Beyond 100-kbit/s Transmission over Rolling Shutter Camera-based VLC Enabled by Color and Spatial Multiplexing

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Abstract: The camera-based VLC (CVLC) is a promising technique for various application scenarios. For the first time, we demonstrate a rolling shutter based CVLC system with beyond 100-kbit/s data rate by employing color and spatial multiplexing. © 2020 The Author(s)
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1. Introduction

Visible light communication (VLC) is an emerging field of optical communications that remedies the spectrum deficiency issues in RF wireless communication [1]. By 2021, the total number of smartphone users globally will grow to 3.8 billion, under half (48%) of the global population [2]. Therefore, camera-based VLC system (CVLC) using complementary metal-oxide-semiconductor (CMOS) cameras as receivers is a very promising technique that leverages on the ubiquitously available smartphone's camera. By using CVLC, without requiring extra device (e.g., photodiode), ubiquitous and seamless connectivity can be facilitated for smartphone users in various environments to support multiple services and applications, such as advertising information broadcasting, indoor positioning, and vehicle-to-vehicle communication [3]. In the CVLC system, either LEDs or display screens can be used as the transmitter. However, the deployment of LEDs is much larger than that for the screen due to the widely adopted LED technology for illumination. Thus, the LED-based CVLC system is able to be easily deployed. Since the frame rate of the camera is much lower than the modulation bandwidth of LED, the transmission data rate is severely limited in the LED-based CVLC system. Fortunately, the rolling shutter effect (RSE), which exists in nearly all smartphone cameras, can be employed to boost the data rate [4]. However, the transmission capacity of RSE-CVLC is still limited by the resolution, gap-time and exposure time overlapping [5, 6]. To further increase the data rate, color division multiplexing or color shift keying can be utilized since color filters are typically used on the image sensor. In [7], by using color division multiplexing, a theoretical data rate of 2.38 kbit/frame has been achieved with a single camera. In [8], a data rate of 17.1 kbit/s has been demonstrated in the RSE-CVLC system by using dual cameras on a smartphone to receive signals encoded on color channels and gray levels. Further increase in data rate for RSE-CVLC is still very challenging.

In this paper, we report an RSE-CVLC system that achieves a significant 6-fold improvement in data rate compared with that in [8]. To achieve that, we first employ spatial and color multiplexing with three RGB-LEDs as the transmitters. In addition, double-equalization proposed in [9] is adopted to mitigate the time and spatial dispersions to further enhance the data rate. The effectiveness of our proposed scheme is experimentally verified. It is demonstrated that a data rate of 111 kbit/s can be achieved for the three-LED multiplexing system, which is the first demonstration of RSE-CVLE system that realizes a data rate beyond 100 kbit/s.

2. Principles and experimental setup

In the smartphone, the CMOS image sensor's pixels are activated row by row (or column by column), which is termed as rolling shutter. Therefore, if the data modulated on the LED are different for different rows, the resultant data rate can be much higher than the video frame rate. However, in each row, it records the same state of the LED, thus containing much redundancy in all the pixels of a row. If multiple LEDs are placed horizontally, multiple data can be recorded in each row, thus the data rate is multiplied. We propose to employ a cylindrical lens at the receiver side to couple the multiple horizontal lights into the image sensor. Three LEDs can be captured in the same image without interference. To further increase the transmission speed, color division multiplexing is utilized by modulating signals on red, green, and blue channels respectively.

Fig. 1 (a) shows the experimental setup and decoding algorithm. The transmitted signal was generated by a computer and then uploaded to a field-programmable gate array (FPGA, Xilinx Spartan 6). The RGB-LED was driven by a driving circuit. The spacing between the adjacent RGB-LEDs was around 6 cm. After a 40-cm transmission, at the receiver side, a cylindrical lens was used to condense the incoming light. Then, a plano-convex lens was set in front of a smartphone (Huawei P20 Pro). The signal was captured by a video recording with a frame of 60 frames per second (fps). The resolution of each image was 1080×1920. The exposure compensation was set as -4 EV. Based on that, the exposure time and ISO were adjusted automatically. After that, the signal was processed offline. The time-gap between frames was around 51% of one frame period (1/60s), during which the camera could not record any signal. In this paper, the non-return-to-zero (NRZ) on-off keying (OOK) modulation format was used for each color channel. Therefore, for an LED, one symbol transmitted includes three bits. After the bit generation, the signal was constructed packet by packet. Each packet included a 16-bit header and the payload. To assure the robustness in transmission, each packet was repeatedly transmitted three times.

