Experimental Demonstration of Optical Camera Communications Supporting Dimming Control

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***Abstract*—We experimentally demonstrate an optical camera communication system which achieves full-range dimming control using pulse width modulation with dimming levels from 10% to 100% at data rates within 2.55 Kbit/s and bit error rates <4.2×10^{-3}.**

Keywords—Visible light communication, dimming control, optical camera communication

I. Introduction

Indoor visible light communication (VLC) based on light-emitting diodes (LEDs) has become a powerful alternative or complement to radio frequency communications, offering multiple functions such as illumination, data transmission, and localization [1]. To meet different illumination requirements in our daily life, the light intensity of LEDs needs to be adjusted accordingly. Thus, the dimming control function is indispensable for VLC systems. Dimming control also caters to the concept of energy saving and carbon neutrality [2]-[4]. There have been a lot of theoretical studies on the dimming control issue in indoor VLC systems. They mainly focus on how to increase the spectrum efficiency of VLC systems with dimming control by proposing different schemes involving techniques such as pulse position modulation [2]-[3], pulse width modulation (PWM) [3]-[4], multi-pulse position modulation [5]-[6], orthogonal frequency division multiplexing [4]-[6], and time domain hybrid modulation [7]. There are also some experimental studies on VLC dimming control [8]. However, all these works on dimming control have only focused on photo-detector (PD) receivers. Very few studies have considered other types of receivers.

Recently, by embedding complementary metal-oxide-semiconductor (CMOS) image sensors as a receiver, the optical camera communication (OCC) technology has become a good choice for setting up an indoor VLC link [9]. Compared with PDs, cameras mounted on mobile-phones are more widely used. Current research on OCC mainly focuses on improving data rates or transmitting signals over longer distances. For example, in [10], based on the rolling shutter effect, an OCC link was established for a mobile-phone camera with a data rate higher than its frame rate. In [11], a dynamic column matrix selection algorithm was proposed to extend the transmission distance of the OCC system and enable terminal mobility. However, there is still little research on the dimming control issue of OCC systems, and therefore this paper aims to fill this gap.

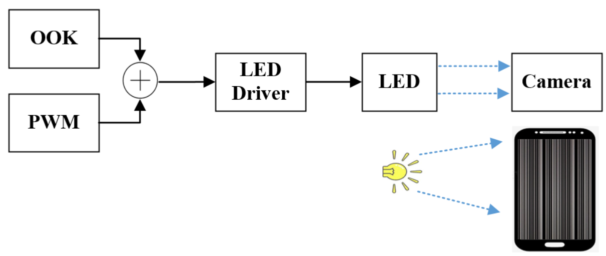

Fig. 1. Schematic diagram of the proposed system.

In this paper, we propose and demonstrate an OCC system based on a dimmable LED and a mobile-phone camera. We combine PWM and on-off-keying (OOK) signals to achieve simultaneous dimming control and data transmission. By controlling the duty cycle of PWM, the system can support a full-range dimming control function with dimming levels from 10% to 100%, and the data rates can be adjusted up to 2.55 Kbit/s at bit error rates (BERs) less than 4.2×10^{-3}. The proposed dimming control scheme for OCC systems is verified by experiments.

The rest of this paper is organized as follows. In Section II, we introduce the principle and the experimental setup of the OCC system with dimming control. Section III provides the experimental results and discussions. Finally, Section IV concludes the paper.

II. Principle and Experimental setup

A. Principle

Fig. 1 shows the proposed OCC system which supports dimming control. We use PWM to control the brightness of a LED light source. At the OCC transmitter, bipolar OOK signals are generated and loaded onto the "ON" period of PWM, and during the "OFF" period of PWM there is no signal transmission. Then, by modulating an LED driver, the combined signals are emitted from the LED. At the receiver,

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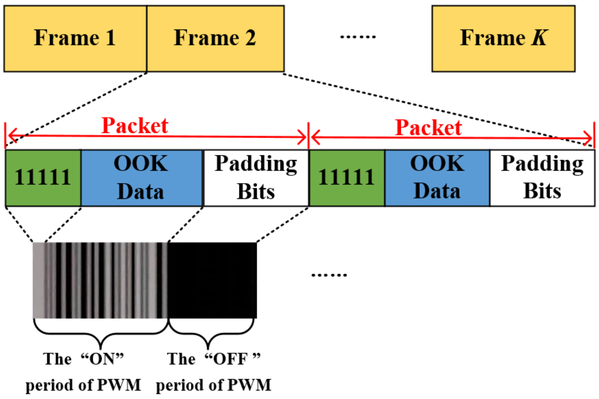

