Additional Bit Transmission Using Space Modulation in Layered Space Time Coded Visible Light Communications

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***Abstract*—For image sensor (IS)-based visible light communication (VLC) systems, space-time coding (STC) was investigated for extended communication range of the VLC link. When an IS receiver is in the distance from the LED array of the transmitter where the number of pixels capturing the transmitter is less than the number of LEDs in the array, the distance is out of the transmission range. To make it the transmission distance, space time coding (STC) was investigated [1], and layered STC was investigated in [2] for further increasing the reception rate with improving the pixel resolution while the receiver was approaching the LED array of the transmitter. This paper proposes spatial modulation (SM) for increasing the reception rate of layered STC. In layered STC system with SM, an additional bit is transmitted by placing the pair of space-time coded bits on either of the main diagonal or anti-diagonal submatrices. Experimental results show that the additional bit by SM is received without any bit errors, without deteriorating the reception quality of layered STC.**

I. Introduction

Visible light communication (VLC) using image sensors (ISs) as the receiver has attracted a lot of researchers and developers [3], [4]. Some have the interests in the outdoor mobile communication system [5] [6]. Many VLC systems aim to operate as a dual function of lighting and information transmission simultaneously. LED-based traffic and vehicle lights can be part of a communication network, which provides dynamic traffic routing, public transportation scheduling, road safety and many others in intelligent transport systems (ITS). Such LEDs form a two-dimensional array. IS receivers have several advantages that light sources are almost perfectly divided on the image plane because ISs have a massive number of pixels each of which separately detects light of LEDs. This prevents signals from becoming mixed, thus allowing communication, even if many LED transmitters and noise sources such as sunlight and streetlights are present.

When, however, the receiver is away from the transmitter, ISs cannot capture each of the LEDs with a sufficient number of pixels. For such a low pixel resolution situation, space-time coding (STC) enables data transmission [1]. Furthermore, layered-STC achieves increased reception rate when the pixel resolution is improved while the receiver approaches the transmitter [2].

In this paper, we introduce spatial modulation (SM) to layered-STC for increasing the reception rate. Although STC bit pair is fixed to be put in the main diagonal submatrices in the layered STC, with SM, the STC bit pair is arranged in either the main diagonal or anti-diagonal submatrices. An experimental prototype of layered STC with SM is built with an 8×8 LED array, where each LED is modulated with on-off keying (OOK) at 1 kbps and a high-speed camera with IS operating at 1000 fps. Our experimental results confirm that the additional bit stream by SM is successfully received up to 210 m, without deteriorating the layered STC bit reception quality.

The remainder of this paper is organized as follows. Section II details layered STC using SM in our VLC system, including a matrix notation for SM and STC. Section III explains a data Streams structure used in the system, and Section IV gives a specific example of the decision rule of three-layered STC with SM. Section V explains our experimental setup and presents measured BER to verify that SM increases the reception rate when the receiver comes close to the transmitter, compared to layered STC without SM. Finally, conclusions are presented in Section VI.

II. Spatial Modulation for Layered STC

A. Spatial modulation for layered STC

The main idea of our scheme is to arrange two bit matrices of each layer in entries on either of the main diagonal or anti-diagonal.

We consider a $2^i \times 2^i$ mathematical Boolean matrix $\boldsymbol{P}$, which can be partitioned into four $2^{i-1} \times 2^{i-1}$ submatrices $\boldsymbol{P}_{11}$, $\boldsymbol{P}_{12}$, $\boldsymbol{P}_{21}$, and $\boldsymbol{P}_{22}$: i.e.,

$$\boldsymbol{P} = \begin{bmatrix} \boldsymbol{P}_{11} & \boldsymbol{P}_{12} \\ \boldsymbol{P}_{21} & \boldsymbol{P}_{22} \end{bmatrix}. \tag{1}$$

To perform SM on such a $\boldsymbol{P}$, "1" and "0" of an SM bit x are mapped to two SM matrices $\boldsymbol{M}_i$ and $\boldsymbol{W}_i$, respectively,

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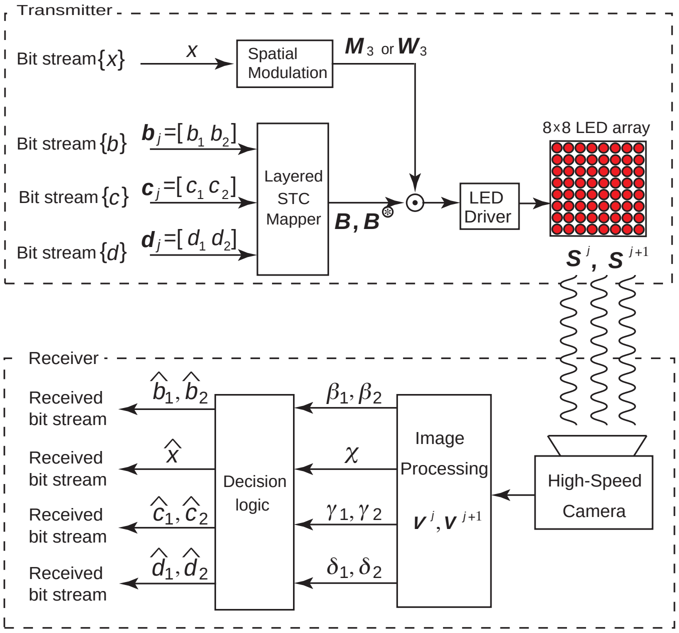


