Adaptive thresholding with cell-size reduction for low-luminance, space-division-multiplexing, uplink optical camera communication

Alisa KAWADE[†a)], ***Nonmember***, **Wataru CHUJO**[†], ***and*** **Kentaro KOBAYASHI**[†], ***Members***

SUMMARY Cell-size reduction based adaptive thresholding is newly proposed and experimentally verified for low-luminance, space division multiplexing, uplink optical camera communication. The uplink consists of a smartphone embedded screen and an indoor camera at a maximum distance of 3.5 m. The adaptive thresholding with cell-size reduction overcomes spatial inter-symbol interference and low luminance screen for simultaneous enhancement of data rate and physical security. When number of the cells per image is 100 × 100, symbol error rate in 1×10^{-4} range was achieved at 300 kilo symbols per second with the lowest screen luminance, 21 cd/m^2, by the adaptive thresholding with cell-size reduction.
keywords: *Visible light communication, Optical camera communication, Space division multiplexing, Inter-symbol interference, Smartphone screen*

1. Introduction

Visible light communication (VLC) provides wireless links without using any radio waves. Among the various VLCs, optical camera communication (OCC) uses an image sensor as a receiver. OCC can easily ensure the link in combination of LED lighting or screen such as liquid crystal display (LCD) or organic light-emitting diode (OLED) and smartphone embedded camera. In particular, downlink OCC from the screen to the smartphone camera has been extensively studied. As the development of micro (μ)-LED technology, the downlink OCC from μ-LED screen to the smartphone camera was reported to increase data rate [1]. On the other hand, since μ-LED panels will likely be used for its wearable devices, uplink OCC from smartphone embedded screen to indoor camera at a sufficient distance is also promising for the wireless link.

We aim for low-luminance, space-division-multiplexing (SDM), indoor uplink OCC at a maximum distance of 3.5 m as shown in Fig. 1. The smartphone screen continuously transmits binary SDM images composed of white and black cells at a frame rate of 30 frames per second (fps).

Short range smartphone-to-smartphone OCC based on SDM has been studied using the smartphone screen and camera [2]. However, there are few studies for the uplink OCC at a long range. As the distance increases, the spatial inter-symbol interference (ISI) prevents to enhance SDM capacity.

In order to increase SDM capacity at 3.5 m, we proposed a new type of adaptive thresholding and experimentally verified the SDM capacity increase [3]. The adaptive thresholding sets the optimal threshold for a center cell with each outer 8-cell pattern in 3×3 cells. The pattern helps to adaptively determine the threshold for the center cell.

In this study, to enhance the SDM capacity and physical security further, adaptive thresholding with cell-size reduction is newly proposed and experimentally verified.

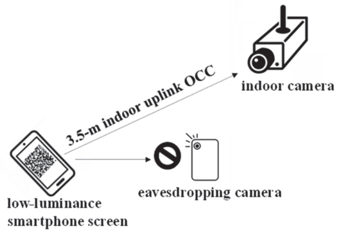


Fig. 1 Schematic diagram of indoor uplink OCC.

2. Adaptive thresholding with cell-size reduction

2.1 Adaptive thresholding [3]

Figure 2 shows the simulation model for 3×3 adaptive thresholding that determines the optimal threshold based on outer 8-cell pattern in every 3×3 cells. Pixel value of each cell on the screen, p_i, is normalized to be ±1 that corresponds to white and black cell, respectively. Since the distance between the screen and camera is relatively long, defocus blur causes the spatial ISI among received pixel values. The received pixel value of the center cell, P_0, is given by

$$P_0 = \sum_{i=0}^{8} w_i p_i, \qquad (1)$$

where w_i is coupling coefficient from each cell to the center due to the spatial ISI, w_0 is normalized to be 1, and $0 \le w_1, \cdots, w_8 \le 1$.

