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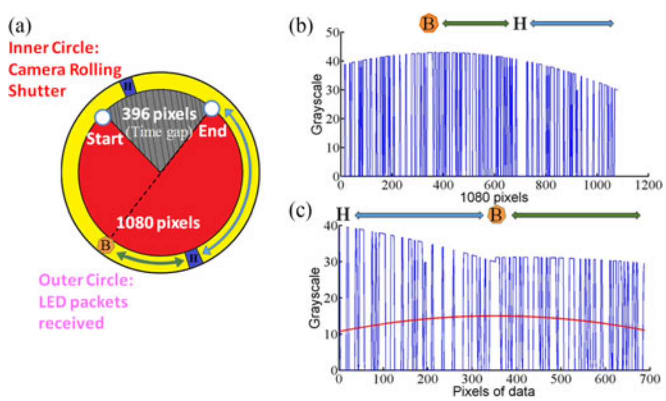

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Beacon Jointed Packet Reconstruction Scheme for Mobile-Phone Based Visible Light Communications Using Rolling Shutter

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Abstract: Mobile-phone based visible light communication (VLC) is an attractive method for optical wireless communication. However, the data rate is typically limited by the complementary metal–oxide–semiconductor image sensor frame rate and the processing time gap in the rolling shutter mode operation. Here, we propose and demonstrate a packet-reconstruction scheme, known as beacon jointed rolling shutter pattern scheme. The mobile-phone based VLC data rate can be increased to a record 10.32 kb/s. The implementation algorithm is discussed; and the bit-error-rate experimental evaluations at different transmission distances and horizontal offsets are performed.

Index Terms: Light emitting diode (LED), visible light communication (VLC), CMOS image sensor.

1. Introduction

Having the advantages of license-free and electromagnetic interference (EMI) free transmission with high security, visible light communication (VLC) will emerge as one of the promising technologies for future wireless communications [1]–[5]. VLC can combine lighting and communication simultaneously; hence can reduce the power consumption and deployment cost. The white light emitting diode (LED) for lighting can be used as the VLC transmitter (Tx). As mobile-phone embedded with image sensor is very common, using the image sensor for VLC can significantly reduce the deployment cost when compared with the VLC using positive-intrinsic-negative (PIN) photodiode (PD) or avalanche photodiode (APD) as VLC receiver (Rx). However, a great challenge in the mobile-phone based VLC is the limited frame rate of the image sensor, which can greatly limit the transmission data rate. An under-sampled frequency shift on-off keying (UFSOOK) technique is proposed; and a data rate of 15 bit/s was demonstrated in image sensor VLC [6]. Then, an under-sampled phase shift on-off keying (UPSOOK) format using dual LED with a designated mapping and framing method was proposed; and a data rate of 150 bit/s over $>$10 m transmission distance

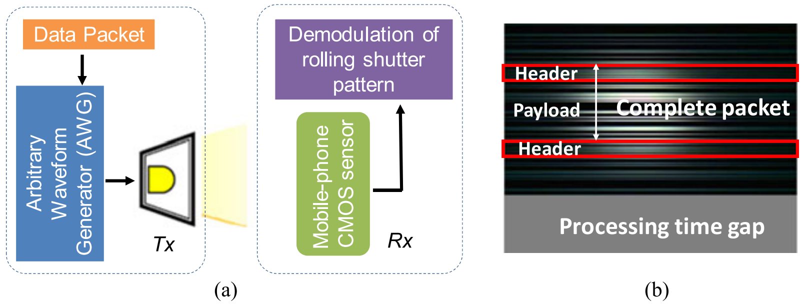

Fig. 1. (a) Experimental setup of the mobile-phone based VLC system using CMOS image sensor. (b) Rolling shutter pattern captured by the CMOS image sensor.

can be achieved [7]. A data rate of 150 bit/s (3×50 bit/s) can also be achieved by using red-green-blue (RGB) LEDs in image sensor based VLC [8]. In order to further increase the data rate, a tailor-made image sensor with built-in PIN PD array was proposed [9]. However, this tailor-made sensor needs relatively complicated fabrication process and is not commercially available. Using the rolling shutter effect of complementary metal–oxide–semiconductor (CMOS) image sensor is a promising technique to increase the mobile-phone based VLC data rate [10], [11]. Recently, by using techniques including blooming mitigation and extinction ratio (ER) enhancement to improve the demodulation of the rolling shutter pattern, and a data rate of 5.76 kbit/s was reported [12]. VLC using two dimensional (2D) LED array [13], [14] or 2D liquid crystal display (LCD) [15] Txs can increase the transmission data rate by using spatial division multiplexing. However, decoding the 2D rolling shutter pattern received by the CMOS image sensor is challenging since the rolling shutter pattern produced by different LEDs in the LED array can merge together. Hence, additional signal processing schemes are required to separate these rolling shutter patterns from different LEDs. In addition, decoding the 1D rolling shutter pattern can allow higher offset tolerance between the LED Tx and CMOS image sensor; and the offset tolerance has been studied [12]. On the other hand, in order to decode the 2D rolling shutter pattern, all the LED sources are needed to be focused at the image sensor; hence reducing the offset tolerance and flexibility during decoding.

