the flag image are judged as noise and are discounted.

Experimental results (a) and (b) are obtained under daytime lighting conditions. While numerous superfluous objects totally disappear from the flag image, the LED regions remain and are accurately detected in real time. Also, at nighttime (c), the LED regions are successfully found without misdetections. In (d) and (e), the LV body reflects the direct sunlight. As with the LED regions, the reflection regions are detected. In (f), the brake lights are turned on, and these are detected in addition to the LED regions. This LED detection technique using the flag image detects not only LED units, but also objects that have strong light intensity equivalent to or exceeding the light intensity of the LED array unit. However, as previously explained, since regions that have no data are skipped, these regions have very little influence on communication performances. These results show that the proposed method using the flag image is very effective and achieves the correct and real-time LED detection even in challenging outdoor lighting environments.

6.2. Measurement Results of Packet Arrival Rate and Bit Error Rate

Table 1 shows the measured packet arrival rate (PAR). When the camera receiver successfully catches both the preamble and the postamble of a packet, “received packets” in Table 1

TABLE 1

Measurement result of the PAR

Sent packets	Received packets	PAR [%]
138,571	126,074	91.0

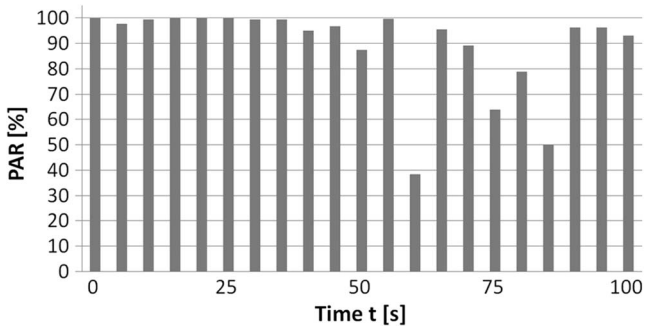


Fig. 12. PAR measurement result per 5 seconds.

TABLE 2

Measurement Results of the BER

BCH code	BER	Error bits / Received bits
uncoded	1.14×10^{-4}	3,767 / 33,017,728
1-bit error correction	1.94×10^{-6}	41 / 21,093,600
3-bit error correction	-	0/ 26,333,888

are counted. Errors in the payload of a packet are not checked. As a result of the measurement, 138 571 packets are sent, and 126,074 packets are successfully received. Therefore, without complicated communication protocols and procedures, this system achieves the 91.0% PAR.

The causes of the packet loss are clarified here. Fig. 12 shows the PAR measurement result per 5 seconds. The PAR greatly decreases occasionally, and the worst PAR is 38% in this figure. Then, the FV is pitched by the uneven road. When large pitching exceeding the LED detection rate occurs during packet waiting or receiving, the receiver fails to capture the preamble and/or the postamble of packets. This measurement ascertains that the vehicle pitching is one of the commonest causes of packet losses. By an improvement of the LED detection rate, i.e., the output rate of the flag image, packet losses will be decreased. Additionally, the PAR would be improved by reducing the payload size. However, the data transmission efficiency will be degraded because the overhead size is relatively increased.

To fix the parameter of the BCH code for bit error correction, the bit error rate (BER) is measured. The measurement results are shown in Table 2. In this measurement, when errors occur in the payload of the arrival packets, the “error bits” in Table 2 are counted. The parameters are “uncoded,” “1-bit error correction,” and “3-bit error correction”. Experimental conditions (such as lightings and driving routes) of each measurement are not identical. As a result, the error-free operation is confirmed at the “3-bit error correction”. Therefore, in subsequent experiments, the BCH code capable of correcting up to 3-bit errors is used.

