Abstract: This paper discusses a visible light communication (VLC) system using a digital signage and an image sensor. We propose a modulation scheme that data information signals are superimposed on a chroma component of the displayed image of the digital signage by taking advantage of the fact that human eyes are difficult to perceive chroma difference than brightness difference. Especially, the proposed scheme utilizes uniform color space to realize hardly perceivable data signal modulation. We show that the proposed scheme has better performance than the conventional scheme with the non-uniform color space.

Keywords: Visible light communication, Digital signage, Image sensor, Uniform color space, Modulation

Classification: Wireless communication technologies

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1 Introduction

Digital signage is a media that displays advertisement images and various useful information using electronic display devices and has already been equipped in many places. Several VLC schemes have been studied in which mobile terminal can receive data information by adding a data transmission function to the digital signage in addition to the displayed image [1-4]. In VLC using a digital signage and an image sensor, data information signals are received by capturing the displayed image with the image sensor of the mobile terminal (e.g. smartphone camera). This system does not require additional communication devices and existing digital signages can be used as communication mediums.

Previous research [3,4] proposed data modulation schemes that superimpose data information signals on the displayed image using chroma components that are difficult for human eyes to perceive. They utilize the fact that difference in the chroma component is more difficult to perceive than that in the luminance component. However, the previous research used a color space ($Y_CbCr$ color space) in which human color perception characteristics are not fully considered. Therefore, a problem arises that the amount of visual difference perceived by human eyes differs for each pixel depending on the modulation color component and the modulation intensity, and it makes the data signals more perceptible to human eyes as color unevenness.

This paper proposes a data signal modulation scheme that utilizes perceptually uniform color space (ULAB color space [5] and $J_2a_2b_2$ color space [6]), which are designed so that color difference perceived as an equal stimulus for human eyes corresponds to an equal distance in the color space. We present trade-off evaluation of the communication quality and visual quality and show that the proposed scheme has better performance than the conventional scheme.

2 System Model

Figure 1 shows the system model. The data signal modulation process at the transmitter and the demodulation process at the receiver are described below.
2.1 Transmitter

The data information is a binary symbol sequence $d(i)$, where “$i$” the frame number, and it is mapped to a two-dimensional $M \times N$ matrix. Note that this data matrix is differentially encoded by taking the difference from the previous data matrix frame. The data signal is represented as an image with $M \times N$ square cells, where the cell corresponds to bit 1 of the data matrix has a pixel value $\alpha$ and the other cell has 0. The visual information of the digital signage is a still image given by the RGB color space and is converted into a desired color space, which is described in Section 3, and the data signal is added in a desired color component of the converted visual information; this means on-off keying modulation with intensity $\alpha$. The data-modulated visual information is re-converted to the original RGB color space and displayed on the digital signage.

2.2 Receiver

To remove the effect of detection of the digital signage in the captured image, we assume that the position of the digital signage is known, and the part of the displayed image is extracted. After converting the captured image $R(i)$ given by the RGB color space to the same color space as the modulation, the absolute difference is calculated between the consecutive frames for removing the visual information components. Then, after averaging pixel values for each cell, a thresholding is performed to determine whether each cell corresponds to bit 1 or 0, and the decoded data matrix $h(i)$ is obtained. Here, the threshold value of each cell is set by the average pixel value of the same cell position in two pilot frames.

3 Data modulation scheme using uniform color space

The proposed modulation scheme attempts to improve the visual quality after the data signal modulation by using uniform color spaces, the ULAB color space and the $J_z a_z b_z$ color space. The conventional scheme uses the $Y C_b C_r$ color space.

3.1 $Y C_b C_r$ color space

The $Y C_b C_r$ color space is a coordinate system that is defined by linear conversion from the RGB color space as Eqs. (1)-(3) and has $Y$ (luminance component), $C_r$ (red component), and $C_b$ (blue component). The conversion of an image from the RGB color space to the $Y C_b C_r$ color space (as well as other color spaces) means...
the conversion of all each pixel of the image. The RGB color space and the YCbCr color space are frequently used, however, the color difference in these color spaces is different from the color difference perceived by human eyes. Therefore, the data signal may be easily perceived by human eyes as color unevenness.

\[ Y = 0.299R + 0.587G + 0.114B \]  
\[ C_r = 0.713(R - Y) + 128 \]  
\[ C_b = 0.564(B - Y) + 128 \]  

### 3.2 ULAB color space

The ULAB color space is a uniform color space that is refined version of LAB color space, which is a typical uniform color space defined by the International Commission on Illumination (CIE), and has better perceptual uniformity. The LAB color space is defined by non-linear transformation of the RGB color space as shown in Eqs. (4)-(8), and the ULAB is obtained by additional non-linear correction to the LAB (see [5]). It is a coordinate system with \( L_u \) (luminance component), \( a_u \) (red component in the positive direction, green component in the negative direction), and \( b_u \) (yellow component in the positive direction, blue component in the negative direction).

\[ \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \]  
\[ L = \begin{cases} 116Y'^{1/3} & (Y' > 0.008856) \\ 903.3Y' & (otherwise) \end{cases} \]  
\[ f(\tau) = \begin{cases} \tau^{1/3} & (\tau > 0.008856) \\ 7.787\tau + 16/116 & (otherwise) \end{cases} \quad \tau \in X', Y', Z' \]  
\[ a = 500(f(X'/0.950456) - f(Y')) \]  
\[ b = 200(f(Y') - f(Z'/1.088754)) \]

where \( R', G', \) and \( B' \) are values after the gamma correction of the RGB values.

