Space division multiplexing by adaptive thresholding for uplink optical camera communication using smartphone screen

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Abstract: To increase symbol rate and security at the physical layer for uplink optical camera communication from a smartphone screen to indoor camera at a distance of 3.5 m, space division multiplexing by adaptive thresholding is proposed and experimentally verified. The adaptive thresholding sets the optimal threshold for a center cell with each outer 8-cell pattern in 3x3 cells. Although the outer 8-cell pattern is estimated from conventional fixed threshold, the pattern helps to determine the threshold adaptively. The adaptive thresholding achieved 216.75 and 168.75 kilo symbol per second using 85x85 and 75x75 cells at luminance of 255 and 95, respectively.

Keywords: visible light communication, optical camera communication, image sensor, smartphone screen, adaptive thresholding

Classification: Wireless communication technologies

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1 Introduction

Visible light communication (VLC) is promising for solving the issue of radio resources’ depletion, interference, and eavesdropping. Among VLcs, optical camera communication (OCC) uses an image sensor as a receiver. Downlink OCC consists of LED lighting transmitter and smartphone-embedded camera receiver has been extensively studied. However, few studies have focused on uplink OCC. Since OCC provides high space resolution and wide-angle field-of-view simultaneously, space division multiplexing (SDM) is suitable for increasing the capacity.

Regarding uplink SDM-OCC using smartphone screen, short distance OCC from a smartphone screen to an opposite smartphone camera has been studied [1], where SDM binary images composed of black and white cells are transmitted from the screen. Gray-scale images captured with the opposite camera are binarized and the optimal threshold is determined with the Otsu method [2].

In this study, we investigate uplink SDM-OCC from smartphone screen to indoor camera at a distance of 3.5 m. Since the distance and number of cells increase significantly, spatial inter-symbol interference (ISI) is caused by defocus blur. Fig. 1(a) shows overlap of received pixel value distributions due to the spatial ISI at 3.5 m. The black and white pixel values spread more and the overlap increases more when number of cells is 85x85. Fig. 1(b) shows transmitted SDM images. Since spatial interference among adjacent cells increases by defocus blur, the spatial ISI strongly depends on the adjacent cell pattern. As number of cells increases, it becomes difficult to make correct symbol decision by a fixed threshold.

To recover from the blurred image in the downlink using LED array transmitter, maximum likelihood decoding (MLD) has been studied. Although MLD algorithm that reduces the computational complexity has been studied [3], processing time for the MLD increases as number of cells increases.

We propose adaptive thresholding aiming for real-time processing. The adaptive thresholding determines the optimal threshold for the center cell in each 3x3 cells based on outer 8-cell pattern adjacent to the center cell. Although there are existing adaptive thresholding approaches for barcode images such as QR code, they select binarization location and size adaptively because of nonuniform illumination [4]. On the other hand, our issue is spatial ISI owing to defocus blur at long distance. Our approach uses only the center pixel of the observed center cell for the binarization. Our idea adaptively determines the optimal threshold for the center cell based on the outer 8-cell pattern that is determined by the fixed threshold.
2 Numerical simulation for adaptive thresholding

The \( n \times n \) cells are split into 3x3 cells as shown in Fig. 2(a). When the spatial ISI from each cell to the center cell is assumed to be \( p_0 \sim p_B \), the received pixel value of the center cell, \( P_0 \) is given by

\[
P_0 = \sum_{i=1}^{B} p_i,
\]

where \( p_0 \) is normalized to be \( \pm 1 \) when the center cell is white and black, respectively. Adaptive threshold is determined for the center cell based on the outer 8-cell pattern using known images. After that, symbol decision for unknown images is made with the adaptive threshold. However, the pixel value of the outer 8 cells is affected by the spatial ISI as well as that of the center cell. In this study, the outer 8-cell pattern is roughly discriminated by the fixed threshold. Even when the estimated 8-cell pattern is slightly different from the original pattern, the

![Fig. 2. Calculated pixel value distributions and SER.](image-url)
estimated pattern contributes to adaptive thresholding. The adaptive thresholding algorithm is explained separately in the following three parts.

2.1 weak spatial ISI

Fig. 2(b) shows pixel value distributions for 3x3 cells calculated by Eq. (1). Black and white mark shows black- and white-cell distributions, respectively, while changing the spatial ISI from the outer 8 cells. When the ISI, $p_1 \sim p_8$, is $\pm 0.1$, classes of black and white cells are completely separated. If the fixed threshold is set to 0.0, error free transmission is possible.

2.2 medium spatial ISI

When $p_1 \sim p_8 = \pm 0.2$, the maximum value of the black-cell class is higher than the minimum of the white-cell class as shown in Fig. 2(b). There is some overlap between black and white classes. If the cells are able to be categorized by the outer 8-cell pattern, the optimal threshold is determined for the center cell in every 3x3 cells. In order to calculate the spatial ISI from further outer 16 cells to the center cell, $p_9 \sim p_{24}$, is added to Eq. (1). Received pixel value of the center cell, $P_0$, is given by

$$P_0 = \sum_{i=1}^{24} p_i.$$

(2)

Fig. 2(c) shows pixel value distribution calculated by Eq. (2) that is categorized by the outer 8-cell pattern, where the outer 8 cells are assumed to be black cells. The spatial ISI is inversely proportional to the square of the distance. When $p_1 \sim p_8 = \pm 0.2$, $p_9 \sim p_{24} = \pm 0.05$. Classes of black and white cells are completely separated due to the classification in each pattern. If the optimal threshold is assigned for the center cell in each pattern, error-free transmission is possible.

