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Y(Luminance)-Based Modulation for Visual-MIMO

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ABSTRACT

In color-space-based Visual-MIMO (Multi-Input Multi-Output), which means the communication between the LED array (LEA) and the camera, we have fixed the luminance (Y) to maintain the same color intensity. In this paper, we propose a method to use Y as a carrier of Visual-MIMO corresponding to the carrier of the RF communication. The key of the proposed method is to make Y act as a carrier as in the RF modulation and to recover the information through the adjustment of the receiver dynamic range and the circular Hough transform at the receiving end.

Key Words : Visual-MIMO, Modulation, Luminance, Dynamic range

Ⅰ. Introduction

Recently, research on the color-space-based Visual-MIMO (Multiple Input Multiple Output), which means communication between an LED array (LEA) and a camera, has been conducted[1-9]. Figure 1 shows the transceiving process block diagram of the color-space-based Visual-MIMO system[3].

A simple example of a constellation generation in the CIE1931 color space can be seen in Fig. 1[10]. Each constellation point in a color space represents a corresponding color (data symbol). Here, constellation points in the color space can be arranged using a similar arrangement to that used in RF circular quadrature amplitude modulation (QAM).

Until now, in Visual-MIMO, we have fixed the luminance (Y) to maintain the same color intensity[3-8]. In this paper, we propose a Y(Luminance) as a carrier of Visual-MIMO corresponding to the carrier of the RF communication. Figure 2 shows the CIE1931 three-dimensional color gamut area. In CIE1931 color space, the triangles are formed by triangulating the positions of the three primary colors. All the colors inside this triangle can be expressed using three primary colors, and this inner area is called the gamut area. In addition, it is generally judged that the color device can display when the color is in the color gamut area. However, while the gamut area of the chromatic coordinate system is two-dimensional space, the actual CIE1931 color is three-dimensional. Therefore, by adding

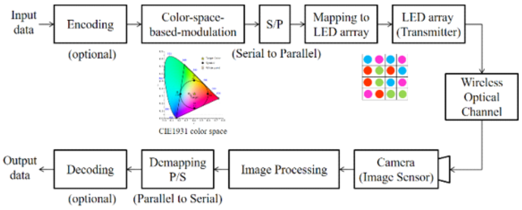

Fig. 1. The transceiving process block diagram of a color-space-based Visual-MIMO system.

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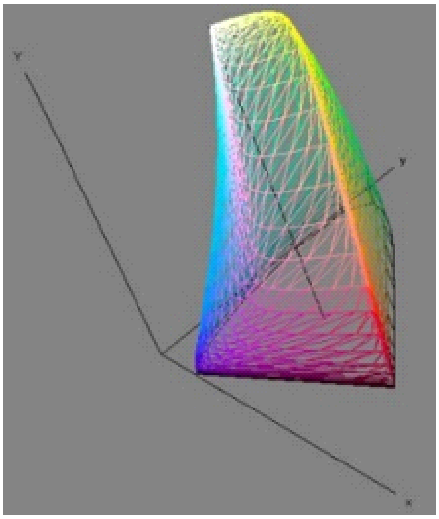


Fig. 2. CIE1931 three-dimensional color gamut area.

Y(Luminance) to the two-dimensional coordinates of x and y, CIE1931 color can be expressed by three-dimensional coordinates of Yxy. This paper proposes a modulation method for Visual-MIMO using Y(Luminance) that performs the same role as a carrier in RF communication.

Ⅱ. Y(Luminance)-based Modulation

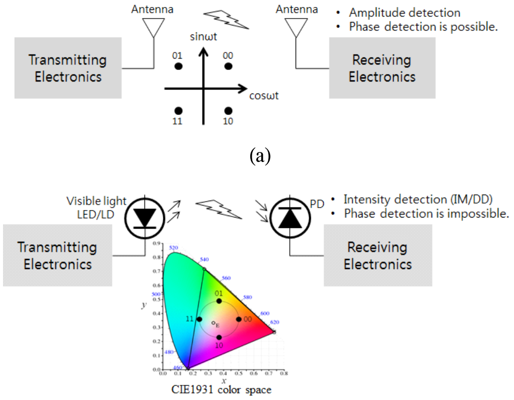
In RF communication, information is carried on a carrier (mainly, $\cos\omega_c t$ or $\sin\omega_c t$, where ω_c is carrier frequency). The greatest contribution of our study is to attempt to serve as a carrier wave as in the RF communication using luminance (Y) in Visual-MIMO. Figure 3 presents a simple conceptual block diagram of a color-space-based VLC system in comparison to a carrier-signal-based RF system[8].