Fig. 1. The diagram of the experimental set-up of a VLC system using transmitter with 8×8 LED array, each LED blinking by 1 ms and a receiver with a 1,000 fps high-speed camera.

written by

$$\begin{cases} \boldsymbol{M}_i = \begin{bmatrix} \mathbf{1}_{2^{i-1}} & \mathbf{0}_{2^{i-1}} \\ \mathbf{0}_{2^{i-1}} & \mathbf{1}_{2^{i-1}} \end{bmatrix}, & \text{for } x = 1 \\ \\ \boldsymbol{W}_i = \begin{bmatrix} \mathbf{0}_{2^{i-1}} & \mathbf{1}_{2^{i-1}} \\ \mathbf{1}_{2^{i-1}} & \mathbf{0}_{2^{i-1}} \end{bmatrix}, & \text{for } x = 0, \end{cases} \tag{2}$$

where $\mathbf{1}_h$ and $\mathbf{0}_h$ are the all-ones and all-zeros square matrices, respectively, of size $h \times h$. Therefore, the matrix for applying SM to $\boldsymbol{P}$ is written as

$$\mathscr{P} = \begin{cases} \boldsymbol{P} \cdot \boldsymbol{M}_i = \begin{bmatrix} \boldsymbol{P}_{11} & \boldsymbol{P}_{12} \\ \boldsymbol{P}_{21} & \boldsymbol{P}_{22} \end{bmatrix}, & \text{for } x = 1 \\ \\ \boldsymbol{P} \cdot \boldsymbol{M}_i = \begin{bmatrix} \boldsymbol{P}_{12} & \boldsymbol{P}_{11} \\ \boldsymbol{P}_{22} & \boldsymbol{P}_{21} \end{bmatrix}, & \text{for } x = 0. \end{cases} \tag{3}$$

B. STC Matrix Pair for 8×8 LED Array

With three-layered STC, we give a specific example of applying SM to it.

Consider an additional bit stream $\{x\}$, in addition to three additional bit streams $\{b\}$, $\{c\}$, and $\{d\}$ for the three-layered STC, as shown in Fig. 1.

1) Matrix Notation for Space-Time Coding: Before explaining layered STC, let us define a mathematical Boolean matrix operation to explain STC operation [2], [7]. To represent the space-time coded (STC) matrix for matrix $\boldsymbol{P}$ in Eq. (1), we define a matrix manipulation operation as

$$\boldsymbol{P}^{\circledast} = \begin{bmatrix} \overline{\boldsymbol{P}}_{22} & \boldsymbol{P}_{12}^{\circledast} \\ \boldsymbol{P}_{21}^{\circledast} & \boldsymbol{P}_{11} \end{bmatrix}, \tag{4}$$

where

1) the matrix on the upper left corner, i.e., $\overline{\boldsymbol{P}}_{22}$, is calculated the binary opposite of submatrix $\boldsymbol{P}_{22}$, namely, all elements of $\overline{\boldsymbol{P}}_{22}$ are complements of the ones of $\boldsymbol{P}_{22}$,
2) the two submatrices on the diagonal going from the lower left corner to the upper right corner (i.e., $\boldsymbol{P}_{21}^{\circledast}$ and $\boldsymbol{P}_{12}^{\circledast}$) are recursively calculated the operation $\circledast$ over and over with the next small-size submatrices until the matrix size is 1×1, where $1^{\circledast} = 0$ and $0^{\circledast} = 1$,
3) the two diagonal submatrices, i.e., $\boldsymbol{P}_{11}$ and $\boldsymbol{P}_{22}$, are swapped.

2) Layered Space-Time Coding: The procedure to construct a bit matrix and its STC matrix of layered STC is that at any given $2^{n-i} \times 2^{n-i}$ matrix,

1) to partition it into four $2^{n-i-1} \times 2^{n-i-1}$ submatrices,
2) to construct two $2^{n-i-1} \times 2^{n-i-1}$ bit matrices, according two bits of layer $i+1$, and to align them along the main diagonal of the $2^{n-i} \times 2^{n-i}$ matrix,
3) to align two $2^{n-i-1} \times 2^{n-i-1}$ matrices, which are the bit matrix from the next layer (i.e., layer $n-i-2$) and its complement, along the anti-diagonal of the $2^{n-i} \times 2^{n-i}$ matrix,
4) to take the matrix manipulation operation defined in Eq. (4) to obtain its STC matrix.

Given two bits from each of n independent bit streams, a $2^n \times 2^n$ bit matrix and its STC matrix are calculated, by repeating the above procedure n times, which we call the matrix pair STC matrix pair.

For a $2^n \times 2^n$ STC matrix pair, the above procedure is repeated n times, being provided two bits from each of n independent bit streams.

