Increasing symbol rate by ensemble averaging with dual camera in rolling-shutter optical camera communication

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Abstract: 
Rolling-shutter (RS) optical camera communication (OCC) is effective to increase symbol rate in indoor OCC from LED lamp to smartphones’ built-in camera. However, exposure time of RS camera is longer than the line interval of the camera. Symbol error rate deteriorates as the symbol rate increases owing to inter-symbol interference (ISI). To reduce ISI, dual camera is adapted. Ensemble averaging in number of decision pixels per symbol with dual camera suppresses ISI. Error-free symbol rate was increased with dual camera more than that with a single camera. The reason for increase in symbol rate is elucidated with the correlation coefficient.

Keywords: visible light communication, optical camera communication, image sensor, rolling shutter, dual camera, inter-symbol interference

Classification: Wireless communication technologies

References
[1] C. Danakis, M. Afgani, G. Povey, I. Underwood, and H. Haas, "Using a CMOS Camera Sensor for Visible Light Communication," IEEE Globecom Workshops, Anaheim, USA, pp.1244–1248, Dec. 2012. DOI:10.1109/GLOCOMW.2012.6477759
[2] H. Aoyama and M. Oshima, "Line Scan Sampling for Visible Light Communication: Theory and Practice," IEEE International Conference on Communications, London, UK, pp.5060–5065, June 2015. DOI:10.1109/ICC.2015.7249126
[3] K. Ohshima, T. Naramoto, K. Yamaguchi, and W. Chujo, "Rolling-shutter-based asynchronous optical camera communication by a cycle pattern of received symbols using smartphones," IEICE Communications Express, vol. 8, no. 3, pp. 49–54, Mar. 2019. DOI:10.1587/comex.2018XBL0141
[4] M. Kinoshita, T. Yamazato, H. Okada, T. Fujii, S. Arai, T. Yendo, and K. Kamakura, “Experimental Evaluation of Visible Light Communication
1 Introduction

Rolling-shutter (RS) optical camera communication (OCC) is effective to increase symbol rate for indoor OCC from LED lamp to smartphones’ built-in camera [1, 2, 3]. RS camera is sequentially exposed on each line of each frame. However, exposure time of off-the-shelf RS camera is much longer than the line interval of the camera. Moreover, shutter timing of the camera is different in each frame. Therefore, long exposure time causes the symbol error due to inter-symbol interference (ISI). When the exposure time is longer than the symbol length, difference in shutter timing deteriorates symbol error rate (SER).

Incidentally, in global-shutter OCC for intelligent transport system applications, to reduce variations in signal power to noise power ratio (SNR) according to vehicle vibration, a receiving technique in combining pixel values by dual camera is evaluated [4]. Measured SER with dual camera is lower than that with a single image.

On the other hand, in indoor OCC with LED lamp, sufficient SNR is maintained because luminance of the lamp is always much higher than ambient luminance. However, long exposure time and difference in shutter timing cause variations of signal power owing to ISI. Therefore, dual camera is adapted to reduce ISI by ensemble averaging in number of decision pixels per symbol in each camera. When transmitter’s symbol length is several times longer than the line interval of RS camera in on-off keying (OOK), each symbol image captured with the camera consists of several pixels. After symbol decision is made with the threshold pixel value at each line interval, number of “1” and “0” per symbol is averaged. In this study, three averaging methods, dual camera with parallel or orthogonal scan directions, and a single camera with parallel scan directions were compared.

2 Principle of ensemble averaging with dual camera

Fig. 1(a) (left and center) shows the lamp densely or sparsely consist of LED chips, and (right) shows the lamp image captured with RS camera. Since each pixel line of RS camera is sequentially exposed, received pixel value at each line corresponds to the luminance at different time. When the chips are densely arranged in the lamp, received pixel values are almost spatially constant. On the other hand, when the chips are sparsely arranged in the lamp, received pixel values are spatially not constant.

Even when LED luminance is spatially varied, if the exposure time of RS camera is sufficiently short, error-free transmission can be achieved by selecting appropriate threshold pixel value [3]. However, the exposure time is generally much longer than the line interval of RS camera. It becomes difficult to recover correct symbols owing to ISI as the symbol rate increases. To suppress ISI, dual
camera with parallel or orthogonal scan directions is adapted.

(a) (left and center): difference between LED lamps densely and sparsely consist of LEDs chips, (right): LED lamp image captured with RS camera

(b) (left): symbol error rate versus symbol rate using a single camera, (center and right): examples of received pixel values, where symbol rate is 9,640 and 10,016 symbols/s, respectively.

(c) configuration of dual camera receiver with parallel or orthogonal scan directions (upper left and right), and a single camera receiver with parallel scan directions (lower center)

(d) procedure for ensemble averaging in number of decision pixels per symbol, where symbol length is three times longer than the line interval (sampling interval) of RS camera.

