Improvement of Symbol Rate and Flicker-Free Performance of LED Visible Light Communication with Low-Frame-Rate CMOS Camera

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***Abstract*—In order to improve conveniences and comforts of LED visible light communication with a low-frame-rate CMOS camera, synchronization scheme applicable up to the symbol rate limit that is close to the frame rate of the CMOS camera is investigated. In addition, flicker-free operation utilized subcarrier modulation techniques for low-symbol-rate visible light communication is investigated. First, synchronization scheme up to 25 symbols per second using 30-frames-per-second CMOS camera was developed and experimentally verified. Second, triangular and sinusoidal waves are utilized as a subcarrier for LED modulation to realize flicker-free operation. LED flickering was eliminated and error-free operation was achieved when the symbol rate is less than 5 symbols per second.**

Keywords—visible light communication; image sensor; frame rate; synchronization; flicker-free; LED

I. Introduction

LED visible light communication with a CMOS camera consisting of image sensors has various advantages that are easiness of position adjustment for both transmitter and receiver, simplicity of long-distance or multiple communication, suppressing of background light, etc. utilizing its high spatial resolution [1]. However, it has the disadvantage that feasible symbol rate with the CMOS camera is low because of its low frame rate. The symbol rate is limited by the frame rate of the camera because it needs to access many image pixels as a receiver. In order to overcome the drawback, image-sensor-based visible light communication using LED array and high-frame-rate, 1000-fps, CMOS camera has realized 25 kbps [2]. Since 500 sets of LEDs are used, the symbol rate per LED is 500 symbols per second that is one-half of the frame rate of the CMOS camera, 1000 fps. However, if appropriate synchronization scheme is applied to a receiver with a CMOS camera, symbol rate can be increased up to the frame rate of the CMOS camera. In this paper, the relationship between feasible symbol rate per LED and the frame rate of the camera is clarified. Synchronization scheme applicable up to the symbol rate limit against the frame rate of the camera is developed. The synchronization scheme is verified experimentally using a low-frame-rate, 30-fps, CMOS camera and FPGA for signal processing.

On the other hand, LED lighting causes a perceptible flicker due to the low symbol rate performance of visible light communication with a CMOS camera. In general, in order to avoid the flickering, modulation frequency of more than 100 Hz is required [3]. Our approach is different from these modulation techniques to raise the frequency. We utilize human characteristics that fluent brightness transition cannot be perceived by the human eye. Flicker characteristics and bit error rate utilized the triangular and sinusoidal waves as a subcarrier for LED modulation are compared with those using the conventional rectangular wave.

II. System Configuration

Configuration of LED visible light communication transceiver with a low-frame-rate CMOS camera is shown in Fig. 1. The transmitter consists of white LED array and a FPGA for signal processing and the receiver consists of a 30-fps CMOS camera and a FPGA. On-off keying or 2-ASK is used for modulation. Overall picture of the transceiver with a 30-fps CMOS camera and a FPGA is shown in Fig. 2.

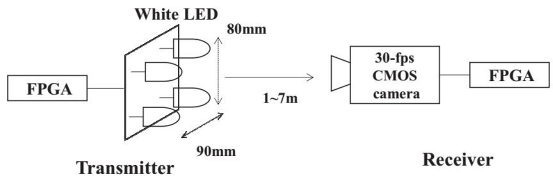

Fig. 1. Configuration of LED visible light communication transceiver with a low-frame-rate CMOS camera.

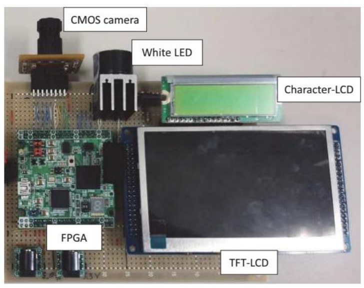

Fig. 2. Overall picture of a transceiver with a CMOS camera and a FPGA.