6.3. Experimental Results of Vehicle Internal Data and Image Data Transmission

The optical V2V communication system challenges the various vehicle internal data and front-view image transmission, which is our final goal in this paper. Experimental results under

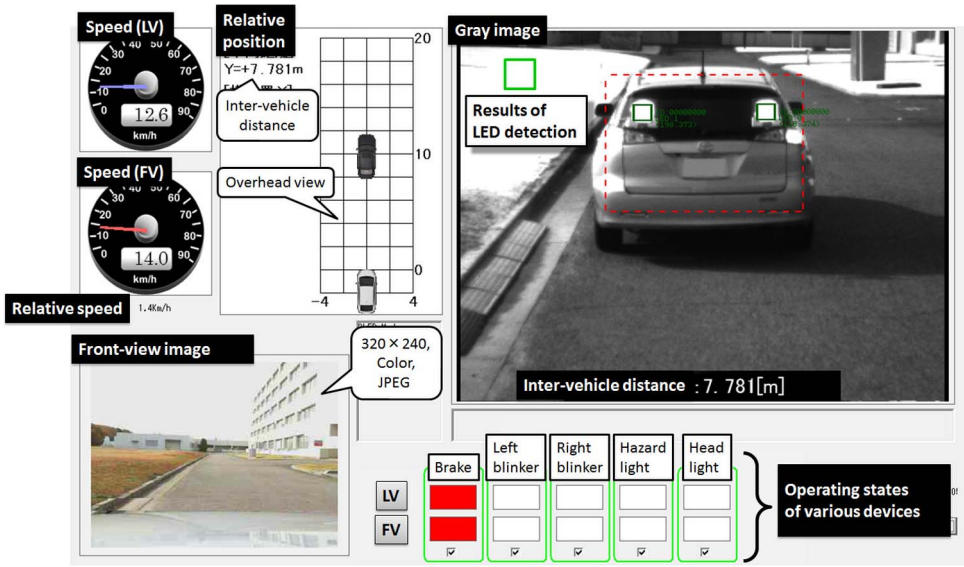


Fig. 13. Reception result of vehicle internal data and front-view image in the daytime.

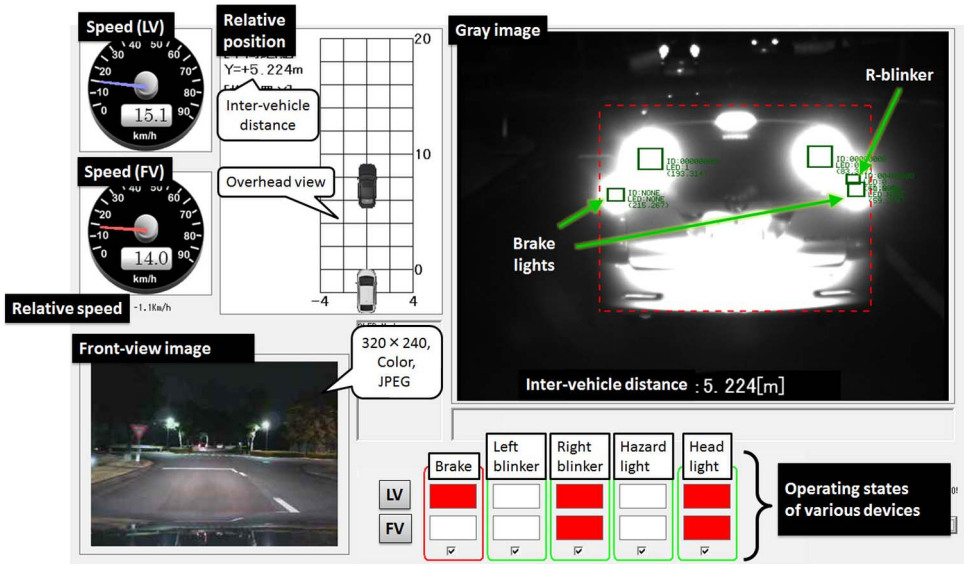


Fig. 14. Reception result of vehicle internal data and front-view image in the nighttime.

daytime and nighttime lighting conditions are shown in Figs. 13 and 14, respectively (These figures are a screenshot of application software for displaying received data in the PC on the FV, and various captions are added on these screenshot images). As shown in Fig. 13, the received LV speed is 12.6 km/h, and the FV speed is 14.0 km/h. Additionally, both vehicle drivers are braking as shown by the solid red rectangles in “Operating states of various devices”. The received front-view image is displayed at the lower left side of the figure. The calculated relative speed is 1.4 km/h and inter-vehicle distance is 7.781 m. Also, in the nighttime, the receiver system successfully receives various data. As shown in Fig. 14, the brake lights, right blinker, and headlights of the LV are on. The right blinker and headlights of the FV are on. These experimental results show that the optical V2V communication system achieves transmissions of the vehicle internal data and 320 $\times$ 240 color image data under real outdoor environments while driving.