In this work, we propose and demonstrate a packet-reconstruction scheme, known as beacon jointed rolling shutter pattern scheme, to increase the data rate of the mobile-phone based VLC. By using the beacon jointed rolling shutter pattern scheme, the original data packet can be recovered. The implementation algorithm is discussed; and the bit-error-rate (BER) experimental evaluation is performed.

2. Algorithm and Experiment

Fig. 1(a) shows the experimental setup of the mobile-phone based VLC system using CMOS image sensor as VLC Rx. The data packet is constructed by using Matlab, and it is applied to a phosphor-based white-light LED (Cree XR-E) with color temperature of 5500 K via an arbitrary waveform generator (AWG, Tektronix AFG3252C) with sampling rate of 2 GSample/s and bandwidth of 240 MHz. A lens is used in front of the LED with the field of view (FOV) of 10°. The Rx is a mobile-phone CMOS image sensor (Apple Iphone6) with resolution of 1920×1080 pixels. When the CMOS image sensor is operated in rolling shutter mode, the pixel row is activated sequentially; hence bright and dark fringes can be captured in an image frame as shown in Fig. 1(b). However, one challenge of using CMOS image sensor in VLC is that after the all pixel rows are exposed in an image frame, there is a frame-to-frame processing time gap [10], [11]. During this processing time gap, the CMOS image sensor cannot detect any light; and this time gap can be up to 30% of the frame period. This means that unlike the PD or APD, the image sensor is operated in “burst-mode”.

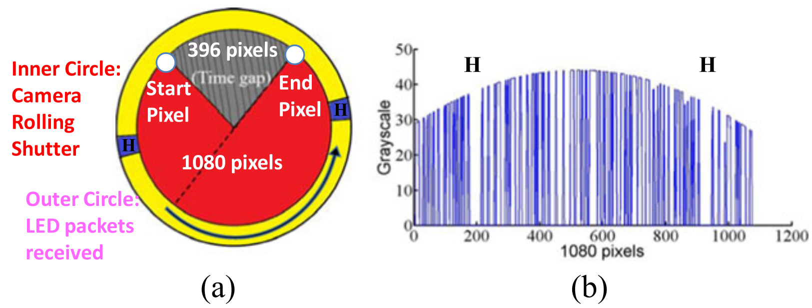

Fig. 2. (a) Experimental setup of the mobile-phone based VLC using CMOS image sensor. (b) Rolling shutter pattern captured by the CMOS image sensor.

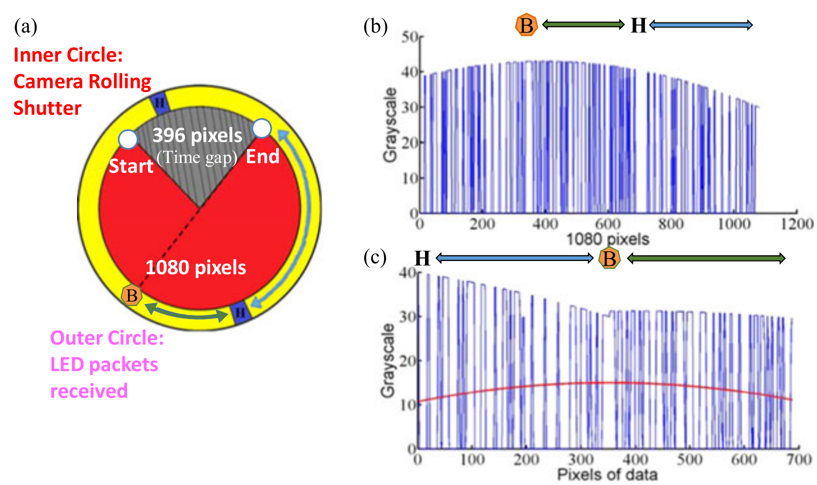

Fig. 3. (a) Schematic diagram to illustrate only one header "H" is observed. The grayscale pattern (b) show an incomplete data packet, with "B" and "H" indicating the beacon and header respectively; (c) after the beacon jointed rolling shutter pattern scheme to recover a VLC packet.