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III. SYNCHRONIZATION SCHEMES

The relationship between transmitted symbol and received one obtained from frame image of the CMOS camera is shown in Fig. 3. In the figure, T_s and T_r are the transmitted and received symbol length, respectively, T_f is the frame duration of the camera, and ΔT is offset time between the transmitted and received symbol. In the symbol rate of less than one-half of the frame rate as shown in Fig. 3(a), time, t_{f1} and t_{f2}, when the first and second image is received respectively, is given as

$$0 \le t_{f_1} \le \frac{1}{2} T_s, \quad \frac{1}{2} T_s \le t_{f_2} \le T_s. \tag{1}$$

Since at least two correct images are obtained during one transmitted symbol length, either one of the two images can be chosen as described below in subsection *A* [4]. On the other hand, in the symbol rate of more than one-half of the frame rate as shown in Fig. 3(b), the time, t_{f1} and t_{f2}, when the first and second image is received respectively, is given as

$$0 \le t_{f_1} \le T_s, \quad \frac{1}{2} T_s \le t_{f_2} \le 2T_s. \tag{2}$$

Since only one correct image is obtained during one symbol length, the correct image cannot be received without knowledge of the transmitted symbol timing as described in subsection *B* [5].

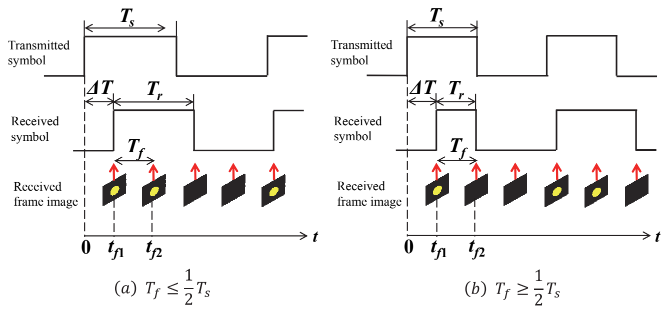

Fig. 3. Relationship between transmitted symbol and received frame image.

A. *Synchronization Scheme without Knowledge of Transmitted Symbol Timing*

If the received timing is chosen to the center of the received symbol regardless of the transmitted symbol timing (see Fig. 3(a)), the proper received time range, t_r, is given as

$$\frac{1}{2} T_s \le t_r \le T_s. \tag{3}$$

Therefore, in the symbol rate of less than one-half of the frame rate, since at least two correct images are obtained during one symbol length as given in Eq. (1), the correct frame image is constantly received even if the received timing is chosen without knowledge of the transmitted symbol timing.

B. *Synchronization Scheme by Estimating Transmitted Symbol Timing*

In the symbol rate of more than one-half of the frame rate, as the symbol rate increases, time period while the correct symbol is received decreases. The proper received time range, t_r, when the correct frame image is received, is given as

$$T_f \le t_r \le T_s. \tag{4}$$

If the transmitted symbol timing is estimated from the received symbol pattern, the proper timing to get correct frame image can be found from the transmitted symbol timing. Since the transmitted symbol length, T_s, is known from the preamble, we can estimate when the time offset between the transmitted and received symbol, ΔT, is minimum (see Fig. 3(b)). Synchronization algorithm to estimate when to receive the correct frame image is shown in Fig. 4. The received symbol length, T_r, is compared with the transmitted symbol length, T_s, which is known from the preamble. If the received symbol length is shorter than the transmitted one, estimated transmitted symbol timing is adjusted and the minimum offset timing is assumed to be the transmitting symbol timing. The proper received timing, t_r, is chosen a frame duration, T_f, late.

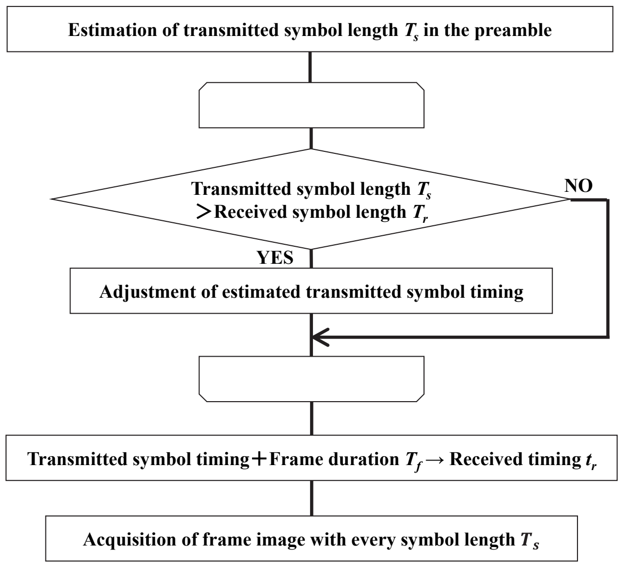

Fig. 4. Synchronization algorithm.

