Rolling-Shutter-Sensor-Based Visible Light Communication for Multi-user Long-range Communication and Positioning

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Abstract: We propose a rolling-shutter-sensor-based visible light communication (RS-VLC) system using a cross-screen filter suitable for intelligent transport system (ITS) scenarios. The proposed system uses a cross-screen filter to diffuse the received light in the scanning direction of the rolling-shutter sensor, thus improving the intensity of the received signal and increasing the communication range. The experimental results show that the proposed system can improve the communication range. We also show that the proposed system is capable of multi-user communication and positioning.

Keywords: visible light communication, ITS, rolling-shutter sensor, cross-screen filter, phase-shift keying

Classification: Wireless Communication Technologies

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1 Introduction

Visible light communication (VLC), which utilizes an LED as a transmitter (Tx) and an image sensor as a receiver (Rx), has been attracting attention as a new communication technology in intelligent transport system (ITS) scenarios (e.g., vehicle-to-vehicle communication), since it offers the advantages of multi-user communication and positioning by image information [1, 2]. A VLC system that achieves a high data rate using the rolling-shutter effect of a commercial camera (rolling-shutter-sensor-based VLC; RS-VLC) can not only enable these functions but also use a smartphone camera as a VLC Rx [3]. However, it is challenging to achieve both long-distance and high-speed communication in existing RS-VLC systems, and the current communication range is limited to the order of several meters [4]. Therefore, to utilize an RS-VLC system for ITS, it is necessary to achieve long-distance and high-speed communication while enabling multi-user communication and positioning.

To address this issue, we proposed a single-user visible light communication system using a cross-screen filter [6]. In [6], it was found that this filter can improve the communication range by diffusing the received light in the scanning direction of the rolling shutter sensor and improving the received signal power. In this paper, we study the feasibility of multi-user communication and positioning using the proposed system, which was not clarified in [6]. In the following section, we design the proposed system, perform experiments with it, and evaluate its performance.

Fig. 1. Block diagram of RS-VLC system using cross-screen filter and vehicle-to-vehicle communication in ITS scenario.
2 System overview

Fig. 1 shows a block diagram of the proposed RS-VLC system using a cross-screen filter. Below we explain signal processing in the Tx and Rx (the detailed configuration of the transmitter and receiver is described in [7]).

2.1 Transmitter

Let us define a binary data block \( b_l = (b_{l,0}, b_{l,1}, \ldots, b_{l,N-1}) \), where \( b_{l,n} = \{0, 1\} \), \( l = 0, 1, \ldots, L - 1 \), \( n = 0, 1, \ldots, N - 1 \), \( l \) is the block number, \( L \) is the total number of data blocks, and \( N \) is the block length. The Tx converts the binary data \( b_{l,n} \) to the symbol data \( d_{l,n} \), as

\[
  d_{l,n} = \begin{cases} 
    1 & (b_{l,n} = 1) \\
    -1 & (b_{l,n} = 0) 
  \end{cases}.
\]  

Next, the Tx performs phase-shift keying (PSK) modulation by multiplying the symbol data \( d_{l,n} \) and the carrier signal by the frequency of \( f_c \). The PSK modulated payload signal \( p_l(t') \) \( (0 \leq t' \leq T_d, T_d: \text{length of payload signal in time}) \) can be expressed as

\[
  p_l(t') = a\Re \left[ d_{l,n}e^{j2\pi f_c t'} \right] + a_{\text{off}} \left( \frac{n}{N} T_d \leq t' < \frac{n+1}{N} T_d \right),
\]

where \( a \) and \( a_{\text{off}} \) are the amplitude and DC offset of the signal, respectively. Then, the Tx calculates a transmitted signal block \( s_l(t') \) \( (0 \leq t' \leq T_b, T_b: \text{length of signal block in time}) \) by adding a header (a known sequence of data used to identify the start of a data block) on \( p_l(t') \) and transmits a signal as a fast-blinking light from an LED.

2.2 Receiver

The Rx diffuses the incoming light by a cross-screen filter, captures the incoming light using a rolling-shutter sensor as images, and converts the images to a signal. Then, the Rx obtains a received payload signal that contains information on the transmitted signal block \( s_l(t') \) by detecting a header (a known sequence of data used to identify the start of a data block) on \( p_l(t') \) and transmits a signal as a fast-blinking light from an LED.

Fig. 2(a) shows the relationship between the transmitted and received signals in the previous RS-VLC system (without a cross-screen filter). As the figure shows, in the previous system the incoming light is captured directly by the rolling-shutter sensor. In a rolling-shutter sensor, only the area of the light source captured on the sensor has signal power strong enough to be suitable for communication. Therefore, the previous system is used mainly for short-range communication, where the light source exists over the entire sensor area (the longer the communication range, the smaller the area with large signal power, resulting in poor communication quality).