**Fig. 1.** Principle of ensemble averaging in number of decision pixels per symbol with dual camera and a single camera.
Fig. 1(b) (left) shows measured SERs versus symbol rate when a single camera is used as a receiver. Transmitted symbols are modulated with OOK. Each chip simultaneously transmits repetition symbols of “1” and “0.” As the symbol rate increases, symbol error occurs in the lamp densely or sparsely consist of the chips. Fig. 1(b) (center and right) shows examples of received symbol pattern to clarify influence of ISI due to difference in shutter timing. When symbol rate is 9,640 symbols per second (symbols/s), received pixel values alternatively repeat the symbols “1” and “0” because the exposure time of RS camera seems to be still shorter than the symbol length. On the other hand, when symbol rate is increased to 10,016 symbols/s, received pixel values of the symbol “0” increase due to ISI because the exposure time of the camera seems to be longer than the symbol length. If the shutter timing is suitably selected, correct pixel value is obtained. However, shutter timing of the camera is different in each frame. Therefore, ensemble averaging in number of decision pixels per symbol is adapted to reduce ISI.

Fig. 1(c) shows configuration of dual camera receiver with parallel or orthogonal scan directions, and a single camera receiver with parallel scan directions. Dual camera is placed with parallel or orthogonal scan directions to capture LED lamp from spatially different positions of the lamp surface. Both cameras’ shutter timings are not adjustable. However, both receiving timings are synchronized with internal clock of a FPGA. Therefore, difference in shutter timing between dual camera is less than the line interval. In comparison with the dual camera, a single camera with parallel scan directions are also evaluated.

Fig. 1(d) shows procedure for ensemble averaging in number of decision pixels per symbol with dual camera. When transmitter’s symbol length is three times longer than the line interval of RS camera, each symbol consists of three pixels that correspond to 7,234 symbols/s. If transmitter’s symbol sequence is “1010,” proper decision pixel sequence is “111 000 111 000.” First, appropriate threshold pixel value is selected for symbol decision, “1” or “0.” Second, symbol decision is made with the threshold at each pixel. Third, number of “1” or “0” per symbol in each camera, $w_1$ and $w_2$, are averaged as follows.

$$ w = \frac{w_1 + w_2}{2}, $$

where $w$ is ensemble averaging in number of decision pixels per symbol. Finally, symbol decision is made with $w$. Number of decision pixels per symbol is 3. If $w$ is not less than 1.5, symbol, “1,” is recovered and if $w$ is less than 1.5, symbol, “0,” is recovered.

3 Comparison in SER based on ensemble averaging among dual cameras and a single camera

SER based on ensemble averaging among dual camera with parallel or orthogonal scan directions and a single camera with parallel scan directions are compared. Fig. 2 shows measured SERs versus symbol rate. Since number of measured symbols is more than $10^3$, SER=$10^{-3}$ indicates error-free transmission. Fig. 2(a) shows SER using the lamp sparsely consists of LED chips when both decision pixels are arranged on the LED chips. Fig. 2(b) shows SER using the same
lamp as Fig. 2(a) when one decision pixel is arranged on the chip and another pixel is arranged off the chip. Fig. 2(c) shows SER using the same lamp when both decision pixels are arranged on the chip. However, parallel scan directions are orthogonal to those of Fig. 2(a). On the other hand, Fig. 2(d) shows SER using the lamp densely consists of LED chips when both decision pixels are arranged on the chip. Threshold of 8-bit pixel value is 210.

In all scan directions, there is clear difference in SER between dual cameras and a single camera when the symbol rate is 9,649 and 10,020 symbols/s. In a
single camera, SER based on ensemble averaging is almost the same as that with each scan direction. Error-free transmission is not obtained because the shutter timings of two pixels are the same. On the other hand, in dual camera with parallel or orthogonal scan directions, error-free transmission is achieved based on ensemble averaging when the symbol rate is 9,649 and 10,020 symbols/s in all scan directions. Difference in shutter timing between dual camera improves SERs. Ensemble averaging is certainly effective in all scan directions with dual camera, regardless of parallel or orthogonal scan directions, and regardless of the lamp densely or sparsely consists of LED chips.

4 Difference in correlation coefficient between decision pixels with dual cameras and a single camera

To elucidate the reason for SER improvement due to ensemble averaging in number of decision pixels with dual camera, correlation coefficients between decision pixels of parallel or orthogonal scan directions were measured. Fig. 3 shows correlation coefficient versus symbol rate. The decision pixels in Fig. 3(a), (b), (c), and (d) correspond to those in Fig. 2(a), (b), (c), and (d), respectively.

![Fig. 3. Correlation coefficient between decision pixels versus symbol rate.](image)

In Fig. 3(a), (b), (c) and (d), correlation coefficient with dual camera is always less than that with a single camera. Since correlation coefficient with a single camera is close to 1, ensemble averaging was not effective with a single camera. By contrast, ensemble averaging was effective with dual camera due to low correlation coefficient because there is slight difference in shutter timing between dual camera.

5 Conclusion

To suppress ISI and increase error-free symbol rate in RS OCC, ensemble averaging in number of decision pixels per symbol with dual camera is adapted. In dual cameras and a single camera, SERs based on ensemble averaging with parallel or orthogonal scan directions are compared to those with each scan direction. Ensemble averaging with dual camera improves SERs. Error-free symbol rate is increased with dual camera more than that with a single camera, regardless of parallel or orthogonal scan directions, and regardless of the lamp densely or sparsely consists of LED chips. The reason for SER improvement is elucidated with the correlation coefficient between decision pixels of parallel or orthogonal scan directions. Low correlation coefficients using dual camera indicate that there is slight difference in shutter timing between dual camera. Therefore, ensemble averaging with dual camera is effective to improve SERs.