Performance Analysis and Evaluation of Outdoor Visible Light Communication Reception

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Abstract. Thanks to the properties of light emitting diodes (LEDs), visible light communication (VLC) technology is very competitive in providing high-speed communication and high-precision positioning services. Compared with indoor systems, outdoor VLC faces more challenges due to the strong ambient light disturbance. In this paper, we evaluate and analyze the performance of outdoor VLC systems by conducting outdoor experiments on VLC systems with two types of receivers. For the image sensor-based VLC system, we measure the hit rate and analyze the captured rolling shutter patterns by image processing methods. For the photo detector (PD)-based VLC system, we observe the received signal by an oscilloscope and add a DC-offset to enhance the performance. The results show that when the image sensor-based VLC system is placed in the sun, it can achieve the maximum hit rate of 55% under the communication distance of about 0.3 m. Besides, the PD-based VLC system with a DC-offset can successfully identify and decode transmitted signals under much longer distance. However, PD-based receiver strictly requires the alignment between the LED and the receiver and is not readily available on mobile devices.

Keywords: Visible light communication · Photo detector and image sensor · Outdoor free space optical communication

1 Introduction

Visible light communication (VLC) systems utilize light emitting diodes (LEDs) as transmitters to transmit data at a high speed and provide illumination at the same time [1]. Due to the light-of-sight (LOS) property of visible light beam, VLC signals in different rooms are independent and private. Besides, compared with radio frequency (RF) systems, VLC systems have higher bandwidth and require lower cost. Therefore, VLC technology is very competitive in providing indoor intelligent illumination [2], communication [3] and positioning [4] services.

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VLC can also be applied to outdoor scenarios. Existing researches on outdoor VLC systems mainly focus on vehicle to vehicle (V2V) [5] and vehicle to infrastructure (V2I) [6] systems. If we enable VLC technology on mobile devices and integrate it with smart street lightings, the high-precision positioning and high-speed data rate performances of VLC technology and the wide distribution of street lightings can intensely contribute to the implement of diverse public services. However, outdoor applications face more challenges due to the strong ambient light disturbance [7] and optical defects in lens. The power of the incident parasitic light can be up to 10 mW/cm^2, compared to the power of the light containing the information which can be as low as few μW/cm^2. Addressing and solving these challenges enables VLC technology in outdoor application and leads to the perspective of fully exploiting the advantages of VLC [7].

In this paper, we conduct experiments on outdoor VLC systems with two types of receivers including photo detector (PD) and image sensor. We measure the hit rates of the image sensor-based VLC system and analyze the captured rolling shutter patterns by image processing methods. Furthermore, we evaluate the performance of PD-based VLC systems and add a DC-offset to filter the high-intensity ambient sunlight.

2 VLC Reception

For outdoor VLC systems, the main challenge is to overcome the high light intensity of ambient sunlight. We conduct outdoor experiments on image sensor-based VLC system and PD-based VLC system to evaluate their availability in outdoor environments.

2.1 Two Types of VLC Receivers

Compared with PDs, image sensors are cheaper and more widely equipped on mobile devices. Figure 1 shows an image sensor-based VLC system. The LED-based transmitter is controlled by a VLC enabled LED driver to transmit optical waveforms. The bright bars correspond to the transmitted data 1 and the dark bars correspond to the transmitted data 0. Then at the receiver side, the CMOS image sensor on the smart phone captures the pixel from top to bottom [8] ad recodes the rolling shutter patterns.

In a PD-based VLC system, the PD-based receiver converts the optical power to electrical current. Compared with an image sensor-based VLC system, a PD-based system can achieve higher data rate. The detection areas of PDs are very small. Therefore, PD-based VLC systems require precise alignment between LED and PD for signal detection [8]. The studies on PD-based VLC systems only provide simulation results [10].