3) STC matrix pair for 8×8 LED array: For the jth symbol duration, when two bits b_1 and b_2 from bit stream $\{b\}$ are fed into the layered STC mapper, they form two 4×4 matrices $\boldsymbol{B}_1$ and $\boldsymbol{B}_2$:

$$\boldsymbol{B}_1 = b_1 \otimes \boldsymbol{J}_4 = \begin{bmatrix} b_1 & b_1 & b_1 & b_1 \\ b_1 & b_1 & b_1 & b_1 \\ b_1 & b_1 & b_1 & b_1 \\ b_1 & b_1 & b_1 & b_1 \end{bmatrix}, \tag{5}$$

$$\boldsymbol{B}_2 = b_2 \otimes \boldsymbol{J}_4 = \begin{bmatrix} b_2 & b_2 & b_2 & b_2 \\ b_2 & b_2 & b_2 & b_2 \\ b_2 & b_2 & b_2 & b_2 \\ b_2 & b_2 & b_2 & b_2 \end{bmatrix}, \tag{6}$$

where $\otimes$ denotes the Kronecker product operation and $\boldsymbol{J}_4$ is the all-ones square matrix of size 4×4. Therefore, the two bits of layer-1 (bit stream $\{b\}$) form an 8×8 STC matrix pair expressed as

$$\boldsymbol{B} = \begin{bmatrix} \boldsymbol{B}_1 & \overline{\boldsymbol{C}} \\ \boldsymbol{C} & \boldsymbol{B}_2 \end{bmatrix}, \qquad \boldsymbol{B}^{\circledast} = \begin{bmatrix} \overline{\boldsymbol{B}}_2 & \overline{\boldsymbol{C}}^{\circledast} \\ \boldsymbol{C}^{\circledast} & \boldsymbol{B}_1 \end{bmatrix}, \tag{7}$$

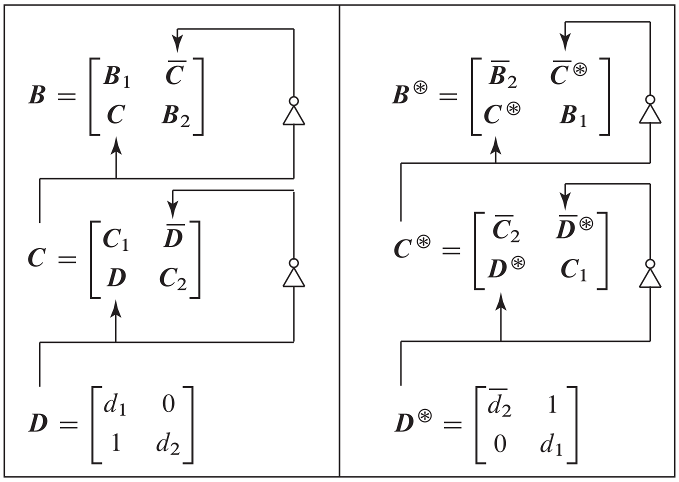


Fig. 2. Procedure is shown of how an 8×8 STC matrix pair are constructed.

where $\boldsymbol{C}$ is a 4×4 matrix, constructed with two bits from the two bit streams $\{c\}$ and $\{d\}$ transmitted in the same symbol durations.

For the 4×4 matrix $\boldsymbol{C}$ in Eq. (7), when two bits c_1 and c_2 from layer-2 (bit stream $\{c\}$) are fed to the mapper, it generates two 2×2 matrices, expressed as

$$\boldsymbol{C}_1 = c_1 \otimes \boldsymbol{J}_2 = \begin{bmatrix} c_1 & c_1 \\ c_1 & c_1 \end{bmatrix}, \tag{8}$$

$$\boldsymbol{C}_2 = c_2 \otimes \boldsymbol{J}_2 = \begin{bmatrix} c_2 & c_2 \\ c_2 & c_2 \end{bmatrix}. \tag{9}$$

The two matrices are aligned along the main diagonals of the matrix $\boldsymbol{C}$. Therefore, the 4×4 STC matrix pair of layer-2 are expressed as

$$\boldsymbol{C} = \begin{bmatrix} \boldsymbol{C}_1 & \overline{\boldsymbol{D}} \\ \boldsymbol{D} & \boldsymbol{C}_2 \end{bmatrix}, \qquad \boldsymbol{C}^{\circledast} = \begin{bmatrix} \overline{\boldsymbol{C}}_2 & \overline{\boldsymbol{D}}^{\circledast} \\ \boldsymbol{D}^{\circledast} & \boldsymbol{C}_1 \end{bmatrix}, \tag{10}$$

where $\boldsymbol{D}$ is the 2×2 matrix, constructed according to two bits from the next bit stream $\{d\}$ in the same symbol duration.