We now describe the operation principle of the proposed beacon jointed rolling shutter scheme. Fig. 2(a) shows the schematic diagram, in which the inner circle represents the CMOS image sensor, and the number of pixel rows is P_{cmos}. The "Start" pixel, "End" pixel, and the processing time gap are also indicated in Fig. 2(a). The processing time gap can be transformed to the time needed for the pixel row exposure. In our measurement, the processing time gap is equivalent to the exposure time needed for 396 pixel rows (P_{gap}), and this value is a constant for the smart phone used in the experiment (i.e., Iphone 6). Hence, the total number of pixels in the inner circle can be represented as: $P_{cmos} + P_{gap} = 1080 + 396 = 1476$ pixels.

As mentioned before, the outer circle is rotating continuously, and one of the headers will fall in the processing time gap as shown in Fig. 3(a). This means that a complete data packet cannot be received in an image frame; and Fig. 3(b) shows the grayscale pattern of an incomplete data packet received. Hence the proposed beacon jointed rolling shutter pattern scheme is applied. First, the "End" pixel is found, which is the 1080th pixel (i.e., the maximum number of pixel rows in the image sensor). Then, the beacon, which is at the opposite side of the inner circle can be positioned, which is equal to the P_{cmos}–$(P_{cmos} + P_{gap})/2 + 1 = 1080$–$(1080 + 396)/2 + 1 = 343$rd pixel in the inner circle, as indicated as "B" in Fig. 3(a) and 3(b). Finally, the grayscale pattern from "B" to the beginning of "H" can be copied and pasted to the "End" pixel; hence the complete VLC packet can be recovered as shown in Fig. 3(c).

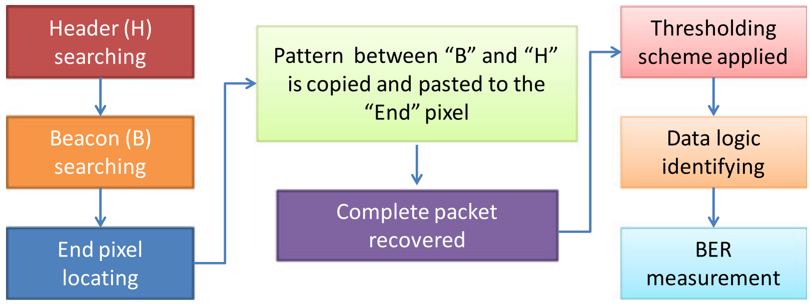

Fig. 4. Flow-diagram of the implementation of the beacon joined rolling shutter pattern scheme.

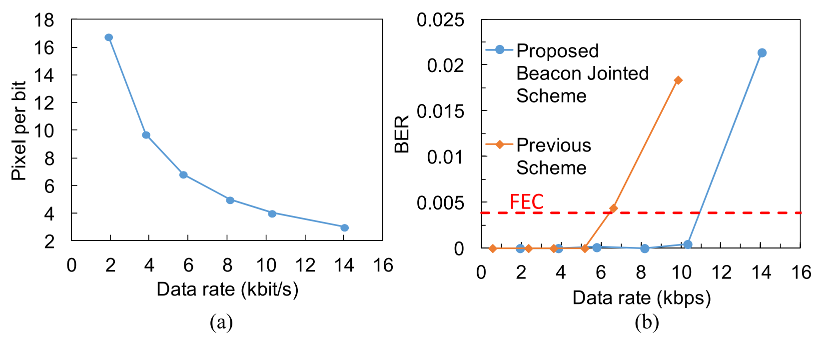

Fig. 5. (a) Pixels per bit and the (b) BER performance at different data rates.

Fig. 4 summaries the implementation of the beacon joined rolling shutter pattern scheme in flow-diagrams. After the complete packet is recovered, thresholding is required to identify the data logic 1 and data logic 0. Different thresholding schemes, such as polynomial curve fitting, iterative scheme or quick adaptive scheme can be used [16]. After the thresholding scheme is applied, the data logic 1 and data logic 0 can be identified. By comparing the received data logic with the transmitted data logic, the BER can be obtained.