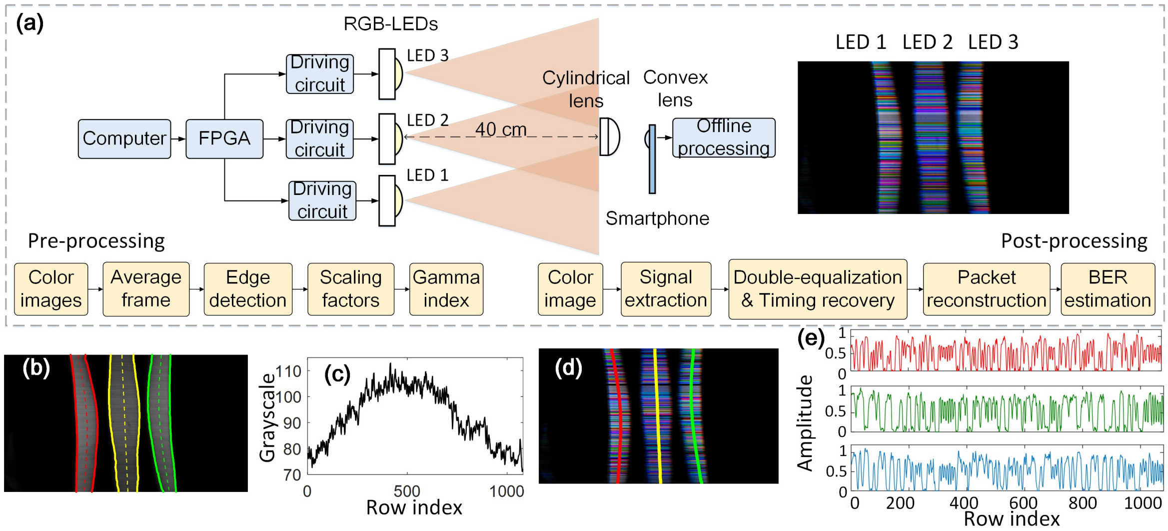

Fig. 1 (a) Experimental setup and decoding algorithm. (b) Edge detection. (c) Scaling factors of LED-1. (d) Signal extraction. (e) Signals of LED-1 after scaling and gamma correction.

The decoding algorithm used is mainly based on double-equalization proposed in [9]. In the preprocessing part, firstly, the edges of three LED patterns are estimated. An average frame is generated by averaging 200 frames, which indicate the mean grayscale of each pixel. Then, the average frame is converted to a binary frame and the edges are detected as shown in Fig. 1 (b). Each LED pattern can be segmented by two edges. The middle line between the two edges is used as the signal extraction curve for that LED pattern. In the post-processing part, the signals are extracted based on the extraction curve of each LED. Next, double-equalization will be applied, which includes the first equalization (scaling and gamma correction) to mitigate the amplitude variation and nonlinear distortion and the second equalization (linear equalization) to compensate the time and spatial dispersions. The scaling factors and gamma index are derived in the pre-processing part, which is detailed in [9]. The optimization of the parameters in the least mean square (LMS) based linear equalizer will be shown later.

3. Experimental results

For each LED, three fractional LMS linear equalizers are applied to decode the received signals on red, green, and blue channels respectively. The BER performance of LED-1, LED-2, and LED-3 under various settings is shown in Fig. 2. In the study, the number of symbols input to equalizer is set as either 1, 3, or 5. The oversampling ratio is set as 1, 2, 3, or 5. For a symbol rate of 36 kbaud/s per LED, the BER with five symbols input is slightly better than that with three symbols input. The BER results have no significant difference when the oversampling ratio is larger than 2. To ensure the optimal performance in this system, the number of symbols is set as 5 and the oversampling ratio is set as 2 in the following. The data for training and test is generated separately and recorded by two videos. In the training procedure, 50 frames of received data are used to initialize the coefficients.