For the 2×2 matrix $\boldsymbol{D}$, when two bits d_1 and d_2 from layer-3 (bit stream $\{d\}$) are fed to the mapper, it calculates two 1×1 matrices $\boldsymbol{D}_1$ and $\boldsymbol{D}_2$, expressed as

$$\boldsymbol{D}_1 = d_1 \otimes \boldsymbol{J}_1 = d_1, \qquad \boldsymbol{D}_2 = d_2 \otimes \boldsymbol{J}_1 = d_2, \tag{11}$$

which are scalars. The two bits of the third bit stream form the minimum-size matrices of the layered STC, expressed as

$$\boldsymbol{D} = \begin{bmatrix} d_1 & 0 \\ 1 & d_2 \end{bmatrix}, \qquad \boldsymbol{D}^{\circledast} = \begin{bmatrix} \overline{d_2} & 1 \\ 0 & d_1 \end{bmatrix}. \tag{12}$$

In short, for the 8×8 LED array, the mapper first calculates the layer-1 matrix $\boldsymbol{B}$, based on two bits from bit stream $\{b\}$. The mapper repeats it for layer-2 and -3, with halving the matrix size until it is 1×1, as shown in Fig. 2. Once $\boldsymbol{D}$, $\boldsymbol{C}$, and $\boldsymbol{B}$ are determined, their STC matrices $\boldsymbol{D}^{\circledast}$, $\boldsymbol{C}^{\circledast}$, and $\boldsymbol{B}^{\circledast}$ are constructed, according to Eqs. (7), (10), and (12).

4) Spatial Modulation of 8×8 STC matrix pair: This subsubsection explains SM which is performed on $\boldsymbol{B}$ and $\boldsymbol{B}^{\circledast}$ as

$$\mathcal{B} = \begin{cases} \boldsymbol{B} \cdot \boldsymbol{M}_3 = \begin{bmatrix} \boldsymbol{B}_1 & \overline{\boldsymbol{C}} \\ \boldsymbol{C} & \boldsymbol{B}_2 \end{bmatrix}, & x = 1 \\ \boldsymbol{B} \cdot \boldsymbol{W}_3 = \begin{bmatrix} \overline{\boldsymbol{C}} & \boldsymbol{B}_1 \\ \boldsymbol{B}_2 & \boldsymbol{C} \end{bmatrix}, & x = 0 \end{cases} \tag{13}$$

$$\mathcal{B}^{\circledast} = \begin{cases} \boldsymbol{B}^{\circledast} \cdot \boldsymbol{M}_3 = \begin{bmatrix} \overline{\boldsymbol{B}}_2 & \overline{\boldsymbol{C}}^{\circledast} \\ \boldsymbol{C}^{\circledast} & \boldsymbol{B}_1 \end{bmatrix}, & x = 1 \\ \boldsymbol{B}^{\circledast} \cdot \boldsymbol{W}_3 = \begin{bmatrix} \overline{\boldsymbol{C}}^{\circledast} & \overline{\boldsymbol{B}}_2 \\ \boldsymbol{B}_1 & \boldsymbol{C}^{\circledast} \end{bmatrix}, & x = 0. \end{cases} \tag{14}$$

5) Signal waveform of 8×8 STC matrix pair: Now we consider signal waveform. Let $\boldsymbol{U}(t)$ denote an 8×8 LED matrix whose elements are all

$$u_1(t) = A, \qquad 0 \leq t \leq T \tag{15}$$

where T is the symbol duration and A is a constant intensity of LED light source transmitting for symbol "1."

Given an 8×8 STC matrix pair for the jth and $(j+1)$th symbol durations, which are modulated by the SM bit $x = 1$, the digitally modulated symbols transmitted from each of the LEDs in the 8×8 array are written as

$$\begin{aligned} \boldsymbol{S}^j &= \mathcal{B}^j \circ \boldsymbol{U}(t - jT) \\ &= \begin{pmatrix} b_1 & b_1 & b_1 & b_1 & \overline{c_1} & \overline{c_1} & d_1 & 0 \\ b_1 & b_1 & b_1 & b_1 & \overline{c_1} & \overline{c_1} & 1 & d_2 \\ b_1 & b_1 & b_1 & b_1 & \overline{d_1} & 1 & \overline{c_2} & \overline{c_2} \\ b_1 & b_1 & b_1 & b_1 & 0 & \overline{d_2} & \overline{c_2} & \overline{c_2} \\ c_1 & c_1 & \overline{d_1} & 1 & b_2 & b_2 & b_2 & b_2 \\ c_1 & c_1 & 0 & \overline{d_2} & b_2 & b_2 & b_2 & b_2 \\ d_1 & 0 & c_2 & c_2 & b_2 & b_2 & b_2 & b_2 \\ 1 & d_2 & c_2 & c_2 & b_2 & b_2 & b_2 & b_2 \end{pmatrix} \\ &\quad \circ \boldsymbol{U}(t - jT), \end{aligned} \tag{16}$$

