Symbol Synchronization Performance of Image-Sensor VLC with Rolling Shutter

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***Abstract*—Sequential estimation method is successfully applied to symbol synchronization for image-sensor visible light communication (VLC) with rolling shutter in order to achieve error-free performance at an arbitrary symbol rate of more than several kilobits per second (bps). In addition to symbol synchronization performance at an arbitrary symbol rate, degradation performance of the synchronization due to difference between the transmitted symbol rate and assumed one in the image-sensor receiver is studied to overcome inaccuracy of the line rate of the image sensor such as smartphone cameras. Simulation results show that symbol rates with a long cycle received pattern make symbol synchronization easier. Experiment results show that error-free performance is achieved with a long cycle pattern at 5287.9 symbols per second (sps). Furthermore, error-free performance is accomplished up to relative difference in symbol rate of more than 3000 ppm.**

Keywords—visible light communication; image sensor; rolling shutter; symbol synchronization; sequential estimation

I. INTRODUCTION

Image-sensor visible light communication (VLC) uses an image sensor as a receiver. Since the image-sensor receiver has high spatial resolution performance in conjunction with wide angle coverage one, the receiver can be easily aligned with the LED transmitter. Also, the receiver can easily distinguish multiple transmitters and remove the interference signals and background noise [1]-[3]. However, in the image-sensor VLC, transmitted symbol rate is limited by the frame rate of the image sensor. Since the frame rate of commercially available image sensor such as smartphone cameras is around 30-120 frames per second (fps), the image sensor with rolling shutter is a promising candidate to increase the symbol rate to a hundred times to a thousand times faster than the frame rate. Although achievable symbol rate depends on the line rate and the image resolution of the image sensor, several kilobits per second (bps) has been achieved with the rolling shutter in practice [4]-[8], [14].

However, unlike a receiving rate of less than a symbol per image frame in the conventional image sensor, it is necessary to receive the transmitted symbol at each pixel line in the rolling shutter. Since capture cycle per line is influenced by changing environmental conditions such as operating system design of the processor and stability of the image-sensor clock, it is difficult to achieve error-free performance with the rolling shutter.

In this study, we adapt sequential estimation method for symbol synchronization of the image-sensor VLC with the rolling shutter. The sequential estimation method has been successfully applied to the synchronization with a symbol per image frame. Error-free performance has been achieved when the symbol rate is less than a symbol per image frame [9]-[11]. The sequential estimation accomplishes symbol synchronization at an arbitrary symbol rate of less than the frame rate.

In previous studies on the image-sensor VLC with the rolling shutter, the symbol rate was limited to equivalent value with the line rate or integer divisions of the line rate in order to prevent the synchronization issue. We aim at symbol synchronization and error-free performance at an arbitrary symbol rate of less than the line rate with rolling shutter.

In addition, tolerance range of the difference between the transmitted symbol rate and assumed one in the image-sensor receiver is investigated. When the transmitted symbol rate is slightly different from the assumed one in the image-sensor receiver, symbol synchronization algorithm using maximum likelihood sequence detection algorithm is studied [12], [13]. We simply adapt the sequential estimation to the rolling shutter for the synchronization, where assumed symbol rate is slightly different from the transmitted one. The sequential estimation can be applied at an arbitrary symbol rate even though the assumed symbol rate is slightly different from the transmitted symbol rate.

The remainder of this paper is organized as follows. Section II introduces simulation model for symbol synchronization with the rolling shutter. Section III describes simulation results of the symbol synchronization using the sequentially estimation method for the rolling shutter. Section IV describes experiment results of symbol synchronization performance using 30-fps image sensor with the rolling shutter. Section V summarizes conclusions and future work.

II. SIMULATION MODEL

First, transmitted symbol model, $s(t)$, represents the product of rectangular pulse, $g(t-mT_s)$, and transmitted symbol sequence, $d(m)$, as shown in Fig. 1, where T_s represents transmitted symbol length and transmitted symbol sequence, $d(m)$, repeats "1" and "0" alternatively for symbol synchronization in the preamble.