2.3 strong spatial ISI

Fig. 2(d) shows pixel value distributions calculated by Eq. (2) when $p_1 \sim p_8 = \pm 0.5$ and $p_9 \sim p_{24} = \pm 0.125$. Since the spatial ISI becomes strong, the black-cell class partially overlaps with the white-cell class. Even when the pixel value distribution is categorized by the outer 8-cell pattern, the maximum value of the black-cell class is higher than the minimum of the white-cell class. Classification by outer 8-cell pattern is not adequate for the strong ISI.

2.4 adaptive thresholding algorithm

Fig. 2(e) shows symbol error rates (SERs) calculated by Eqs. (1) and (2). When the spatial ISI is less than 0.1, error-free transmission is obtained by the fixed threshold. When the ISI is from 0.1 to 0.2, the adaptive thresholding is effective. However, when the ISI is more than 0.2, the outer 8-cell pattern is not adequate for correct symbol decision. Further outer 16-cell pattern needs to be considered for the decision.

Fig. 2(f) shows symbol decision procedure for adaptive thresholding. The preamble consists of known images and the payload consists of unknown images. In advance, by using known images at the preamble, the optimal threshold is adaptively determined for the center cell by the outer 8-cell pattern. At the same time, fixed threshold is determined between the maximum pixel value in black-cell class and the minimum pixel value in white-cell class. Even when black- and white-cell classes are overlapped, the fixed threshold is assigned between black and white classes.
Next, unknown images are categorized by the outer 8-cell pattern with the fixed threshold at the payload. Even when the outer 8-cell pattern is slightly different from the original pattern, optimal threshold changes slowly. Finally, symbol decision is made for the center cell with the adaptive threshold based on the outer 8-cell pattern.

| smartphone screen transmitter | indoor camera receiver |
|-------------------------------|------------------------|
| frame rate                    | 30 fps                 |
| image resolution              | 1920x1080 pixels       |
| 8-bit luminance               | 0-255                  |
| smartphone                    | ASUS-Z5670KS           |
|                               | 8-bit pixel value      |
|                               | 0-255                  |
| image sensor                  | SONY IMX219            |

(a) experimental specifications

(b) SER at luminance of 255

(c) SER at luminance of 127

(d) SER at luminance of 95

(e) captured image in each luminance

(f) pixel value distribution: 75x75 cells

(g) pixel value distribution: 85x85 cells

(h) SER comparison due to the difference in outer 8-cell pattern discrimination

Fig. 3. Measured SER versus symbol rate and pixel value distributions.
3 Experimental results

Fig. 3(a) shows experimental specifications. Smartphone-embedded organic light emitting diode (OLED) screen transmits SDM images at 30 frames per second (fps) and indoor camera captures the images at 60 fps. Transmitter image size is 600x600 pixels. Number of cells per image for SDM-OCC is altered from 60x60 that corresponds to 108 kilo symbol per second (k symbol/s) to 100x100 that corresponds to 300k symbol/s. On-off-keying modulation assigns symbol 0 to luminance 0 and symbol 1 to luminance 255, 127, and 95.

SER was measured at 3.5 m under fluorescent light conditions with pseudo-random binary sequence 15 (PRBS15). SER=10^{-6} indicates error-free transmission. Figs. 3(b) and (c) shows SER when the luminance is 255 and 127, respectively. The adaptive thresholding achieves error-free transmission up to 85x85 cells (216.75k symbol/s). Fig. 3(d) shows SER when the luminance decreases to 95. The adaptive thresholding achieves error-free transmission up to 75x75 cells (168.75k symbol/s). Fig. 3(e) shows captured images at 3.5 m when error-free transmission is achieved. When the luminance is 95, it is almost impossible to recognize the image with the human eye.

4 Discussion

Effectiveness of adaptive thresholding to spatial ISI was analyzed from the experimental results. Fig. 3(f) shows measured pixel value distributions of 75x75 cells at the luminance of 95. Black- and white-cell classes are completely separated when the outer 8 cells are black. Effectiveness of adaptive thresholding is clearly shown. On the other hand, Fig. 3(g) shows measured pixel value distributions of 85x85 cells at the luminance of 95 when errors occurred. The black- and white-cell classes are slightly overlapped when the outer 8 cells consist of 6 black and 2 white cells.

Finally, to improve SER further by the adaptive thresholding, outer 8-cell pattern was also discriminated by the adaptive thresholding. Fig. 3(h) shows SER comparison due to the difference in outer 8-cell pattern discrimination. SER was improved at luminance of 255 and 127 when the outer 8 cells are discriminated by the adaptive thresholding. However, to improve SER further, spatial ISI from further outer 16-cell pattern needs to be considered.

5 Conclusion

Adaptive thresholding simultaneously increased symbol rate and security by increasing number of cells and lowering the luminance for uplink SDM-OCC using smartphone screen at a distance of 3.5 m. Error-free transmission up to 75x75 cells (168.75k symbol/s) was achieved at low luminance of 95.

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