### 3.3 Jzazbz color space

The \( Jzazbz \) color space is a coordinate system that is defined by non-linear conversion from the RGB color space as Eqs (9)-(14) and, like ULAB, has \( J_z \) (luminance component), \( a_z \) (red component in the positive direction, green component in the negative direction), and \( b_z \) (yellow component in the positive direction, blue component in the negative direction). It is a newer uniform color space proposed for better perceptual uniformity and lower computational cost than the conventional one.

\[ \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \]  
\[ \begin{bmatrix} X'' \\ Y'' \\ Z'' \end{bmatrix} = \begin{bmatrix} 1.15X' \\ 0.66Y' \\ -0.34X' \end{bmatrix} \]  
\[ \begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.41478972 & 0.579999 & 0.0146480 \\ -0.2015100 & 1.120649 & 0.0531008 \\ -0.0166008 & 0.264800 & 0.6684799 \end{bmatrix} \begin{bmatrix} X'' \\ Y'' \\ Z'' \end{bmatrix} \]
\[
\{L' \ M' \ S'\} = \left( \frac{c_1 + c_2 \left( \frac{L \ M \ S}{10000} \right)^n}{1 + c_3 \left( \frac{L \ M \ S}{10000} \right)^2} \right)^p
\]  
(12)

\[
\begin{bmatrix}
I_x \\
a_x \\
b_x
\end{bmatrix} = \begin{bmatrix}
0.5 & 0.5 & 0 \\
3.524000 & -4.066708 & 0.542708 \\
0.199076 & 1.096799 & -1.295875
\end{bmatrix} \begin{bmatrix}
L' \\
M' \\
S'
\end{bmatrix}
\]  
(13)

\[
J_x = \frac{(1 + d)I_x}{1 + dI_x} - d_0
\]  
(14)

where \( c_1 = 3424/2^{12} \), \( c_2 = 2413/2^7 \), \( c_3 = 2392/2^7 \), \( n = 2610/2^{14} \), \( p = 1.7 \times 2523/2^5 \), \( d = -0.56 \), and \( d_0 = 1.6295499532821566 \times 10^{-11} \).

### 4 Experimental evaluation

The system is required to be realized without interfering the provision of visual information of the digital signage. Therefore, we performed a trade-off evaluation of the communication quality and visual quality. The parameters of our experimental evaluation are shown in Table 1. As visual information, we used three standard test images [7]. Here, both the transmitter and receiver are stationary.

The bit error rate is used as an evaluation index for the communication quality. It is calculated by comparing the transmitted data matrix \( d(i) \) and the decoded data matrix \( h(i) \) for all transmitted data frames and averaging ten times experiments. To quantify the deterioration of visual quality caused by data signals, the color difference CIEDE2000 [8] defined by the CIE is used as an evaluation index for visual quality. The CIEDE2000 quantitatively measures the visible color difference in consideration of human color perception characteristics. The color difference between each pixel of the image before the data signal modulation and that after the data signal modulation is calculated, and then, the root mean square of the color difference values for all pixels and its average value (\( \bar{\Delta E} \)) for all transmitted data frames is calculated. \( \bar{\Delta E} \) is used as an index of the visual quality.

| Table 1 Parameters |
|---------------------|
| **Transmitter**     |
| Product name        | LG Electronics OLED55CXPIJA |
| Transmitting image rate | 15[fps]                     |
| Resolution of transmitting image | 3840×2160[pixel]             |
| Color temperature of white point | 6500[K]                     |
| Brightness of white point | 193[cd/m²]                  |
| Cell construction \((M, N)\) | (16, 9)                     |
| **Receiver**        |
| Product name        | The Imaging Source DFK37BUX178 |
| Capture frame rate  | 30[fps]                      |
| Exposure time       | 30000[μs]                    |
| Resolution of receiving image | 1920×1080[pixel]             |
| Color temperature of white point | 6500[K]                     |
| Distance between the display and the camera | 3.0[m]                     |
| Ambient light (under indoor fluorescent light) | 1200[lux]                   |
4.1 Trade-off evaluation of communication quality and visual quality

Fig. 2 shows the trade-off evaluation based on the measured bit error rate and the calculated color difference for several data signal intensity. It is known that human eyes are difficult to perceive difference of which color difference is less than 1 [8] and this value is widely used for a color accuracy measure of displays. Therefore, we focus on the bit error rate corresponding to the color difference of 1. In Fig. 2(a) and (b), all modulation schemes by the ULAB and Jz a z b z uniform color space achieved better performance than the conventional Cr and Cb modulation by the YCbCr. In Fig. 2(a), the a z and b z modulation by the Jz a z b z showed better performance. In Fig. 2(c), although the conventional Cb modulation showed better performance than au modulation by the ULAB and az modulation by the Jz a z b z, bu modulation by the ULAB and bz modulation by the Jz a z b z achieved much better performance. These results show that the proposed modulation by the uniform color space has better performance than the modulation by the YCbCr. Among them, the bz modulation by the Jz a z b z color space has good overall performance and achieves the bit error rate of less than 0.001 at the color difference of 1, which will be more reliable with appropriate forward error correction such as CRC-aided Polar codes.

5 Conclusion

This paper proposed a data signal modulation scheme that, by using perceptually uniform color space, makes it difficult for human eyes to perceive data information signals superimposed on the digital signage’s image. It was shown that the modulation by the ULAB and Jz a z b z uniform color spaces can achieve better performance than the modulation by the YCbCr color space, which does not fully consider human color perception characteristics. Among them, the bz modulation by the Jz a z b z color space showed good overall performance.

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