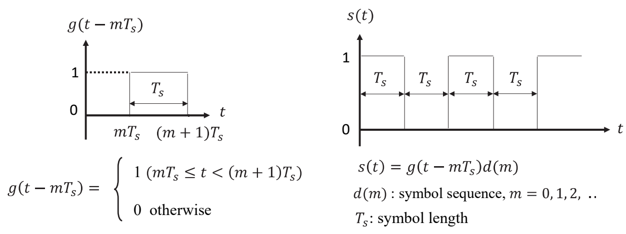

Fig. 1. Transmitted symbol model.

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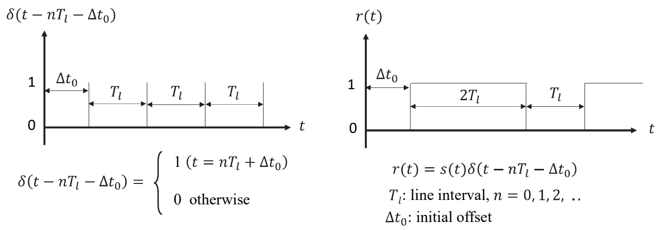


Fig. 2. Received symbol model.

Next, received symbol model, $r(t)$, represents the product of the transmitted symbol, $s(t)$, and impulse sequence of the line timing, $\delta(t\text{-}nT_l\text{-}\Delta t_0)$, as shown in Fig. 2, where T_l represents line interval of the image sensor and Δt_0 represents unknown initial offset time between the transmitted and received symbols.

Finally, comparable symbol model, $c(t)$, represents the product of rectangular pulse, $g(t\text{-}mT_s\text{-}t_c)$, and transmitted symbol sequence, $d(m)$ as shown in Fig.3, where t_c represents the comparable symbol timing, Δt_1 represents sequentially estimated offset time, and Δt_e represents finally estimated offset time by the sequential estimation.

First, in the sequential estimation, the comparable symbol is generated with the same length as the transmitted symbol length, T_s, at the line timing, $\delta(t\text{-}nT_l\text{-}\Delta t_0)$. If the next received symbol timing is earlier than the next comparable symbol timing, the comparable symbol timing, t_c, is reset to the line timing, $\delta(t\text{-}nT_l\text{-}\Delta t_0)$, to reduce the length of the offset time between the transmitted and comparable symbols (see Fig. 3). The sequential estimation method repeats the comparison of the length of the received symbol with that of the comparable symbol in order to set the estimated comparable symbol timing as close to the transmitted symbol timing as possible. Finally, the proper received timing is set within the length of the time, $T_s - T_l$, to synchronize with the transmitted symbol.

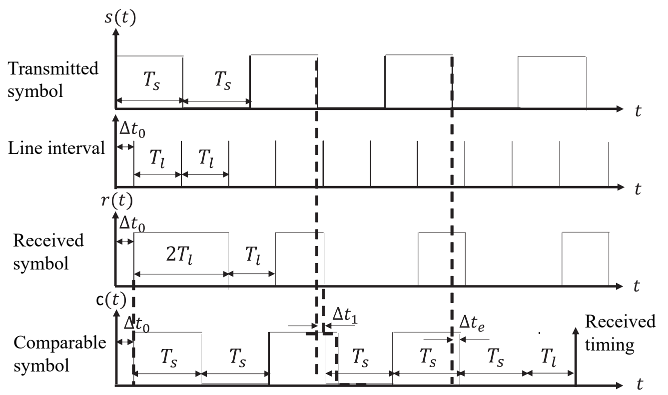


Fig. 3. Comparable symbol, $c(t)$, and sequentially estimated procedure of the transmitted symbol timing ($T_l < T_s \leq 2T_l$).

III. Simulation Results

In the image-sensor VLC with rolling shutter, continuous symbol synchronization and symbol decision are prevented from non-exposure time in each image frame. Fig. 4 shows relationship between transmitted packet and an image frame with rolling shutter, where the nominal frame rate is 30 fps and the image resolution is 320 x 240 pixels (QVGA). Modulation scheme is on-off keying (OOK).