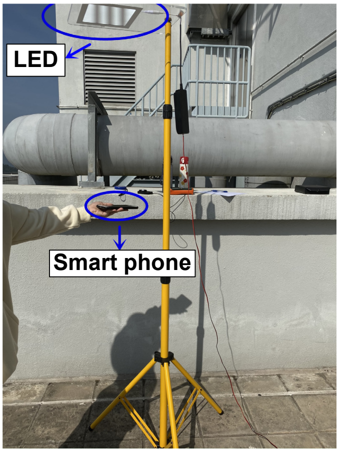

Fig. 1. The image sensor-based outdoor VLC system

2.2 Experiments on the Image Sensor-Based Outdoor VLC System

We evaluate the performances of the image sensor-based outdoor VLC system in two cases. In case 1, we place the system in the sun as shown in Fig. 1 and the sunlight intensity is 67,800 lx. In case 2, we measure the hit rates in the shade with light intensity of 6,800 lx. The power of the lamp panel is 18 W.

Table 1. The results of outdoor image sensor-based VLC experiments.

Case 1	Distance (m)	1.0	0.9	0.8	0.5	0.3
	Hit rate (%)	2	4	11	40	55
Case 2	Distance (m)	1.0	0.9	0.8	0.5	0.3
	Hit rate (%)	6	60	93	97	97

The experiment results are given in Table 1. The results show that the hit rates of the VLC transmission in the sun are much lower than these in the shade. In case 1, when the distance is about 0.3 m, we can obtain the maximum hit rate of 55%. However, the transmission distance of 0.3 m is much shorter than the required minimum detection distance for outdoor communication and positioning.

When we conduct the outdoor experiment in the sun, the very low hit rate is due to the indistinct rolling shutter pattern captured by the camera as shown in Fig. 2. Then we perform image processing algorithms to analyze the performance.

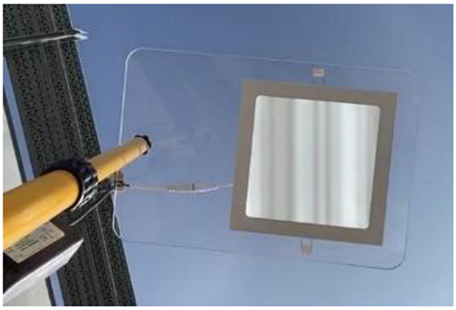

Fig. 2. The rolling shutter patterns captured in the sun

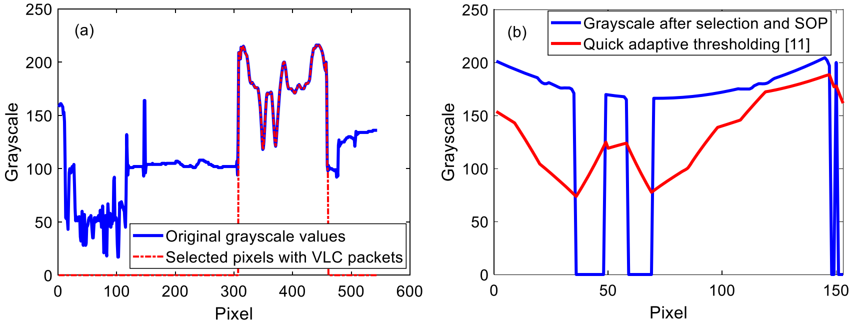

Fig. 3. The grayscale values of the rolling shutter patterns captured in the sun

Firstly, we extract the pixels with VLC pocket as shown in Fig. 3(a). Then second-order polynomial (SOP) and quick adaptive thresholding [11] are applied to reduce the extinction ratio fluctuation and identify data logic. It can be obviously observed from the Fig. 3(b) that the rolling shutter patterns cannot be decoded correctly.

Compared with the patterns captured in the sun, the rolling shutter patterns captured in the shade are much more distinct and clearer as shown in Fig. 4. Then we perform similar image processing algorithms to analyze the performance and the results are illustrated in Fig. 5. We can find that the patterns can be successfully decoded.