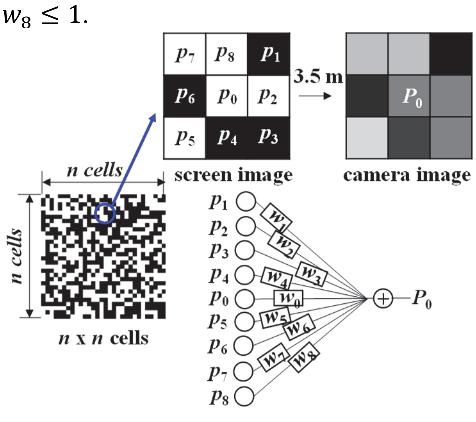


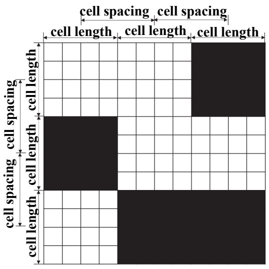
Fig. 2 Simulation model for 3×3 adaptive thresholding.

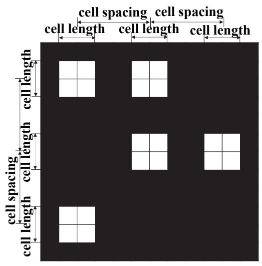
[†]The authors are with Meijo University.
[a)] E-mail: 213427010@ccmailg.meijo-u.ac.jp

First, adaptive thresholding estimates $p_{1,\cdots,}p_8$ from the received pixel value by the conventional fixed threshold. Every 3 × 3 cells are classified by the outer 8-cell pattern, $p_{1,\cdots,}p_8$. Next, the center-cell symbol, ±1, is determined by the optimal threshold in every classes. The simulation results are shown in the next session with cell-size reduction.

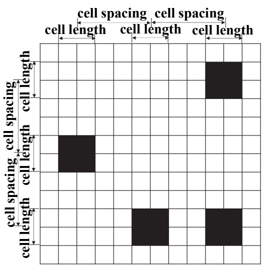
2.2 Cell-size reduction

The adaptive thresholding is effective against the spatial ISIs. However, as the screen luminance decreases, it becomes difficult to discriminate the symbol correctly because of low pixel value image and the spatial ISI. In order to adjust the luminance, we propose the cell-size reduction arrangement as shown in Fig. 3.





(a) conventional arrangement (b) reduced-size cell on black background



(c) reduced-size cell on white background

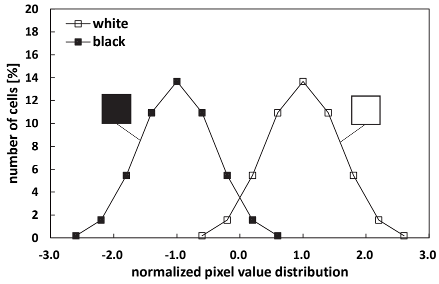
Fig. 3 Conventional and cell-size reduction arrangements.

Figure 3(a) shows conventional cell arrangement in which cell length and spacing are equal. Since the cell length and spacing are equal, the spatial ISI becomes more severe as the number of cells increases. On the other hand, Figures 3(b) and (c) show the cell-size reduction arrangement on black and white background, respectively. Both arrangements reduce only the cell area without reducing the cell spacing and number of cells per image. The black and white background decreases and increases the screen luminance, respectively. The luminance is adjusted by the cell-size reduction and background luminance. In particular, the luminance can be decreased by the cell-size reduction without decreasing the luminance value itself.

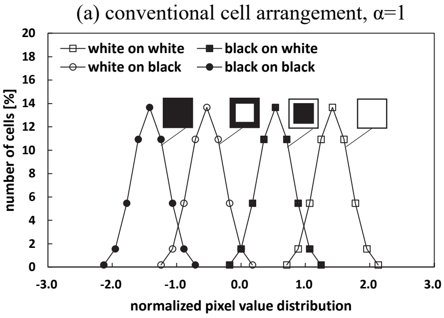
Figure 4 shows received pixel value distribution calculated by Eq. (1) when the cell size is reduced. Coupling coefficient, $w_1, \cdots, w_8 = 0.2$ and α is reduction rate of the cell area. When $\alpha = 1$, the pixel value distributions of white and black cells are considerably overlapped due to the spatial ISI. As α decreases, the ISI decreases. The cell-size reduction is effective to decrease the ISI. Whereas, the luminance itself also decreases with the cell-size reduction. As a result, the overlap ratios of the pixel value distributions are almost the same in spite of the cell-size reduction.