Each transmitted packet consists of preamble and data symbols. Symbols, "1" and "0," are repeated alternatively for symbol synchronization in the preamble. Since a part of the preamble and data symbols may not be received during the exposure duration, it is necessary to send the transmitted packet twice during one image frame [14]. Measured line interval of the image sensor, T_l, is 125.44 µs and the line rate is 7971.9 lines per second (lps). In the simulation, 11 symbols are used for synchronization in the preamble and (120 x T_l/T_s – 11) symbols are used for data symbols.

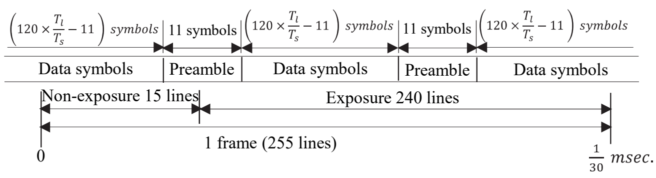
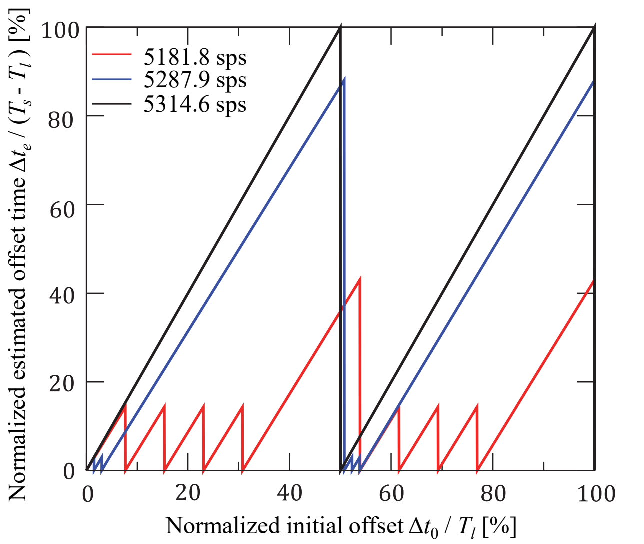
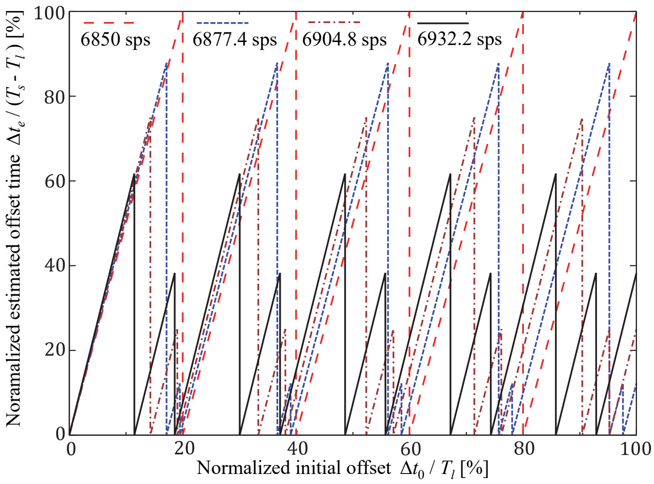


Fig. 4. Relationship between each transmitted packet and an image frame with rolling shutter, where the nominal frame rate is 30 fps and the image resolution is 320 x 240 pixels (QVGA).



(a) 5181.8, 5287.9, and 5314.6 sps



(b) 6850, 6877.4, 6904.8 and 6932.2 sps

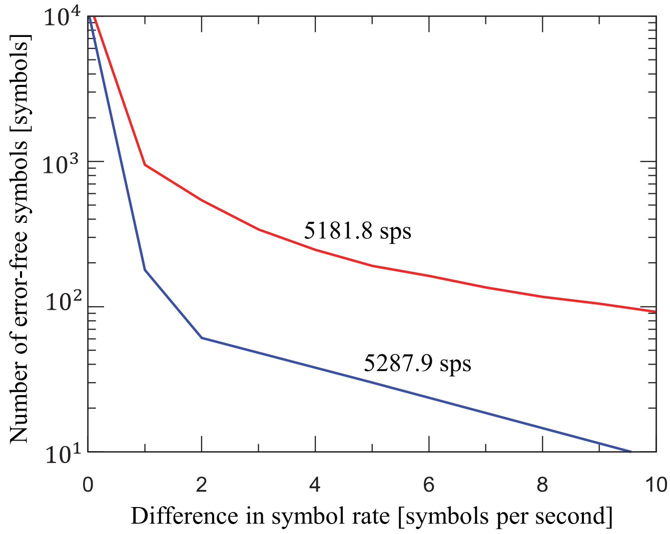
Fig. 5. Initial offset, Δt_0 versus estimated offset time, Δt_e, where the initial offset is normalized by the line interval, T_l, and the estimated offset time is normalized by the length of the time, $T_s - T_l$.