$$\begin{aligned} \boldsymbol{S}^{j+1} &= (\mathcal{B}^j)^{\circledast} \circ \boldsymbol{U}(t - (j+1)T) \\ &= \begin{pmatrix} \overline{b_2} & \overline{b_2} & \overline{b_2} & \overline{b_2} & c_2 & c_2 & \overline{d_2} & 1 \\ \overline{b_2} & \overline{b_2} & \overline{b_2} & \overline{b_2} & c_2 & c_2 & 0 & d_1 \\ \overline{b_2} & \overline{b_2} & \overline{b_2} & \overline{b_2} & d_2 & 0 & \overline{c_1} & \overline{c_1} \\ \overline{b_2} & \overline{b_2} & \overline{b_2} & \overline{b_2} & 1 & \overline{d_1} & \overline{c_1} & \overline{c_1} \\ \overline{c_2} & \overline{c_2} & d_2 & 0 & b_1 & b_1 & b_1 & b_1 \\ \overline{c_2} & \overline{c_2} & 1 & \overline{d_1} & b_1 & b_1 & b_1 & b_1 \\ \overline{d_2} & 1 & c_1 & c_1 & b_1 & b_1 & b_1 & b_1 \\ 0 & d_1 & c_1 & c_1 & b_1 & b_1 & b_1 & b_1 \end{pmatrix} \\ &\quad \circ \boldsymbol{U}(t - (j+1)T), \end{aligned} \tag{17}$$

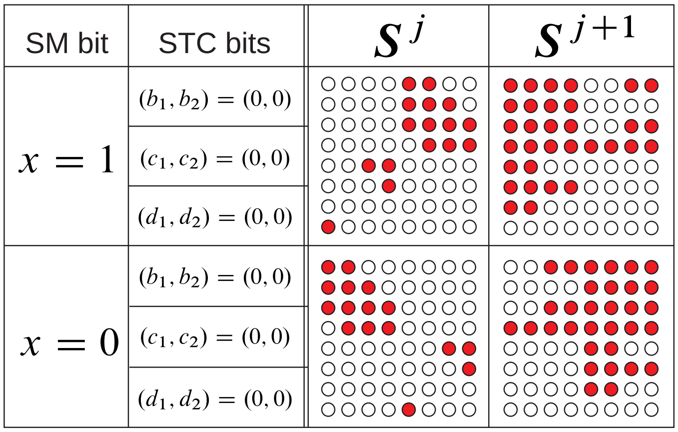


Fig. 3. Example of three-layered STC matrix mapping of the 8×8 LED array for the SM bit $x = 1$ and 0 when $[b_1, b_2] = [0, 0]$, $[c_1, c_2] = [0, 0]$, and $[d_1, d_2] = [0, 0]$.

where $\circ$ denotes the Hadamard product operation. The Hadamard product of $\boldsymbol{A} = (a_{kl})$ and $\boldsymbol{B} = (b_{kl})$ is defined as $\boldsymbol{C} = \boldsymbol{A} \circ \boldsymbol{B} = (c_{kl}) = (a_{kl} b_{kl})$ for $k \in \{1, \ldots, m\}$ and $l \in \{1, \ldots, n\}$, where $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ are all $m \times n$ matrices. Since the Hadamard product is simply entrywise multiplication, both $\boldsymbol{A}$ and $\boldsymbol{B}$ need to be the same size, and the resulting matrix is also the same size as the original matrices. Note that in Eqs. (16) and (17), entries of $\mathscr{B}$ and $\mathscr{B}^{j\circledast}$ are expressed when $x = 1$. When $x = 0$, they are expressed as

$$\boldsymbol{S}^{j} = \mathscr{B}^{j} \circ \boldsymbol{U}(t - jT)$$
$$= \begin{pmatrix} \overline{c_1} & \overline{c_1} & d_1 & 0 & b_1 & b_1 & b_1 & b_1 \\ \overline{c_1} & \overline{c_1} & 1 & d_2 & b_1 & b_1 & b_1 & b_1 \\ \overline{d_1} & 1 & \overline{c_2} & \overline{c_2} & b_1 & b_1 & b_1 & b_1 \\ 0 & \overline{d_2} & \overline{c_2} & \overline{c_2} & b_1 & b_1 & b_1 & b_1 \\ b_2 & b_2 & b_2 & b_2 & c_1 & c_1 & \overline{d_1} & 1 \\ b_2 & b_2 & b_2 & b_2 & c_1 & c_1 & 0 & \overline{d_2} \\ b_2 & b_2 & b_2 & b_2 & d_1 & 0 & c_2 & c_2 \\ b_2 & b_2 & b_2 & b_2 & 1 & d_2 & c_2 & c_2 \end{pmatrix}$$
$$\circ \boldsymbol{U}(t - jT), \tag{18}$$

$$\boldsymbol{S}^{j+1} = \mathscr{B}^{j\circledast} \circ \boldsymbol{U}(t - (j+1)T)$$
$$= \begin{pmatrix} c_2 & c_2 & \overline{d_2} & 1 & \overline{b_2} & \overline{b_2} & \overline{b_2} & \overline{b_2} \\ c_2 & c_2 & 0 & d_1 & \overline{b_2} & \overline{b_2} & \overline{b_2} & \overline{b_2} \\ d_2 & 0 & \overline{c_1} & \overline{c_1} & \overline{b_2} & \overline{b_2} & \overline{b_2} & \overline{b_2} \\ 1 & \overline{d_1} & \overline{c_1} & \overline{c_1} & \overline{b_2} & \overline{b_2} & \overline{b_2} & \overline{b_2} \\ b_1 & b_1 & b_1 & b_1 & \overline{c_2} & \overline{c_2} & d_2 & 0 \\ b_1 & b_1 & b_1 & b_1 & \overline{c_2} & \overline{c_2} & 1 & \overline{d_1} \\ b_1 & b_1 & b_1 & b_1 & \overline{d_2} & 1 & c_1 & c_1 \\ b_1 & b_1 & b_1 & b_1 & 0 & d_1 & c_1 & c_1 \end{pmatrix}$$
$$\circ \boldsymbol{U}(t - (j+1)T), \tag{19}$$