Fig. 2. The data structure of transmitted frames (D = 60%).

to recover the OOK signals, a mobile-phone camera is employed to capture the image frames carrying data information in the form of bright and dark stripes. In this way, by adjusting the duty cycle of the PWM, we can control the dimming levels of the LED while performing OCC.

Fig. 2 shows the data structure of the transmitted frames when the duty cycle D of PWM is set to be 60%. Here, the total length N of each packet is fixed, which contains a 5-bit header ("11111"), the effective OOK data, and the padding bits (for dimming control and not carrying data) used for dimming control. The header and OOK data are modulated during the "ON" period of PWM. The length of padding bits is equal to that of the "OFF" period of PWM. When the duty cycle of PWM is 1, i.e., a full dimming level, there is no padding bits in data packets. When reducing the duty cycle, padding bits are filled in and the length of effective data in a packet becomes shorter, which is given by:

$$N_e = N \cdot D - 5. \tag{1}$$

For a practical CMOS camera, it is unable to continuously receive information from two adjacent frames when shooting. This is due to the processing time between two consecutive frames, which is called "blind" period [11]. During the "blind" period, the camera cannot receive any data. Therefore, to avoid data loss in the "blind" period, we repeat the data packet twice or more in each frame to ensure that at least one complete packet can be captured by the camera. After constructing the data frames, the transmitted symbol rate of OCC signals during PWM "ON" periods is determined basded on the parameters of the camera:

$$V = \frac{2 \cdot N \cdot F}{(1 - B\%)}, \tag{2}$$

where F is the frame rate of the camera, $B\%$ is the proportion of the "blind" period in each frame. Based on Eqs. (1) and (2), the transmitted signal can be defined.

At the receiver, the camera captures the frames for signal demodulation. To extract OOK signals, we need to compare the grayscale value of each pixel in a selected row of each frame with a decision threshold, which is calculated by:

$$T = \frac{\sum_{1 \le i \le L, g(i) > t} g(i)}{l}. \tag{3}$$

Here, L is the total number of pixels, $g(i)$ is the grayscale value of the pixels during the "ON" period of PWM, and l is the total number of $g(i)$. In practice, $g(i)$ is affected by both noise and consecutive "0"s. To improve decision accuracy, we only

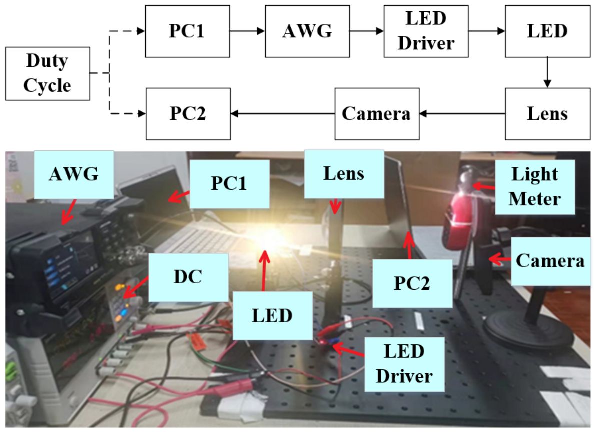

Fig. 3. Experimental setup of the proposed OCC system.

count $g(i)$ whose value is larger than a threshold t, e.g., in this work, we set $g(i)$>15. Based on the threshold decision, the transmitted data can finally be recovered.

B. Experimental Setup

To verify the feasibility of the OCC system supporting dimming control, we design a proof-of-concept experiment as shown in Fig. 3. The system can achieve various diming levels by using different duty cycles of PWM (D = 10%, 20%, 30%, …, 100%). The distance between the LED and the camera is 20 cm. A light meter beside the camera evaluates the brightness at different dimming levels.