IV. SNCHRONIZATION RESULTS

A. *Synchronization Results without Knowledge of Transmitted Symbol Timing*

The two synchronization schemes described in the previous section were experimentally verified. OOK is used for modulation. The synchronization and data acquisition procedure without knowledge of the transmitted symbol timing is shown in Fig. 5. First, the transmitted symbol length, T_s, is calculated in the preamble consisted of 64 symbols sampled at intervals of 100 μsec. The received symbol timing, t_r, is chosen to the center of the received symbol in the end of the preamble. Next, 500 symbols are received in the data acquisition. The resynchronization consisted of 5 symbols for synchronization adjustment and data acquisition of 500 symbols are subsequently repeated. Bit error rates were measured under fluorescent lights indoor as shown in Fig. 6. Error-free operation of less than 10^{-4} was achieved up to 15 symbols per second that is just one-half of the frame rate of the CMOS camera, 30 fps. However, it is difficult to receive correct symbol at 16 symbols per second without knowledge of the transmitted symbol timing.

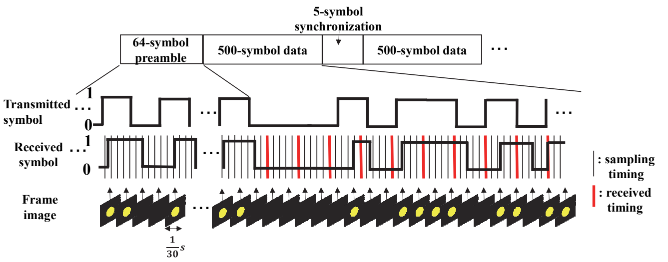

Fig. 5. Synchronization and data acquisition procedure without knowledge of the transmitted symbol timing.

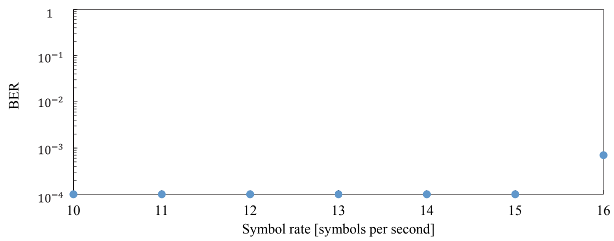

Fig. 6. BERs versus symbol rate based on the synchronization scheme without knowledge of the transmitted symbol timing.

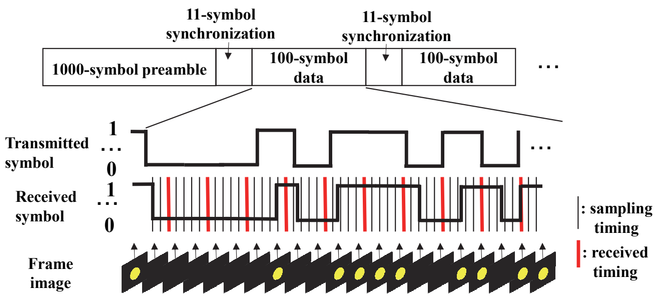

Fig. 7. Synchronization and data acquisition procedure by estimating the transmitted symbol timing.

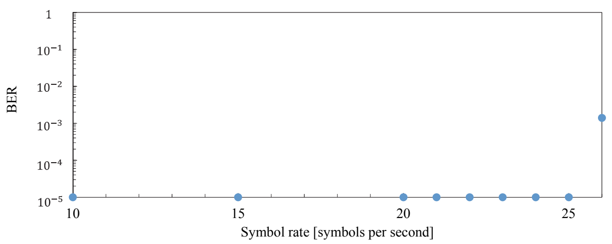

Fig. 8. BERs versus symbol rate based on the synchronization scheme by estimating the transmitted symbol timing.