In Fig. 3, an example of LED pattern of the SM three-layered STC is shown for the jth and $(j+1)$th symbol durations when $x = 0$, $[b_1, b_2] = [0, 0]$, $[c_1, c_2] = [0, 0]$, and $[d_1, d_2] = [0, 0]$ are fed into the mapper.

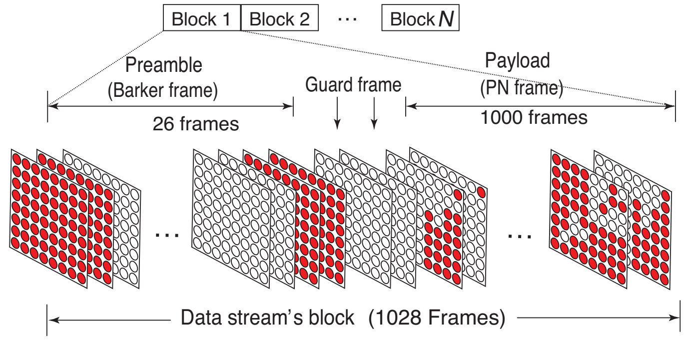


Fig. 4. The data stream structure consisting of 26 preamble frames, two guard frames, and 1000 data frames.

C. Complemented waveforms

According to "1" or "0" of $\mathscr{B}$ and $\mathscr{B}^{\circledast}$, each element of $\boldsymbol{S}(j) = \left(s_{kl}^{(j)}\right)$ and $\boldsymbol{S}(j+1) = \left(s_{kl}^{(j+1)}\right)$ has a waveform represented by either of $u_1 = A$ or $u_0 = 0$, respectively, for one symbol interval, where $u_1 \triangleq u_1(t - jT)$ and

$$u_0 \triangleq u_0(t - jT) = 0, \qquad 0 \le t \le T \tag{20}$$

for $j = \{0, 1, 2, \ldots\}$. As mentioned in [1], [3], one waveform is expressed in terms of the other by

$$u_m = -u_\ell + A, \qquad m, \ell \in \{0, 1\}, \quad m \ne \ell. \tag{21}$$

Using an overbar notation, we define the complement of a waveform u_m as $\overline{u}_m$: i.e., $\overline{u}_1 = u_0$ and $\overline{u}_0 = u_1$.

III. Data Streams and VLC Links

Fig. 4 shows the data stream structure used in our experiment, which consists of twenty-six preamble frames, two guard frames, and 1000 payload frames. The preamble frames are inserted for receivers to recognize the position of the LED array on the image plane and to know the symbol timing. The position and size of the LED array image change in each frame, due to the mobility and vibration of the camera (vehicle). By detecting Barker sequence of length 13, which is repeatedly transmitted in the preamble interval, through digital image processing, the receiver decides the pixel area capturing the LED array, and at the same time, it knows when the first data frame of the payload comes. Note that the receiver calculates the average luminance value of symbol "1" transmitted from the LED array at the distance D while detecting Barker sequence. The average value, $\mathcal{A}$, is used in the decision rule described in Section IV.

IV. Decision statistics in the IS receiver

A. Resizing raw images

We consider a case in which the receiver captures the LED array as a $W \times W$ pixel image when it is at a distance of D from the array, although the image size changes

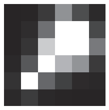
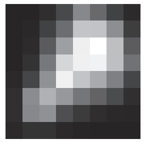
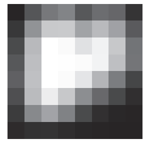
6×6 raw images		8×8 luminance matrices	
j th frame	$(j+1)$th frame	V^j	V^{j+1}
			

Fig. 5. LED array images with 6×6 size trimmed from the whole one and its' 8×8 luminance matrices V^j and V^{j+1} after resizing image processing are shown. Note that the LED patters shown in Fig. 3 are captured by the high-speed camera at the distance of 55 m.

depending on the distance from the array. The raw image is resized to the 8×8 luminance matrix, by OpenCV function `resize` with options `INTER_LINEAR` (eight times enlarge) and `INTER_AREA` (shrink to $1/W$). Therefore, two 8×8 luminance matrices are obtained for the jth and $(j+1)$th frames (symbol durations), expressed as $V^j = \left(v_{kl}^j\right)$ and $V^{j+1} = \left(v_{kl}^{j+1}\right)$, respectively. We consider the luminance value v_{kl} corresponding to the LED placed at the kth row and lth column of the array, where $k, l \in \{1, 2, \ldots, 8\}$. Fig. 5 shows an example of raw images of the LED array with 6×6 and its' luminance matrices after resizing.