Simulation study for symbol synchronization is performed under the above conditions. Fig. 5 shows relationship between the initial offset Δt_0, and the estimated offset time, Δt_e, where the initial offset is normalized by the line interval, T_l, and the estimated offset time is normalized by the length of the time, $T_s - T_l$. If the normalized estimated offset time is less than 100 %, symbol synchronization is made. Fig. 5(a) shows the relationship at symbol rate of 5181.8, 5287.9 and 5314.6 sps which corresponds to the ratio of line interval to symbol length, T_l/T_s = 19.5/30, 19.9/30, and 20/30, respectively. Fig. 5(b) shows the relationship at a symbol rate of 6850, 6877.4, 6904.8, and 6932.2 sps which corresponds to the ratio, T_l/T_s = 25/30, 25.1/30, 25.2/30, and 25.3/30, respectively.

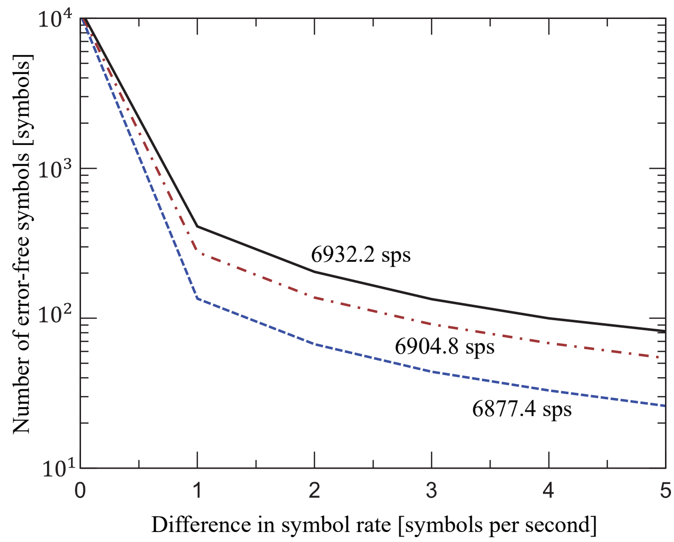
In every symbol rate, symbol synchronization can be made because the normalized estimated offset time is less than 100 %. However, when the symbol rate is 5314.6 and 6850 sps which corresponds to the ratio, T_l/T_s = 20/30 and 25/30, respectively, the normalized estimated offset time is close to 100 %. If the line rate is influenced by changing environmental conditions, the image-sensor receiver has a possibility of failure in synchronization. However, when the symbol rate is 5181.8 and 6932.2 sps which corresponds to the ratio, T_l/T_s = 19.5/30 and 25.3/30, respectively, the normalized estimated offset time decreases to approximately 40 and 60 %, respectively. If the symbol rate is set to 5181.8 and 6932.2 sps, since a length of time when the received image coincides with the transmitted one increases, it becomes tolerant to the inaccuracy of the line rate of the image sensor.

The difference in the estimated offset time depends on cycle pattern characteristics of the received symbols. The cycle pattern of the received symbols is altered due to the relationship between the transmitted symbol rate and the image-sensor line rate, 7971.9 lps. For example, when the symbol rate is 5314.6 sps, the cycle pattern of the received symbols simply repeats a symbol with a length of T_l and $2T_l$ alternatively. On the other hand, when the symbol rate is 5181.8 sps, the cycle pattern consists of five short cycle patterns and a long cycle one. The short cycle pattern consists of one T_l and one $2T_l$. The long cycle pattern consists of one T_l and two $2T_l$. Therefore, the cycle pattern consists of six T_l and seven $2T_l$ (see Fig. 9(a)). As the length of the cycle pattern is longer, the estimated offset time is reduced.