B. Synchronization Results by Estimating Transmitted Symbol Timing

The synchronization and data acquisition procedure by estimating the transmitted symbol timing is shown in Fig. 7. First, the transmitted symbol length, T_s, is also calculated in the preamble consisted of 1000 symbols sampled at intervals of 100 µsec. Next, in the synchronization consisted of 11 symbols, the received symbol timing, t_r, is adjusted. The received symbol length, T_r, is compared with the estimated transmitted symbol length, T_s, based on the synchronization algorithm described in the previous section (see Fig. 4). Next, 100 symbols are received in the data acquisition. The resynchronization and data acquisition are consecutively repeated.

Bit error rates were measured under fluorescent lights indoor as shown in Fig. 8. Error-free operation of less than 10^{-5} was achieved up to 25 symbols per second that is five-sixths of the frame rate of the CMOS camera, 30 fps. The synchronization scheme by estimating the transmitted symbol timing is applicable to all the symbol rate from the low symbol rate of less than one-half of the frame rate to the maximum symbol rate that is close to the frame rate of the CMOS camera.

V. SUBCARRIERS FOR FLICKER-FREE MODULATION

In order to vary the intensity of LED light moderately for flicker-free modulation, subcarrier was used to realize intensity modulation with a gentle slope. Structure of the triangular and sinusoidal wave as a subcarrier generated by PWM for the flicker-free is shown in Fig. 9. Pulse width of the PWM is 220 µsec. In order to eliminate LED flickering, intensity ratio was adjusted. Half cycle of each wave is divided into more than 40 and 60 steps in the triangular and sinusoidal wave, respectively.

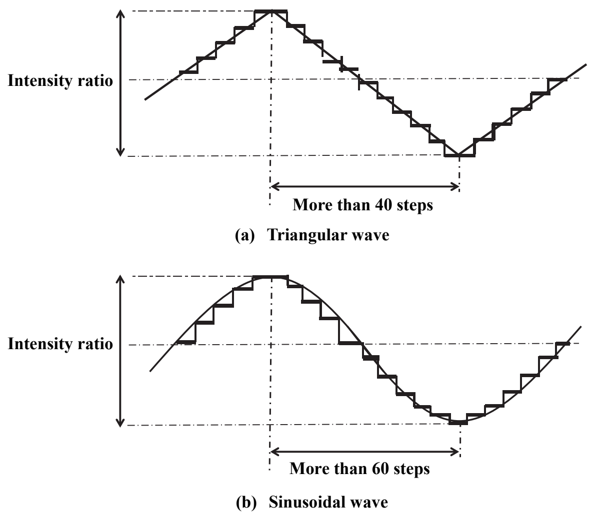

Fig. 9. Structure of the triangular and sinusoidal wave as a subcarrier generated by PWM.

Binary image received by the CMOS camera at a distance of 1 meter, for example, is shown in Fig. 10. Each pixel image was converted to a binary image and total number of white pixels within 14x14 dots is counted and converted into relative intensity. In order to confirm modulation and demodulation accuracy of the ASK modulation using the LED transmitter

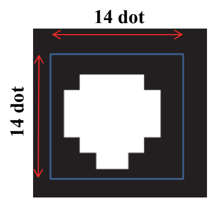

Fig. 10. Binary image.

and the receiver with the CMOS camera, error vector magnitude (EVM) was measured as shown in Fig. 11. Duty ratio of the PWM was changed from 5 to 100 %. Sufficient EVM of less than 4.2 % is obtained up to a distance of 4 meters.

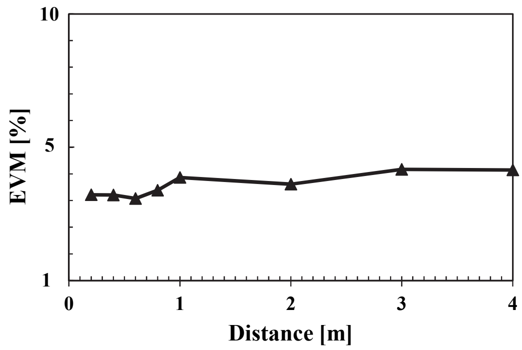

Fig. 11. EVM versus distance.