Fig. 4. The rolling shutter patterns captured in the shade

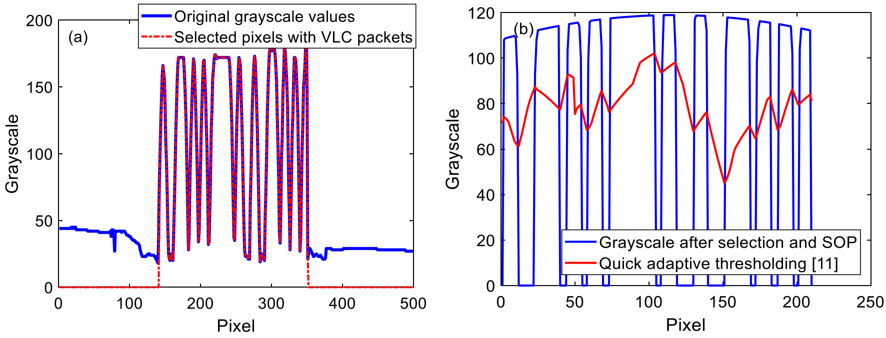

Fig. 5. The grayscale values of the rolling shutter patterns captured in the shade

2.3 Experiments on PD-Based Outdoor VLC System

To evaluate the performance of the PD-based outdoor VLC systems, we set a PD as receiver and use an oscilloscope to observe the signals as shown in Fig. 6. Since the PD is remarkably sensitive to receiving angle, we use a 1 W bulb to assure the alignment between the PD and the LED. The sunlight intensity is the same as that in case 1. The very high sunlight covers the light transmitted by the LED and the signal received by the PD is like noise. Therefore, the PD cannot recover the transmitted signals.

To filter the high-intensity ambient sunlight, a DC-offset is applied at the PD [12]. Then the pattern received by the PD is with very slight flash as shown in Fig. 7. The maximum detection distance of the PD-based VLC system is about 40 cm. Compared with an image sensor-based VLC system, a PD-based system can achieve much longer transmission distance with a lower power transmitter.

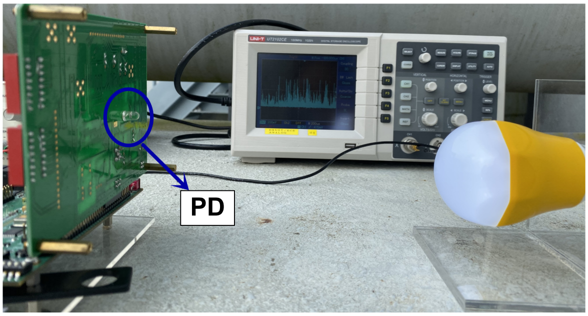

Fig. 6. The PD-based outdoor VLC system

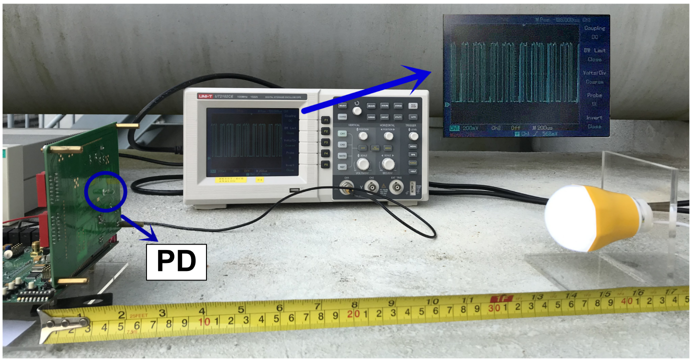

Fig. 7. The PD-based outdoor VLC system with DC-offset

3 Conclusion

In this paper, we evaluate the performances of outdoor VLC systems with two types of receivers. From the measured hit rates and captured rolling shutter patterns we can find that when the image sensor-based VLC system is in the sun, the communication distance is much shorter than the required minimum detection distance. Compared with image sensor-based systems, PD-based systems with DC-offset can successfully identify and decode transmitted signals under much longer distance of the same sunlight intensity. However, due to the strict requirement of the alignment between the LED and PD-based receiver, existing PD-based VLC systems cannot achieve angular diversity and provide communication and positioning services for mobile devices in both outdoor and indoor environments.

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