In commercially available image sensor such as smartphone cameras, since the line rate is influenced by the changing environmental conditions, symbol synchronization performance against the variation of the line rate needs to be investigated. Degradation performance of the synchronization due to difference between the transmitted symbol rate and assumed one in the receiver was calculated. Fig. 6 shows number of error-free symbols received continuously after symbol synchronization when the difference in symbol rate becomes large due to changing line rate. If the number of error-free symbols received continuously is more than 109 symbols, error-free packet transmission is accomplished at any symbol rate of less than the line rate (see Fig. 4). As the length of the received symbol cycle becomes longer, error-free operation can be accomplished even with larger difference between transmitted symbol rate and assumed one in the receiver. For example, in order to accomplish error-free performance continuously with 240 lines when the symbol rate is assumed to be 5181.8 and 6932.2, difference in symbol rate of more than 8 and 3 sps is allowed respectively, as shown in Figs. 6(a) and (b).



(a) Symbol rate is assumed to be 5181.8 and 5287.9 sps, respectively.

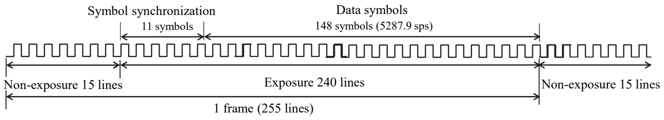


(b) Symbol rate is assumed to be 6877.4, 6904.8 and 6932.2 sps, respectively.

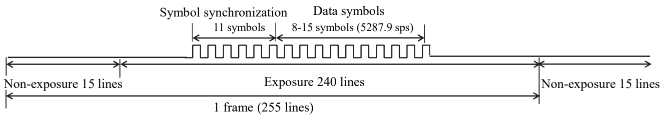
Fig. 6. Number of error-free symbols received continuously at image-sensor receiver versus difference betweem the transmitted symbol rate and assumed one in the image-sensor receiver.

IV. EXPERIMENTS

In order to make sure of the simulation results, received symbol pattern was measured using 30-fps image sensor with rolling shutter. Fig. 7 shows procedure for symbol transmission. Measured distance is set to 10 and 80 centimeters, respectively. Since 11 symbols are used for the symbol synchronization, rest of the symbols are used for data transmission. Therefore, when the symbol rate is 5287.9 sps, 148 and 19 symbols are used for data transmission at a distance of 10 and 80 centimeters, respectively. However, as with the preamble, “1” and “0” symbols are repeated alternatively for the data symbols in order to start symbol synchronization at the beginning of exposure line and the beginning of LED image line for every frame at a distance of 10 and 80 centimeters, respectively.

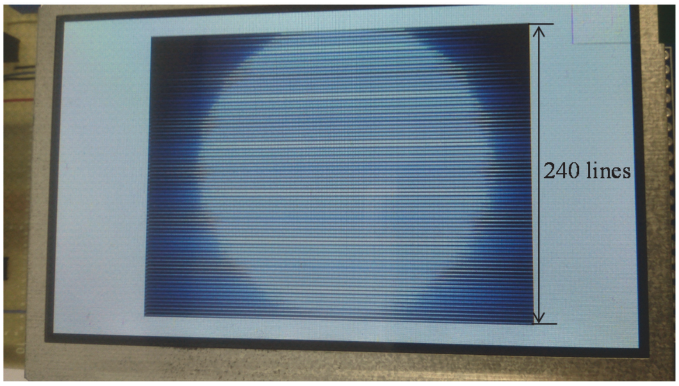


(a) Measured distance is 10 centimeters.