However, the cell-size reduction contributes to adjusting the screen luminance. As α decreases on the black background, the pixel value decreases. Even when the luminance is high, the low luminance image is obtained by the cell-size reduction.

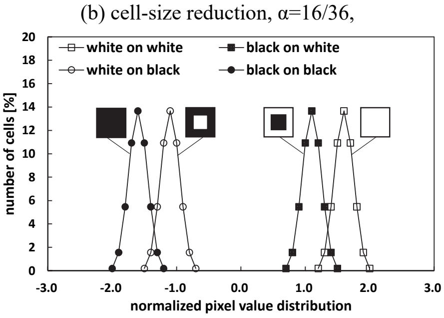
In addition to the cell-size reduction, the adaptive thresholding mentioned above is effective for the spatial ISI. Figure 5 shows the received pixel value distribution categorized by the outer 8-cell pattern, where all the outer 8 cells are black. The black- and white-cell distributions are clearly separated by the outer 8-cell pattern classification.



(a) conventional cell arrangement, α=1



(b) cell-size reduction, α=16/36,



(c) cell-size reduction, α=4/16

Fig. 4 Variation of pixel value distribution due to cell size.

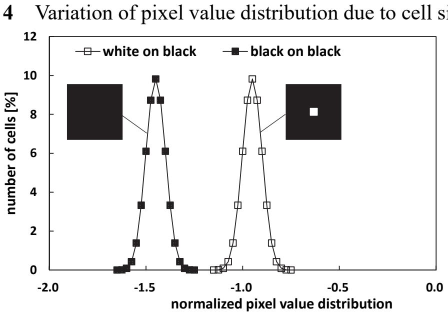


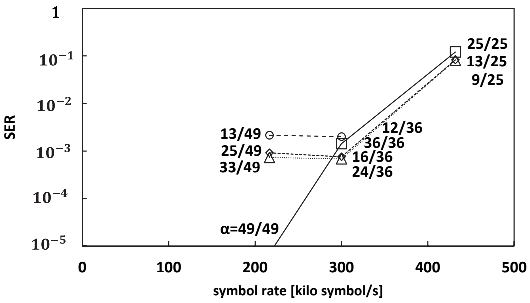
Fig. 5 Received pixel value distribution classified by the outer 8-cell pattern when the cell-size reduction, α=16/36.

3. Experimental results

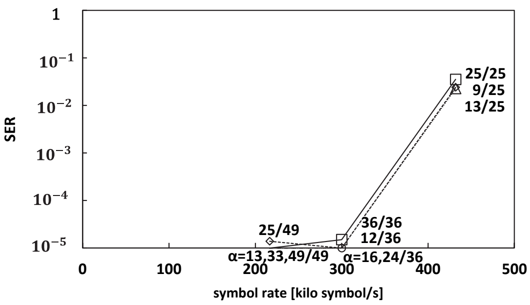
Symbol error rate (SER) was measured at a distance of 3.5 m while changing the reduction rate of cell area, α. To decrease the screen luminance, the cell sizes are reduced on the black background. Table 1 shows the measurement specifications. The white-cell pixel value was changed to 255, 127, and 95. Pseudo-random binary sequence 20 (PRBS20) was used for both known and unknown cell data.