At the transmitter, the combined OOK and PWM signals are generated by PC1 and then fed to an arbitrary waveform generator (AWG, RIGOL DG2102). The modulation index of OOK is 0.67 as compared with the DC component of the PWM "ON" slot. To evaluate the link performance under different data rates, we set N to be 70 or 90. Then, based on Eq. (2), the transmitted OOK symbol rate during PWM "ON" periods at the AWG can be calculated as 5 Ksymbols/s for N = 70 and 6.2 Ksymbols/s for N = 90, respectively. For a specific D, the AWG outputs a corresponding analog signal to the LED driver to control the brightness of an LED (Cree XLamp XR-E). A plano-convex lens is placed in front of the LED to convert the divergent light into a parallel light.

After the free-space transmission, the optical signals are recorded as a video (with a duration of several minutes) by a mobile-phone camera (Xiaomi 9). For Android smartphones, we use the camera app named FiLMic Pro for video recording. To mitigate the blooming effect, we use a piece of oil paper as the light diffuser in front of the camera. To record the video successfully at different dimming levels, the parameters of the camera need to be adjusted carefully. In this system, the camera records the video at a frame rate of 30 frames per second (fps) with a resolution of 1080 × 1920. The exposure time needs to be adjusted based on specific duty cycles. For a shorter duty cycle, because the LED brightness is relatively low, a long exposure time is required; otherwise, images would be dark. Thus, we set the exposure time at 1/3840 s for D from 10% to 40%. In contrast, for a long duty cycle, to avoid the blooming effect, we set the exposure time at 1/7680 s or 1/15360 s for D from 50% to 100%. The sensor sensitivity (ISO) of the camera is fixed at 4000.

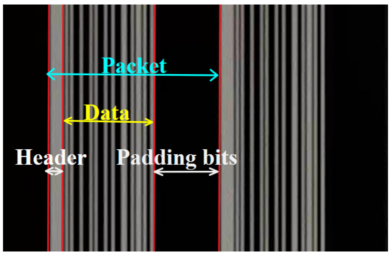

Fig. 4. Example of an image frame at the duty cycle of 60% (N = 70).

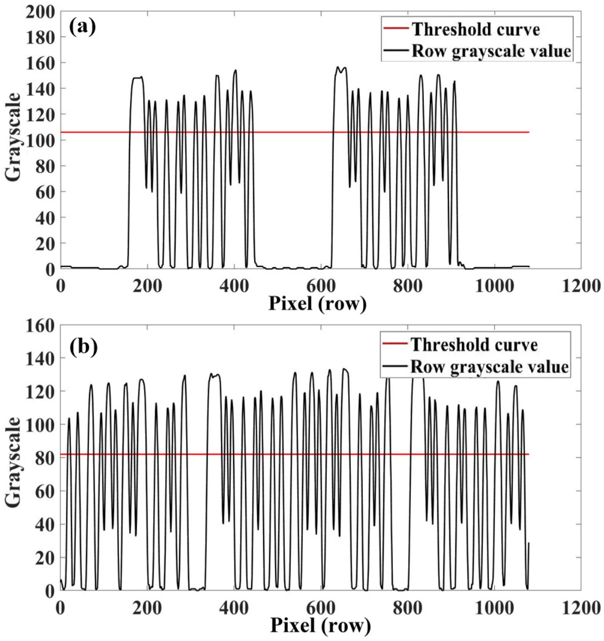

Fig. 5. Threshold decision under different duty cycles: (a) D = 60%; (b) D = 90%.

To recover the original data, the captured video needs to be processed offline. We input the video to PC2 and then divide the video into image frames using MATLAB. In each frame, a row of pixels near the image center is selected, where the grayscales of these pixels are extracted and normalized. A low-pass filter (LPF) with coefficients of [1/3, 1/3, 1/3] is used to smooth the grayscale curve. Then, based on Eq. (3), the "OFF" period of PWM can be removed and the OOK data can be recovered after down-sampling and frame synchronization. Finally, by comparing the data in PC1 and PC2, the BER can be obtained.

III. Results and Discussions

To evaluate the performance of the proposed OCC system, we first show in Fig. 4 an example of an image frame captured by the mobile-phone camera when the duty cycle of PWM is 60%. Here, the total length of each packet is 70. In Fig. 4, we see that the image frame contains two identical data packets and one of them will be used for signal demodulation. During PWM "ON" periods, the widest bright stripe corresponds to the header followed by effective data. During PWM "OFF" periods, the widest dark stripe corresponds to padding bits.