VI. RESULTS OF FLICKER-FREE MODULATION

LED flickering observed on a sheet of white paper in a dark room was evaluated by participants while intensity ratio and symbol rate of the LED transmitter for 2-ASK was changed. The relationship between the flicker-free intensity ratio and symbol rate is shown in Fig. 12. Although the sinusoidal wave can eliminate the flickering with a symbol rate of less than 3 symbols per second, the triangular wave can eliminate the flickering with a symbol rate of less than 5 symbols per second because a slope of the triangular wave intensity is constant and lower than that of the sinusoidal wave. On the other hand, the rectangular wave can eliminate flickering when the symbol rate is more than 60 symbols per second.

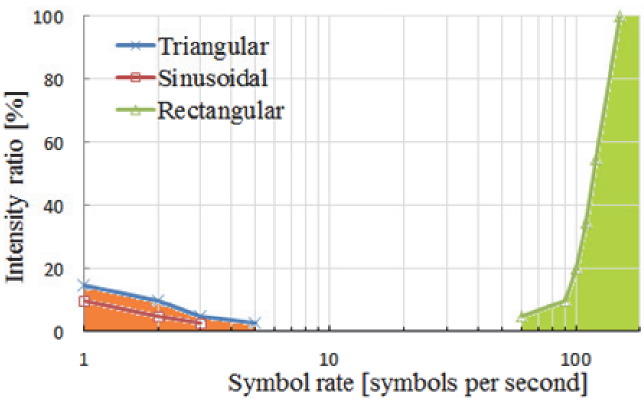

Fig. 12. Flicker-free intensity ratio versus symbol rate for 2-ASK.

Bit error rates for 2-ASK were measured as shown in Fig. 13 while the intensity ratio and distance was changed. In the figure, the distance means where BERs of less than 10^{-4} were obtained. Colored area shows the range of the intensity ratio and distance in which the flicker-free communication was achieved. Both the triangular and sinusoidal wave of the same intensity ratio achieved the same distance under the condition of the flicker-free operation. However, the symbol rate of the triangular wave is higher than that of the sinusoidal wave. In particular, BERs of less than 10^{-4} and flicker-free operation were achieved at a distance of 1.5 meters utilizing the triangular wave under the condition that the intensity ratio is 15 % and symbol rate is 1 symbols per second.

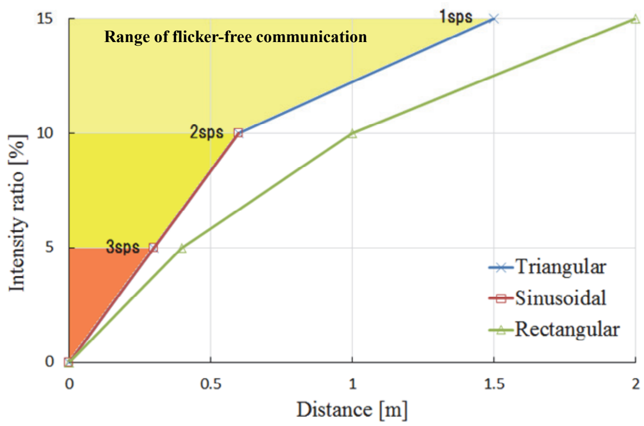

Fig. 13. Flicker-free intensity ratio and symbol rate for 2-ASK versus distance.

VII. COCLUSION

The relationship between the feasible symbol rate per LED and the frame rate of a CMOS camera for the image-sensor-based visible light communication was clarified. The synchronization scheme applicable up to the symbol rate close to the frame rate of the CMOS camera was developed and verified experimentally using FPGA. BERs of less than 10^{-5} were achieved up to the symbol rate of 25 symbols per second for OOK modulation using the low-frame-rate, 30-fps, CMOS camera. In addition, in order to achieve the flicker-free communication, triangular and sinusoidal wave were utilized as a subcarrier for 2-ASK modulation. LED flickering was eliminated and BERs of less than 10^{-4} were achieved under the condition that LED intensity ratio is less than 15 % and/or symbol rate is less than 5 symbols per second utilizing the triangular subcarrier.

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