Table 1 Measurement specifications.

smartphone screen		camera receiver	
frame rate	30 fps	frame rate	60 fps
image resolution	2448×1080 pixels (Full HD+)	image resolution	640×480 pixels (VGA)
refresh rate	144 Hz	Lens focal length	5-50 mm
8-bit luminance	0-255	8-bit pixel value	0-255
smartphone	ASUS ROG Phone 5	image sensor	SONY IMX219



(a) fixed threshold

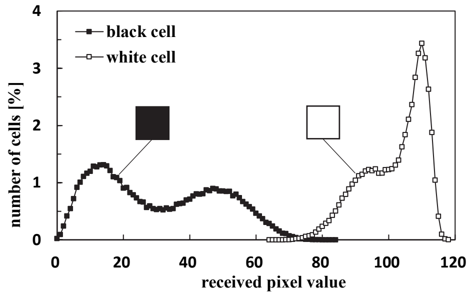


(b) adaptive threshold

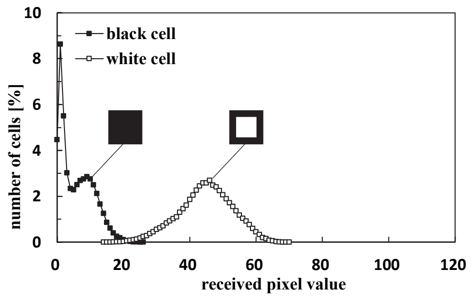
Fig. 6 SER comparison while changing α when the white-cell pixel value is 255.

Figure 6 compares the measured SERs while changing α on the black background. The white-cell pixel value of the smartphone screen is 255. Although the fixed thresholding causes symbol errors as the symbol rate increases, it is clear the adaptive thresholding contributes to decreasing the errors. The adaptive thresholding with cell-size reduction also works well to decrease the errors at the white-cell pixel value of 255. Even when α=12/36, SER=1×10^{-5} is maintained at 300 kilo symbols per second (symbol/s).

Figure 7 compares the received pixel value distribution between α=36/36 and 12/36 at 300k symbol/s. When α=36/36, average pixel value of received white cells is 102. When α=12/36, the average value decreases to 45. It is clear that the cell-size reduction is effective to decrease the luminance. Even when the white-cell pixel value is the maximum value of 255, the received pixel value can be decreased by the cell-size reduction on the black background.

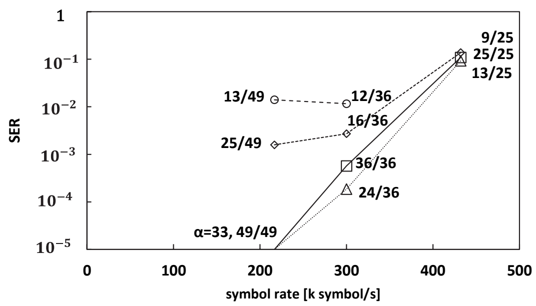


(a) conventional cell arrangement, α=36/36

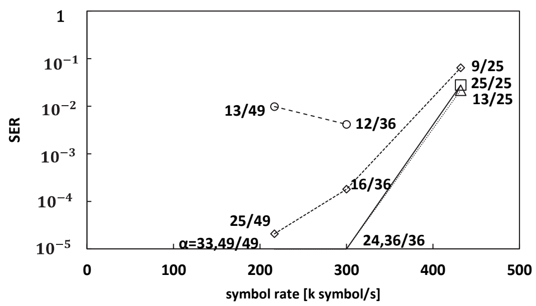


(b) cell-size reduction, α=12/36

Fig. 7 Comparison of pixel value distributions at 300k symbol/s.



(a) fixed threshold



(b) adaptive threshold

Fig. 8 SER comparison while changing α when the white-cell pixel value is 127.

Next, the white-cell pixel value was decreased to 127. Figure 8 shows the SER comparison while changing α on the black background. As well as that of the white-cell pixel value of 255, the adaptive thresholding decreases the number of errors. However, it becomes difficult to reduce the cell size without symbol errors owing to decrease in the luminance. When α=16/36, SER=1.8×10^{-4} was obtained at 300k symbol/s by the adaptive thresholding with cell-size reduction.

Figure 9 shows the received pixel value distribution when the cell-size reduction, α=16/36, at 300k symbol/s. The average pixel value of received white cells decreases to 12. The pixel value was able to decrease almost to the minimum value by the combination of both the cell-size and luminance reduction. SER in 1×10^{-4} range was obtained in spite of the low pixel value.