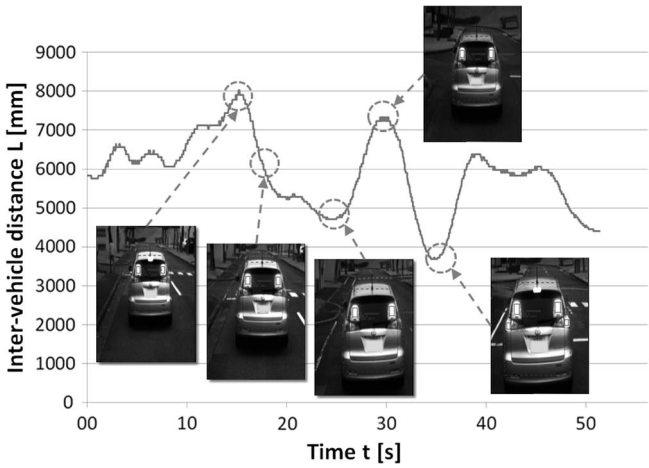


Fig. 15. Calculation result of the inter-vehicle distance for 50 seconds.

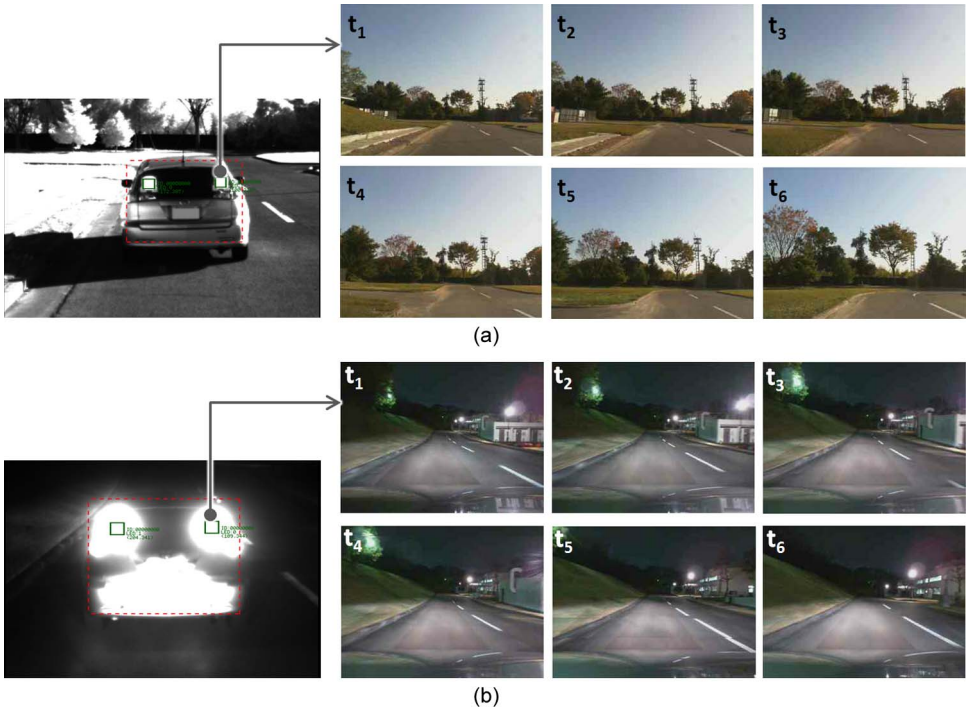


Fig. 16. Reception results (extracted per approximately 1 s) of consecutive front-view images. (a) Under the daytime lighting condition. (b) Under the nighttime lighting condition.

Fig. 15 shows the calculation result of inter-vehicle distance L for 50 seconds. Without additional sensing devices, complicated processing technologies and cost increases, this optical communication system has obtained the ranging function.