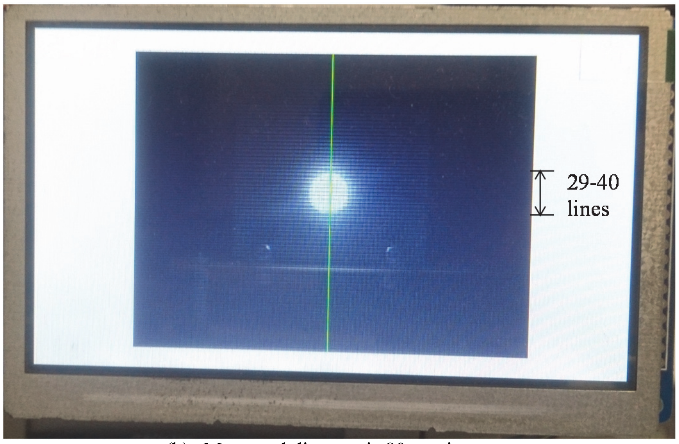


(b) Measured distance is 80 centimeters.

Fig. 7. Procedure for symbol transmission.



(a) Measured distance is 10 centimeters.



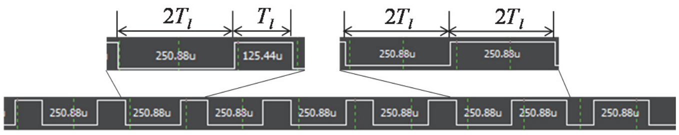
(b) Measured distance is 80 centimeters.

Fig. 8. LED image captured by 30-fps image sensor with rolling shutter, where the image resolution is 320 x 240 pixels (QVGA).

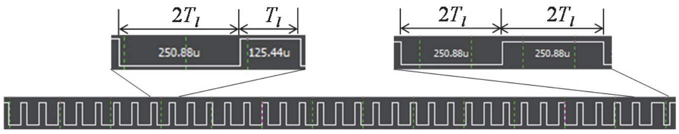
Fig. 8 shows transmitted LED image captured by 30-fps image sensor with rolling shutter, where distance is set to 10 and 80 centimeters, respectively. The image resolution is 320 x 240 pixels (QVGA). In order to use all the 240 lines for reception of the LED image, it is necessary to bring the image-sensor receiver close to the LED transmitter. When the distance is 80 centimeters, 29-40 lines can be used for reception of the LED image.

Received symbol pattern of the 30-fps image sensor with rolling shutter was outputted from the FPGA ports and measured by the logic analyzer. Fig. 9 shows received symbol pattern measured at symbol rate of 5181.8, 5287.9 and 5314.6 sps which corresponds to the ratio of line interval to symbol length, T_l/T_s = 19.5/30, 19.9/30, and 20/30, respectively. In the figure, the line interval of the QVGA image, T_l, is 125.44 μs. Measured distance is 10 centimeters.

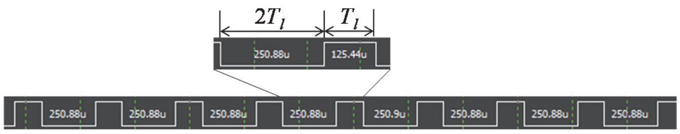
Fig. 9(a) shows received symbol pattern measured at 5181.8 sps. The cycle pattern consists of five short cycle patterns and a long cycle one. The short cycle pattern consists of one T_l and one $2T_l$ and the long cycle pattern consists of one T_l and two $2T_l$. Fig. 9(b) shows received symbol pattern measured at 5287.9 sps. Similarly, the short cycle pattern consists of one T_l and one $2T_l$ and the long cycle pattern consists of one T_l and two $2T_l$. Since the cycle pattern consists of 31- or 32-short cycle patterns and a long cycle one, the cycle pattern consists of 32- or 33-T_l and 33- or 34-$2T_l$. Fig. 9(c) shows received symbol pattern measured at 5314.6 sps. The cycle pattern simply consists of one T_l and one $2T_l$.