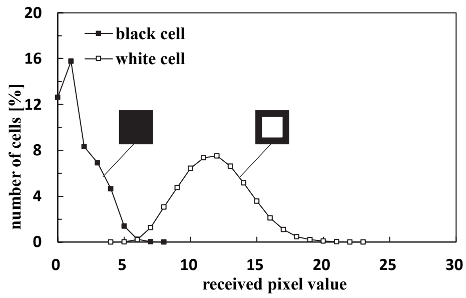
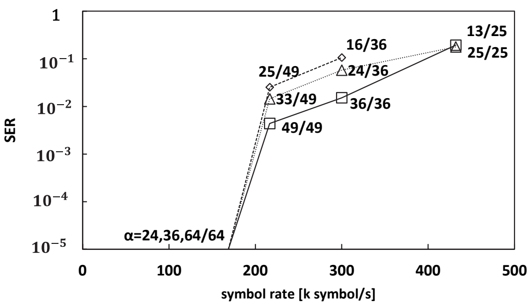
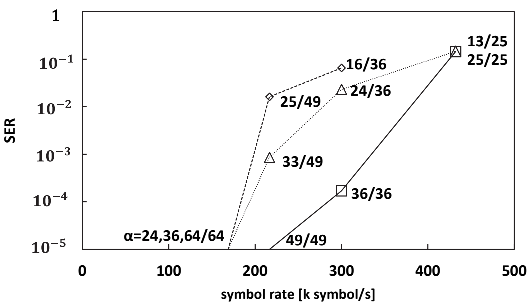


Fig. 9 Received pixel value distribution when the cell-size reduction, α=16/36, at 300k symbol/s.



(a) fixed threshold



(b) adaptive threshold

Fig. 10 SER comparison while changing α when the white-cell pixel value is 95.

Finally, the white-cell pixel value of the smartphone screen was decreased to 95. Figure 10 compares the measured SERs while changing α on the black background. It is almost impossible to reduce the cell size without errors at 300k symbol/s because of the low luminance. Only when the conventional cell arrangement, α=36/36, SER=1.7×10^{-4} was obtained at 300k symbol/s by the adaptive thresholding. The white-cell pixel value of 95 seems to be almost the lowest limit to distinguish black and white cells at 3.5 m.

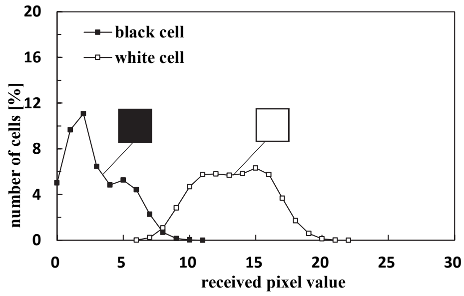


Fig. 11 Received pixel value distribution when conventional cell arrangement, α=36/36, at 300k symbol/s.

Figure 11 shows the received pixel value distribution when α=36/36 at 300k symbol/s. The average pixel value of the received white cells, 13, is almost the same as that when α=16/36 at the white-cell pixel value of 127 (see Fig. 9).

Moreover, each screen luminance was measured by the illuminance meter for comparison. The luminance when α=16/36 at the white-cell pixel value of 127 is 21 cd/m^2, that is lower than the luminance, 24 cd/m^2, when α=36/36 at 95. These results prove that the adaptive thresholding with cell-size reduction is effective to decrease the luminance.

4. Conclusion

To simultaneously enhance the data rate and physical security for uplink SDM-OCC, adaptive thresholding with cell-size reduction was proposed and experimentally verified.

When the smartphone's screen white-cell pixel value is 127 and the reduction rate of the cell area, α=16/36, SER=1.8×10^{-4} was obtained at 300k symbol/s. The average pixel value of the received white cells decreased to 12. These SER and average pixel value are almost the same as those measured when the white-cell pixel value is 95 and α=36/36 without cell-size reduction. The measured luminance, 21 cd/m^2, when α=16/36 at the white-cell pixel value of 127 was lower than that when α=36/36 at 95. It proved that the adaptive thresholding with cell-size reduction can simultaneously enhance the data rate and physical security without decreasing the luminance to the lowest limit.

Acknowledgments

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References

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