Fig. 2(b) shows the relationship between the transmitted and received signals in the proposed RS-VLC system (with a cross-screen filter). In the proposed system, the incoming light passes through the cross-screen filter.
before it is captured by the rolling-shutter sensor. This filter is an optical lens with a slit in one direction, and it diffuses the incoming light in the scanning direction of the sensor. Therefore, it is possible to have a large signal power area on the sensor even if the communication range becomes long, resulting in the improvement of the bit error rate (BER). Moreover, since the proposed system achieves communication while focusing on the transmitted light sources and suppressing their interference, it would be possible to realize multi-user communication and positioning simultaneously.

3 Experiment
3.1 System setup
We evaluated the performance of the proposed system in an indoor experiment. Figs. 3(a) and 3(b) show the experimental environment and parameters, respectively. As the figure shows, both the light source of Tx#1 and that of Tx#2 were placed horizontally because we assume that the transmitter is located on a specific plane considering the vehicle-to-vehicle communication scenario. In this experiment, both Tx#1 and Tx#2 convert random binary data of 10,000 bits, perform PSK modulation, and emit a signal from each LED. The Rx captures images by the sensor with a frame rate of 30 fps and detects the light sources of Tx#1 and Tx#2 by image processing. The Rx then reads the pixel values of the pixel rows above the detected light source and converts them into signals from Tx#1 and Tx#2, performs PSK demodulation, and calculates the BER for each communication range $d$ (Tx#1-Rx distance). Note that the Tx#2-Rx distance is fixed and that the experimental parameters (e.g., transmitted signal power and angle of view) of the previous system and the proposed system are equalized.
Fig. 3. Experimental conditions and results: (a) experimental environment, (b) parameters, (c-1) example of the received frame obtained by the proposed system, (c-2) example of that obtained by the previous system, (d-1) relationship between pixel and pixel value of Tx#1, (d-2) that of Tx#2, (e-1) relationship between communication range \( d \) and BER of Tx#1, and (e-2) that of Tx#2.

### 3.2 Experimental results and discussion

Figs. 3(c)-3(e) show the experiment results. Figures 3(c-1) and 3(c-2) show an example of a received image (when \( d = 1,000 \)) using the proposed system and using the previous system, respectively. The figure also indicates the center coordinates of the transmitted light source detected by image processing [5]. As the figures show, both the proposed and previous systems successfully
detect the coordinates of the transmitted light source from the images.

Figs. 3(d-1) and 3(d-2) show the relationships between a pixel and the pixel values of Tx#1 and Tx#2, respectively (when $d = 1,000$). As the figures show, the pixel value of the proposed system (blue line) is larger than that of the previous system (red line). This is because the cross-screen filter can diffuse the transmitted light in the scanning direction of the rolling-shutter sensor, as described in Section II.

Figs. 3(e-1) shows the relationship between the communication range $d$ and the BER of Tx#1. In the previous system, the BER of Tx#1 (red line) is less than $10^{-3}$ when $d$ is less than 700 mm. In the proposed system, on the other hand, the BER of Tx#1 (blue line) is less than $10^{-3}$ when $d$ is less than 1,400 mm. Therefore, we found that the proposed system can improve the communication range compared to the previous system.

Figs. 3(e-2) shows the relationship between the communication range $d$ and the BER of Tx#2. As the figure shows, the BER of Tx#2 decreases when $d$ increases. This is because when $d$ is large, the interference of the Tx#1 signal with Tx#2 is small, resulting in an increase in the signal-to-noise ratio of Tx#2. In the proposed system, the BER of Tx#2 (blue line) is less than $10^{-3}$ at all distances except 500 mm, which is lower than that of the previous system (red line). This is because the cross-screen filter improves the power of the received signal. Therefore, we confirmed that the proposed system is tolerant against interference from other light sources and is capable of multi-user communication.

4 Conclusion

We proposed an RS-VLC system using a cross-screen filter suitable for ITS applications. The previous systems can achieve only short-range and single-user communication, and long-range multi-user communication and positioning are challenging. To address these issues, we proposed a VLC Rx with a cross-screen filter that diffuses the received light in a specific direction. We evaluated the performance of the proposed system in experiments. The experimental results suggested that the proposed system outperforms the previous system in terms of the received signal power and BER while improving communication range compared to the previous system. We also showed that the coordinates of the transmitted light source can be calculated accurately by processing the images captured by the proposed system and that multi-user communication is possible. Consequently, we conclude that the proposed system can become a viable means of establishing wireless communication links and is suitable for ITS scenarios including vehicle-to-vehicle communication. In the future, we plan to conduct experiments in a real environment.

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