3. Results and Discussions

In each packet, a 12-bit header is used; and a 32-bit, 64-bit, 96-bit, 136-bit, 172-bit and 234-bit are used as the payloads. They represent the net data rates of 1.9 kbit/s (32 bit/frame $\times$ 60 frame/s), 3.84 kbit/s, 5.76 kbit/s, 8.16 kbit/s, 10.32 kbit/s and 14.04 kbit/s respectively. Different payload lengths are used to evaluate different pixel per bit of the CMOS image sensor. On-off keying (OOK) modulation format is used. Fig. 5(a) shows the pixels per bit at different data rates. It is observed that when the data rate increases, the number of pixels required to represent one bit will decrease. In the experiment, at the data rate of 14.04 kbit/s, 3 pixel rows are needed to represent a bit. Hence, if the CMOS image sensor with higher resolution (4K or 8K) or higher frame rate is available, much higher data rate can also be achieved by the proposed scheme. Fig. 5(b) shows the BER performance of the proposed beacon jointed rolling shutter scheme when compared with previous scheme [12] at the illuminance of 1100 lux. We cannot measure any error count when the data rate is increased up to 8.16 kbit/s, which stands for the 4.99 pixel per bit. At the data rate of 10.32 kbit/s (the pixels per bit is 4.01), the BER is 1.01×10^{-4}, and this satisfies the 7% forward error correction (FEC) limit. This net data rate is about two times when compared with the recorded rolling shutter technique in [12]; or about 60 times when compared with image based VLC using global shutter technique [8]. It is worth to point out that in the CMOS image sensor, the pixel row is activated without waiting

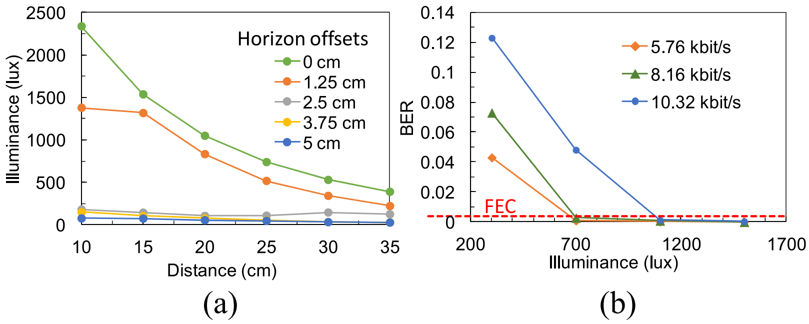

Fig. 6. (a) Measured illuminance received by the image sensor at different mobile-phone based VLC transmission distances and at different horizontal offsets (b) BER performance of different data rates and at different illuminance of the proposed beacon jointed rolling shutter pattern scheme.

for the exposure completion of the previous pixel row. By using the proposed beacon jointed rolling shutter pattern scheme, a recorded net data rate of 10.32 kbit/s can be achieved.

Then, we evaluated the proposed mobile-phone based VLC system at different transmission distances and at different Rx horizontal offsets with respective to the LED Tx. In the experiment, as long as the LED Tx can be focused by the image sensor, we found that the BER performance is only affected by the received illuminance. Fig. 6(a) shows the measured illuminance received by the image sensor at different VLC transmission distances and at different horizontal offsets. At the case of no horizon offset (the green curve), the illuminance decreases continuously from 2340 lux to 530 lux when the transmission distance increases from 10 cm to 30 cm. When the horizon offset increased to 1.25 cm (the orange curve), the received illuminance decrease to 1380 lux and 342 lux at the transmission distances of 10 cm and 30 cm respectively. It is worth to mention that Fig. 6(a) is based on our experimental condition of using a single LED Tx. Fig. 6(b) shows the BER performance of different data rates and at different illuminance of the proposed beacon jointed rolling shutter pattern scheme. We can observe that at the illuminance of 700 lux, no error court is observed at the data rates of 5.76 kbit/s and 8.16 kbit/s. When the data rate is 10.32 kbit/s, the illuminance is 1100 lux, which is corresponding to a 20 cm link distance without horizontal offset.

4. Conclusion

Mobile-phone based VLC can be a potential candidate for the next generation wireless communications, and simultaneously providing indoor lighting. The data rate of mobile-phone based VLC is typically limited by the CMOS image sensor frame rate and the processing time gap in the rolling shutter mode operation. We proposed and demonstrated a packet-reconstruction scheme, known as beacon jointed rolling shutter pattern scheme. By using the beacon jointed rolling shutter pattern scheme, the original data packet can be recovered. By using the proposed scheme, a net data rate of 10.32 kbit/s can be achieved. The proposed mobile-phone based VLC system at different transmission distances and at different Rx horizontal offsets with respective to the LED Tx were also evaluated. The implementation algorithm of the beacon jointed rolling shutter pattern scheme was discussed; and the BER experimental evaluation was performed.

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