B. Decision Statistics of SM with three-layered STC systems

As explained in Section II-B4, different layers are mutually exclusively aligned in the STC matrix pair, and the anti-diagonal elements of the matrices of each layer are complemented. Furthermore, two frames are related as the STC matrix pair, using the property of $\overline{u}_m = -u_\ell + A, m \neq \ell$. Therefore, the decision rule can be simply expressed addition or subtraction of luminance values at the jth and $(j+1)$th frames.

Although the decision is done in order of layer-1, layer-2, and layer-3 in layered STC system without SM, in the system with SM, SM bit decision is done after layer-1 and before layer-2 because the bit decision has to be done based on the SM bit decision.

For the decision rule of each of the STC bit streams $\{b\}$, we form the decision statistics β_1 and β_2 as, respectively,

$$\beta_1 = \sum_{k=1}^{8} \sum_{l=1}^{8} \left(v_{kl}^j + v_{kl}^{j+1}\right) - 64\mathcal{A} \tag{22}$$

$$\beta_2 = \sum_{k=1}^{8} \sum_{l=1}^{8} \left(v_{kl}^j - v_{kl}^{j+1}\right). \tag{23}$$

$\mathcal{A}$ in Eq. (22) is the average luminance value per LED for "1" of Barker sequence observed during the preamble interval, calculated as

$$\mathcal{A} = \frac{1}{9 \cdot 64} \sum_{p} \sum_{k=1}^{8} \sum_{l=1}^{8} v_{kl}^p, \tag{24}$$

where $p \in \{1, 2, 3, 4, 5, 8, 9, 11, 13\}$ is the frame number of Barker sequence with "1."

In the decision logic, $\widehat{b}_i$ is declared to be "1" if the decision statistics β_i is greater than or equal to 0; otherwise, it is declared to be "0."

For the SM bit, we form the decision statistics χ as

$$\begin{aligned}\chi = &\left|\sum_{k=1}^{4} \sum_{l=1}^{4} \left(v_{kl}^j + v_{kl}^{j+1}\right) + \sum_{k=5}^{8} \sum_{l=5}^{8} \left(v_{kl}^j + v_{kl}^{j+1}\right)\right| \\ &- \left|\sum_{k=5}^{8} \sum_{l=1}^{4} \left(v_{kl}^j + v_{kl}^{j+1}\right) + \sum_{k=1}^{4} \sum_{l=5}^{8} \left(v_{kl}^j + v_{kl}^{j+1}\right)\right|.\end{aligned} \tag{25}$$

$\widehat{x}$ is declared to be "1" if the decision statistics χ is greater than or equal to 0; otherwise, it is declared to be "0."

For the decision rule of the STC bit streams $\{c\}$ and $\{d\}$, we form γ_1 and γ_2, and δ_1 and δ_2 as

$$\gamma_1 = \sum_{k=5}^{8} \sum_{l=\{1,5\}}^{\{4,8\}} \left(v_{kl}^j + v_{kl}^{j+1}\right) - \sum_{k=1}^{4} \sum_{l=\{1,5\}}^{\{4,8\}} \left(v_{kl}^j + v_{kl}^{j+1}\right) \tag{26}$$

$$\gamma_2 = \sum_{k=5}^{8} \sum_{l=\{1,5\}}^{\{4,8\}} \left(v_{kl}^j - v_{kl}^{j+1}\right) + \sum_{k=1}^{4} \sum_{l=\{1,5\}}^{\{4,8\}} \left(v_{kl}^{j+1} - v_{kl}^j\right) \tag{27}$$

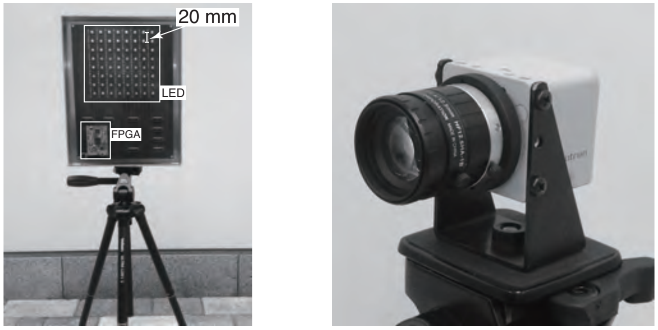
$$\begin{aligned}\delta_1 = &\sum_{k=7}^{8} \sum_{l=\{1,5\}}^{\{2,6\}} \left(v_{kl}^j + v_{kl}^{j+1}\right) - \sum_{k=5}^{6} \sum_{l=\{3,7\}}^{\{4,8\}} \left(v_{kl}^j + v_{kl}^{j+1}\right) \\ &- \sum_{k=3}^{4} \sum_{l=\{5,1\}}^{\{6,2\}} \left(v_{kl}^j + v_{kl}^{j+1}\right) + \sum_{k=1}^{2} \sum_{l=\{7,3\}}^{\{8,4\}} \left(v_{kl}^j + v_{kl}^{j+1}\right)\end{aligned} \tag{28}$$