Fig. 5(a) shows the grayscale value of each pixel in the selected row of the image frame in Fig. 4. The threshold is calculated based on Eq. (3), which can clearly distinguish "0" bits and "1" bits based on the received signals. Note that, the grayscales of pixels change according to specific data information. For example, for data contains consecutive "1"s

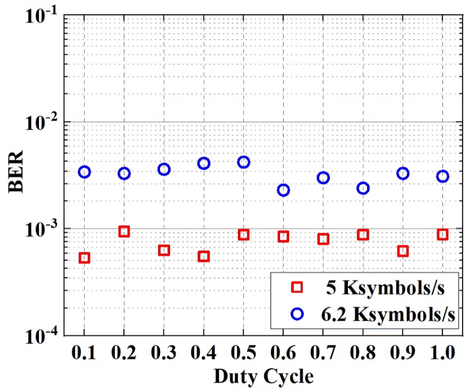

Fig. 6. BER performance under different duty cycles.

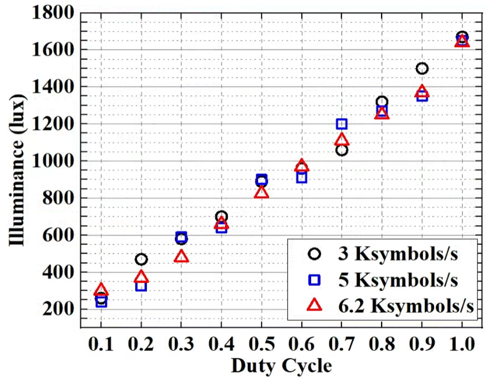

Fig. 7. Illuminance measured under different dimming levels

or consecutive "0"s, the grayscale will approach to maximum or minimum values, respectively, which benefits threshold decision. Otherwise, the fluctuation of the grayscale values becomes smaller. This indicates that for the OCC system with dimming control, adopting higher data rates may result in ambiguity between bright and dark stripes, which degrades link performance. In Fig. 5(b), we also show the grayscale values for threshold decision when D = 90%, which verifies the conclusion that the grayscales are affected by specific data information.

Next, we evaluate the BER performance of the proposed OCC system. Fig. 6 shows the measured BERs under different dimming levels from 10% to 100%. Here, the symbol rate of OOK during PWM "ON" periods at the AWG is set to be 5 Ksymbols/s (N = 70) and 6.2 Ksymbols/s (N = 90) for performance comparison. For the case of 5 Ksymbols/s, a BER less than 9.46×10^{-4} can be achieved when the duty cycle varies from 10% to 100%. When increasing the symbol rate to 6.2 Ksymbols/s, the link performance degrades and a BER less than 4.2×10^{-3} can still be achieved while performing full-range dimming control. If we further increase the symbol rate of OOK at the AWG, the BER will increase due to the ambiguity between bright and dark stripes. Therefore, to achieve reliable link quality, the maximum data rate in our system is calculated as: $(90\times100\%-5)$ bits/frame × 30 frames/second = 2.55 Kbit/s, when the duty cycle is 100% and N = 90. Also, when the duty cycle is 10% and N = 90, the data rate is calculated as: $(90\times10\%-5)$ bits/frame × 30 frames/second = 0.12 Kbit/s.

Finally, we evaluate the illumination performance of the proposed OCC system. Fig. 7 shows the relationship between dimming levels and the illuminance measured by the light meter. Here, different symbol rates of OOK at the AWG are tested. We can observe that the illuminance experiences a nearly linear improvement when increasing the duty cycle. This indicates the feasibility of integrating the dimming control function into OCC systems.

IV. Conclusion

In this paper, we demonstrated an OCC system which can support the dimming control function. The system employed PWM to control the brightness of a LED, and modulated OOK signals during the "ON" period of PWM for data transmission. The data structure of frames and the processing methods at the output of the mobile-phone camera were proposed. Experiments showed that the system can achieve different dimming levels from 10% to 100% at data rates from 0.12 Kbit/s to 2.55 Kbit/s, respectively, while maintaining BERs lower than 4.2×10^{-3}.

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