Fig. 16 show reception results of the consecutive front-view images in the daytime and nighttime. As shown in these figures, the consecutive image data, i.e., video data, receptions are achieved. To confirm the image reception performance of this system, the reception-frame-rate of the front-view image is measured, as shown in Table 3. In this measurement, the lighting conditions are daytime and nighttime. As already explained, send-frame-rate of the front-view image sent from the LV is approximately 15 fps in the daytime and 10 fps in the nighttime. As a result,

TABLE 3

Measurement results of reception-frame-rate of front-view images

Lighting conditions	Send-frame-rate [fps]	Reception-frame-rate [fps]	Image-arrival-rate [%]
Daytime	15	13.0	87
Nighttime	10	8.9	89

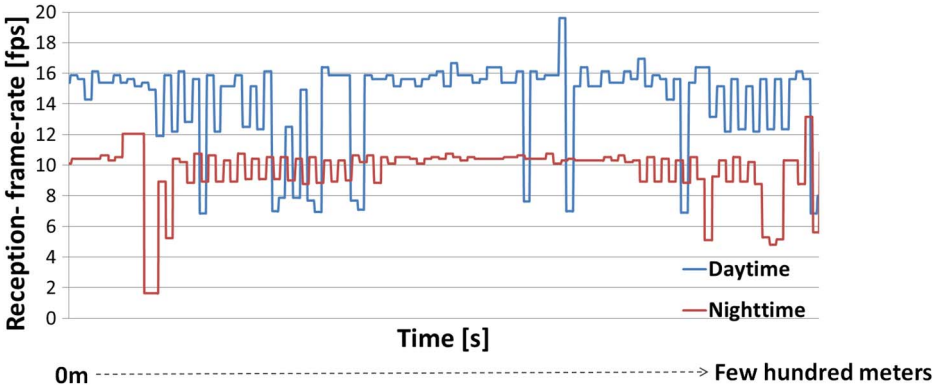


Fig. 17. Measurement result of average reception-frame-rate of front-view images for a few hundred meters.

the average reception-frame-rates are 13.0 fps in the daytime and 8.9 fps in the nighttime. Therefore, the image-arrival-rates at each lighting condition are 87% and 89%, respectively. In fact, lighting conditions have insignificant influence on reception performances. This result significantly shows that the optical V2V communication system is capable of transmitting video data under real driving and outdoor lighting conditions.

Finally, to ascertain the cause of image frame loss, variations of average reception-frame-rate driving for a few hundred meters is confirmed in daytime and nighttime, as shown in Fig. 17. As in the result of the PAR measurement, when the vehicle is pitched by uneven roads, the reception-frame-rate is decreased. Therefore, image frame losses are due to packet losses.

7. Conclusion

This paper has presented a V2V communication system based on OWC technology linked by LED transmitters and a camera receiver. The LED transmitter is capable of sending various data by 10 Mb/s optical signals. The camera receiver equips a special CMOS image sensor, the OCI, which has a CPx array for high-speed optical signal reception and a flag image output function for facilitating LED detection in outdoor environments. By using the OCI, the camera receiver has obtained 10 Mb/s optical signal reception and accurate LED detection capabilities. The LED transmitters and camera receiver using the OCI are respectively mounted on the LV and FV, and the first-step optical V2V communication system is completed.

For confirming the performances and potential of this system, many experiments have been conducted under real driving and outdoor lighting conditions. The LED detection method using the flag image effectively eliminates most unnecessary objects in images and achieves correct and real-time LED detection even in challenging outdoor environments. This capability will significantly contribute to practical automotive applications. In data transmission experiments, the LV simultaneously sends various vehicle internal data and image data (320 $\times$ 240 pixels, color), and the FV successfully receives these data. Then, the front-view images are received at 13.0 fps in the daytime and 8.9 fps in the nighttime. Furthermore, when the result of data

communication is combined with the result of image processing, this system obtains the ranging function of inter-vehicle distance.

In future experiments, long-distance driving experiments under more arduous lighting and movement conditions will be conducted.

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