$$\begin{aligned}\delta_2 = &\sum_{k=7}^{8} \sum_{l=\{1,5\}}^{\{2,6\}} \left(v_{kl}^j - v_{kl}^{j+1}\right) + \sum_{k=5}^{6} \sum_{l=\{3,7\}}^{\{4,8\}} \left(v_{kl}^{j+1} - v_{kl}^j\right) \\ &+ \sum_{k=3}^{4} \sum_{l=\{5,1\}}^{\{6,2\}} \left(v_{kl}^{j+1} - v_{kl}^j\right) + \sum_{k=1}^{2} \sum_{l=\{7,3\}}^{\{8,4\}} \left(v_{kl}^j - v_{kl}^{j+1}\right),\end{aligned} \tag{29}$$

where the curly braces on the summation with l shows that these bit decisions depend on the SM bit decision. The indices written in the left and right within the curly braces are used when $\widehat{x} = 1$ and 0, respectively. $\widehat{c_i}$ and $\widehat{d_i}$ are declared to be "1" if the decision statistics γ_i and δ_i are greater than or equal to 0; otherwise, they are declared to be "0."

V. Experimental Setup and Results

This section describes the experimental setup of layered STC with SM. The transmitter is an 8×8 LED array, as shown in Fig. 6(a), where the LED interval is 20 mm. The



(a)The transmitter of an 8 × 8 LED array (b) The receiver of a High-speed camera

Fig. 6. The receiver and the transmitter used in the experiment.

TABLE I. LED ARRAY SPECIFICATIONS.

LED	TLRE20TP(F), made by TOSHIBA
Luminous Intensity	7000 mcd @ 20 mA
Viewing Angle	7°
Peak Wavelength	644 nm
Dominant Wavelength	630 nm
LED Driver	XC6SLX16 (Spartan-6), made by XILINX
LED Interval	20 mm

other parameters on the transmitter is summarized in Table I. The receiver is a high-speed camera shown in Fig. 6(b), whose specification is listed in Table II. Four pseudo-noise (PN) sequences were generated from FPGA to be used for bit streams $\{x\}$, $\{b\}$, $\{c\}$, and $\{d\}$ of SM, layer-1, -2, and -3, respectively.

Fig. 7 depicts bit error rate (BER) versus the distance between the LED array and the high-speed camera. Note that the BER axis is broken, which shows zero. The upper part from the straight broken sign on the vertical axis is logarithmic, while the lower part is zero. Note also that we break the horizontal axis between 65–150 m, with wavy broken signs, because measured results are dwarfed when they are plotted from long to short distance on a standard linear scale. No errors are observed in the SM bit stream in the range of $D \leq 210$ m, without affecting the error-free transmission distance of the bit stream of layer-1. Therefore, we confirm that SM increase the reception rate in the range of $D \leq 210$ m. We also see that the error-free distances are not reduced, by comparing the distances within which no bit errors can be seen in layer-2 and -3 with and without SM. This means that the introduction of SM does not harm the reception quality of layer-2 and -3.

VI. CONCLUSION

We have proposed SM for further increased information rate of layered-STC used in IS-based VLC systems. The SM layered-STC takes advantages of two-dimension communication to exploit the location-specific property of the LED array as transmitted positions. SM layered STC was demonstrated with the 8×8 LED array each of which operating at 1 kbps and the high speed camera with IS operating at 1000 fps. The results show that the additional bit is received with no errors, without deteriorating the layered STC bit reception.

TABLE II. HIGH-SPEED CAMERA SPECIFICATIONS.

Camera model	IDP-Express R2000-F, made by Photron
Camera head	IDP mono 8-bit Gray scale
Sensor type	CMOS
Frame rate	1000 fps
Shutter speed	1/1000 seconds
Resolution Max	512 × 512 pixel
Lens	HF12.5HA-1B, made by Fujinon
Focus	12.5 mm
f-Number	6

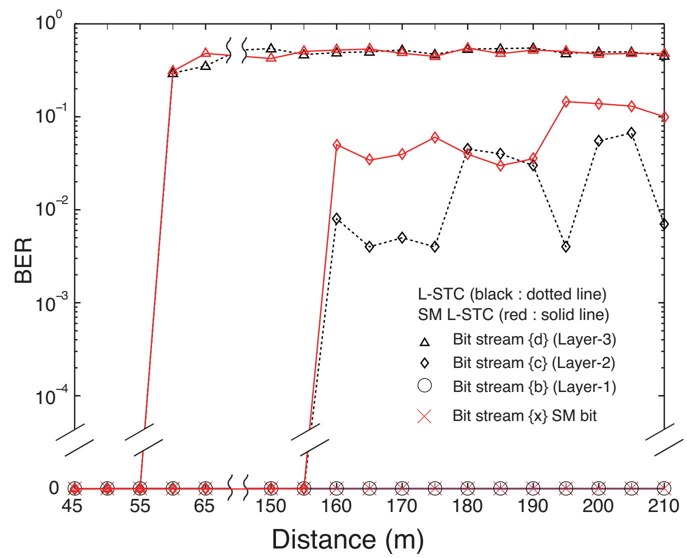


Fig. 7. Measured BER of three-layered STC systems with and without SM are shown as a function of the distance from the receiver to the LED array.

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