(a) 5181.8 sps



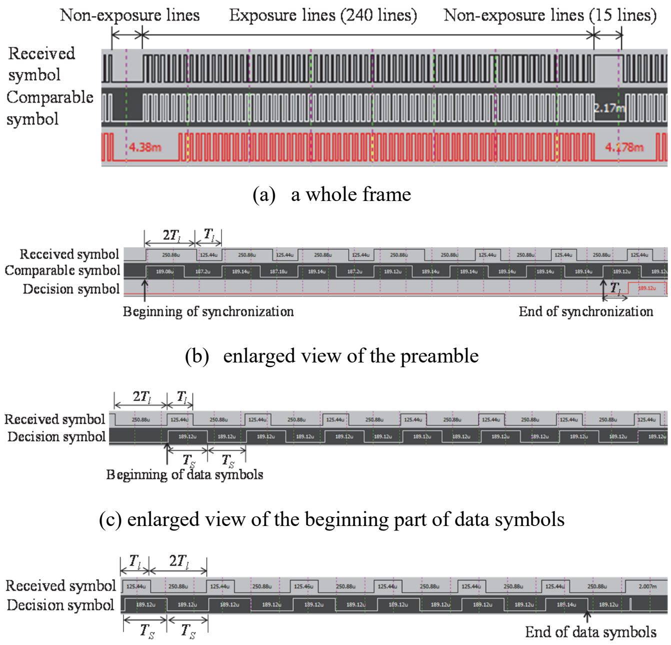
(b) 5287.9 sps



(c) 5314.6 sps

Fig. 9. Received symbol pattern measured at 5181.8, 5287.9, and 5314.6 sps, respectively, where the line interval of the QVGA image, T_l, is 125.44 μs and measured distance is 10 centimeters.

In addition to the received symbol pattern, comparable and decision symbols were simultaneously outputted from the FPGA ports and measured by the logic analyzer. Fig. 10 shows received, comparable and decision symbol pattern measured at symbol rate of 5287.9 sps which corresponds to the ratio of line interval to symbol length, T_l/T_s = 19.9/30. Measured distance is 10 centimeters. Fig. 10(a) shows received, comparable and decision symbols of a whole frame. Both exposure and non-exposure lines are shown. Fig. 10(b) shows enlarged view of the preamble for symbol synchronization. The comparable symbol is generated at the beginning of the exposure lines and the length of the comparable symbol is compared with that of the received symbol. Fig. 10(c) shows enlarged view of the beginning part of the data symbols. Data symbols of “1” and “0” are regularly made by symbol decision. Fig. 10(d) shows enlarged view of the end part of the data symbols. Similarly, data symbols of “1” and “0” are regularly made by symbol decision.



(a) a whole frame

(b) enlarged view of the preamble

(c) enlarged view of the beginning part of data symbols

(d) enlarged view of the end part of data symbols

Fig. 10. Received, comparable and decision symbols measured at 5287.9 sps.

Finally, bit error rates (BERs) were measured in order to make sure of difference in synchronization performance due to the symbol rate. Table I shows configuration of the LED transmitter and the image-sensor receiver with rolling shutter. Communication procedure is the same procedure as shown in Fig. 7(b). Although random sequence is needed to measure BERs correctly, repetition of “1” and “0” was used as data symbols to start symbol synchronization at the beginning of LED image for every frame. Communication distance was set to 80 centimeters to achieve error free performances. 29-40 lines were used for reception of the LED image.

TABLE I. CONFIGURATION OF TRANSMITTER AND RECEIVER.

LED Transmitter		Image-Sensor Receiver	
Total Flux	850 lumens	Lens Focal Length	3.1 mm
Half-Power Beam Width	140 degrees	F -Number	1.8
Modulation	On-Off Keying	Field of View	40 degrees
Data Symbols	Repetition of “1” and “0”	Line Rate	7971.9 lps
FPGA	Cyclone V	FPGA	Cyclone V

Fig. 11 shows measured BERs under fluorescent lights. Since the measured number of symbols is 10^6, BER=10^{-6} indicates error-free operation. BERs were measured while symbol rate was changed from 5181.8 to 5394.3 sps which corresponds to the ratio, T_l/T_s, from 19.5/30 to 20.3/30. In the BER measurements, symbol rate is assumed to be known at the image-sensor receiver. BERs measured with symbol timing estimation are compared with those measured without the estimation. Since all the BERs without symbol timing estimation were more than $1x10^{-2}$, it is obvious that the symbol timing estimation is useful for symbol synchronization. Error-free performance was achieved at 5287.9 sps which corresponds to the ratio, T_l/T_s=19.9/30, with a long cycle received pattern. Moreover, BER of $1.58x10^{-4}$ was obtained at 5341.2 sps which corresponds to the ratio, T_l/T_s=20.1/30, also with a long cycle received pattern. These results indicate that highly accurate symbol timing estimation can be accomplished when the length of the cycle pattern of the received symbols is long. Since the offset time between the transmitted and comparable symbol was reduced at 5287.9 sps because of the long cycle pattern, the symbol synchronization and error-free performance was accomplished.