To evaluate the effectiveness of our spatial multiplexing scheme, we estimate the BER performance with single-LED, two-LED, and three-LED multiplexing scheme. In the single-LED case, we also demonstrate the case where the cylindrical lens is not used so that the LED pattern occupies the whole image frame. In the experiment, the symbol rate per LED varies from 32 kbaud/s to 42 kbaud/s. Considering the header inserted in the packet, the data rate of each LED is less than the transmitted symbol rate. The data rate versus symbol rate for different spatial multiplexing is shown in Fig. 2 (d). In Fig. 3 (a), for the single-LED case, a transmission symbol rate of 40 kbaud/s can be achieved, which corresponds to 37 kbit/s data rate (206 symbol/frame×3 bit/symbol×60 frame/second). In the two-LED multiplexing case, under the hard-decision (HD) forward-error-correction (FEC) limit of 3.8×10^{-3}, the symbol rates of 40 kbaud/s and 38 kbaud/s can be achieved by LED-1 and LED-2, respectively, as shown in Fig. 3 (b). Considering the BER for the aggregated data of the two channels, the symbol rate of 40 kbaud/s can still be used for both transmitters under the HD-FEC limit, which improves the total data rate to 74 kbit/s. When using three LEDs as transmitters with a symbol rate of 40 kbaud/s each, the BER performance is under the HD-FEC limit and the total data rate is 111 kbit/s. Therefore, our proposed spatial multiplexing scheme can effectively boost the transmission data rate from 37 kbit/s to 111 kbit/s, with the data rate enhanced significantly by three times.

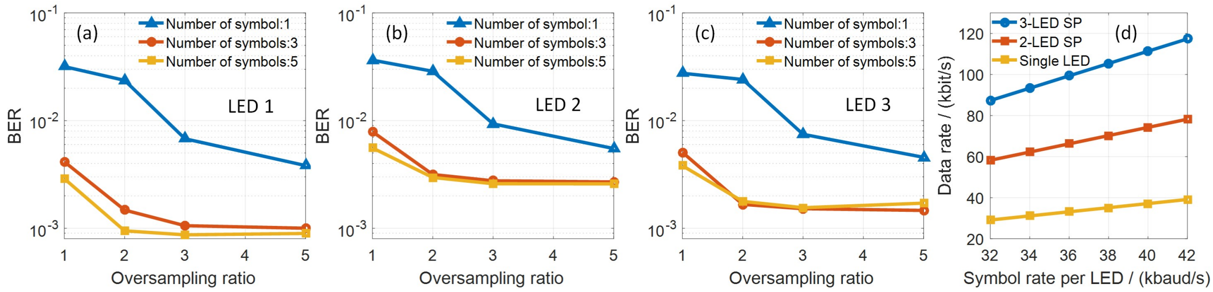

Fig. 2 Optimization of oversampling ratio and number of symbols input to the equalizer using (a) LED-1, (b) LED-2, and (c) LED-3. (d) Data rate versus symbol rate per LED for different spatial multiplexing.

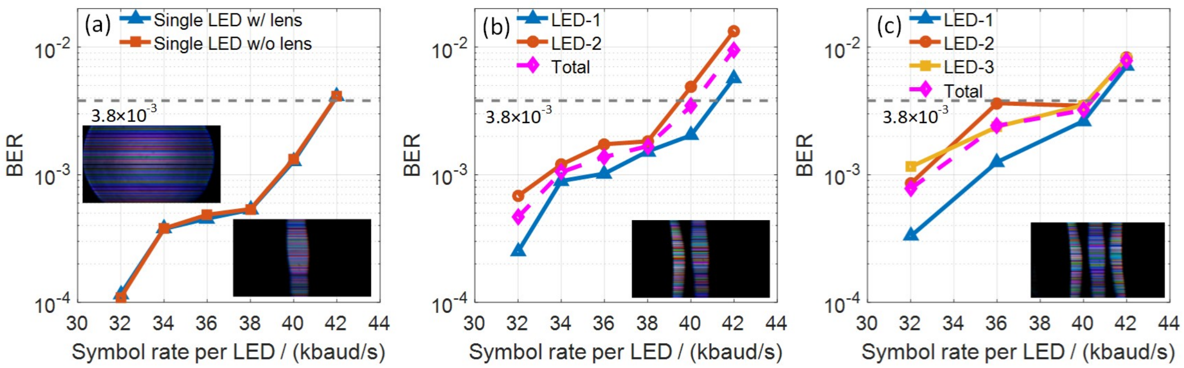

Fig. 3 BER performance with (a) single-LED, (b) two-LED, and (c) three-LED multiplexing.

4. Conclusion

In this paper, we propose and experimentally demonstrate an RSE-CVLC system based on color and spatial multiplexing. To capture multiple LEDs in one image frame, the light output from multiple RGB-LEDs is focused in the horizontal direction. Furthermore, the double-equalization is applied to combat the time and color dispersions. The experimental results show that, the data rate of 111 kbit/s can be achieved for three-LED multiplexing scenario. To the best of our knowledge, this is the first report of an RSE-CVLC system with a data rate beyond 100 kbit/s. *This work was supported by HKSAR RGC grant (GRF 14201818).*

5. References

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