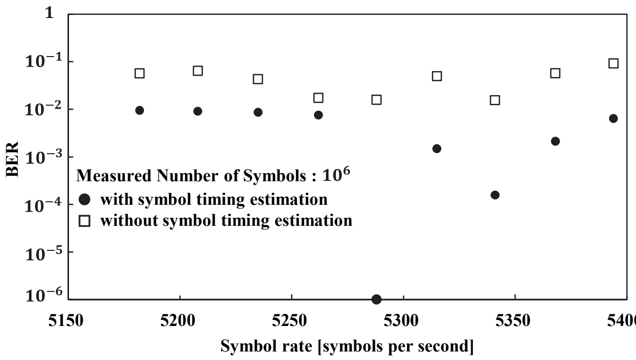


Fig. 11. Measured BERs versus symbol rate, where communication distance is 80 centimeters.

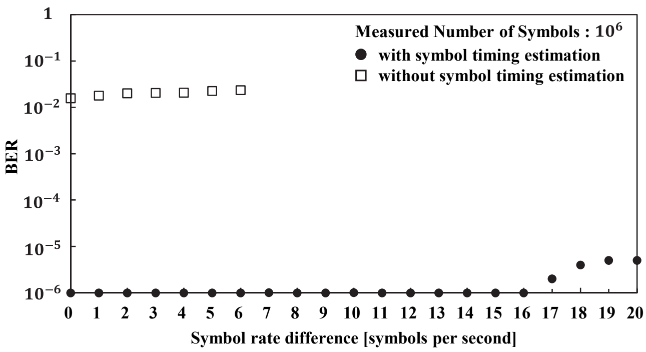


Fig. 12. Measured BERs versus difference in symbol rate, where symbol rate is assumed to be 5287.9 sps in the image-sensor receiver and communication distance is 80 centimeters.

Fig. 12 shows measured BERs when the transmitted symbol rate is slightly different from the received one, where symbol rate is assumed to be 5287.9 sps in the image-sensor receiver for symbol synchronization. As the difference in symbol rate between the transmitter and receiver increases, BER without symbol timing estimation gradually deteriorates. On the other hand, error-free performance was accomplished with symbol timing estimation up to difference in the symbol rate of 16 sps which corresponds to relative difference in the symbol rate of more than 3000 ppm. This result corresponds approximately to the simulated one (see Fig. 6(a)). As the length of the received symbol cycle is longer, the image-sensor receiver becomes more tolerant of difference between transmitted symbol rate and assumed one in the image-sensor receiver.

V. Conclusion

Symbol synchronization performance of the image-sensor VLC with rolling shutter has been investigated based on the sequential estimation method. Simulation results show that the symbol synchronization can be accomplished at symbol rates with a long cycle pattern. Even though the transmitted symbol rate is slightly different from the assumed one in the image-sensor receiver with rolling shutter, the sequential estimation method can be applied to the symbol synchronization at symbol rates with a long cycle pattern.

In addition, experiment results show that error-free performance is achieved at 5287.9 sps which corresponds to the ratio of line interval to symbol length of 19.9/30 with a long cycle received pattern. Furthermore, error-free performance is accomplished up to difference in symbol rate of 16 sps which corresponds to relative difference in the symbol rate of more than 3000 ppm. These results indicate symbol timing estimation can be accomplished accurately and robustly when the length of the cycle pattern of the received symbols is long.

However, further studies are needed in order to achieve error-free performance at an arbitrary symbol rate of less than the line rate of the image sensor, 7971.9 lps.

Acknowledgment

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