In the RF communication, Eq. (1) shows an example of a transmission (modulation) signal to send information A1 and A2 at the same time by carrier $\cos\omega_1 t$ and $\cos\omega_2 t$, respectively.

$$s(t)= A_1\cos\omega_1 t + A_2\cos\omega_2 t \tag{1}$$

The received signal can be described as in (2).

$$r(t)= A_1\cos\omega_1 t + A_2\cos\omega_2 t + n(t) \tag{2}$$



(a)

(b)

Fig. 3. Color-space-based VLC system vs. carrier signal based RF system. (a) RF communication with carrier-based constellation; (b) VLC with color-space-based constellation.

where n(t) represents a noise.

In the case of coherent detection, the demodulation process (for example, restoring information A_1) at the receiver multiplies $\cos\omega_1 t$ by the received signal $r(t)$ and passes to a low pass filter (LPF).

We propose a Y(Luminance) as a carrier of Visual-MIMO corresponding to the carrier of the RF communication. Figure 4 conceptually illustrates the Y-based modulation in a color space.

The transmission signal corresponding to (1) can be expressed as in (3).

$$s(t)= Y_1(x_1 y_1) + Y_2(x_2 y_2) \tag{3}$$

where Y_1 and Y_2 represent luminance 1 and luminance 2, respectively, $(x_1 y_1)$ and $(x_2 y_2)$ and represent color (symbol) information 1 and color (symbol) information 2 in the color space, respectively. The key of the proposed method is to make Y1 and Y2 act as a carrier as in the RF modulation and to recover the information through the adjustment of the receiver dynamic range and the circular Hough transform at the receiving end.

When information 1 and information 2 are transmitted with Y1 (luminance 1) and Y2 (luminance 2), respectively at the same time, we present the method that demodulates only the information received with the Y1 value or demodulates only the information received with the Y2 value.

Figure 4 shows the dynamic range and luminance band of a camera. Luminance of light has a wide band from low luminance of starlight to high luminance of sunlight. If you specify luminance Y1 and luminance Y2 as shown in Fig. 5 (Y1 <Y2), the camera’s dynamic range cannot satisfy both Y1 and Y2 at the same time. Therefore, if both information is transmitted at the same time to the camera, the information of the two luminance (Y1, Y2) can be separated through the image processing. The dynamic range of the camera can be adjusted by controlling the ISO value, and aperture value.

Figure 6 shows the flowchart of the Y-based modulation process of transmitterside (LEA).

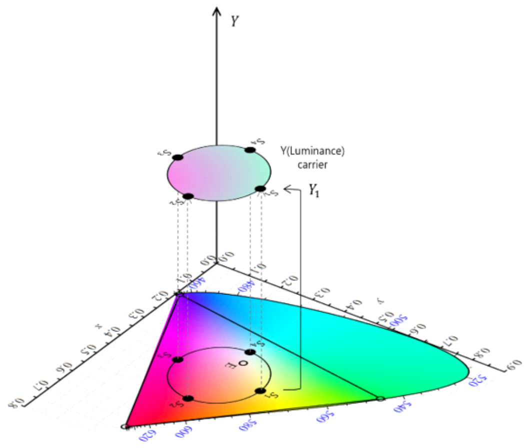


Fig. 4. Conceptual illustration of the Y-based modulation in a color space

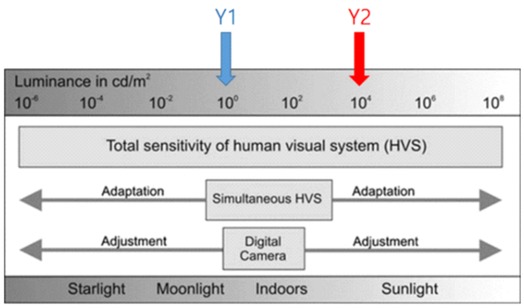


Fig. 5. Example of applying Y1 and Y2 to the camera’s dynamic range and luminance band

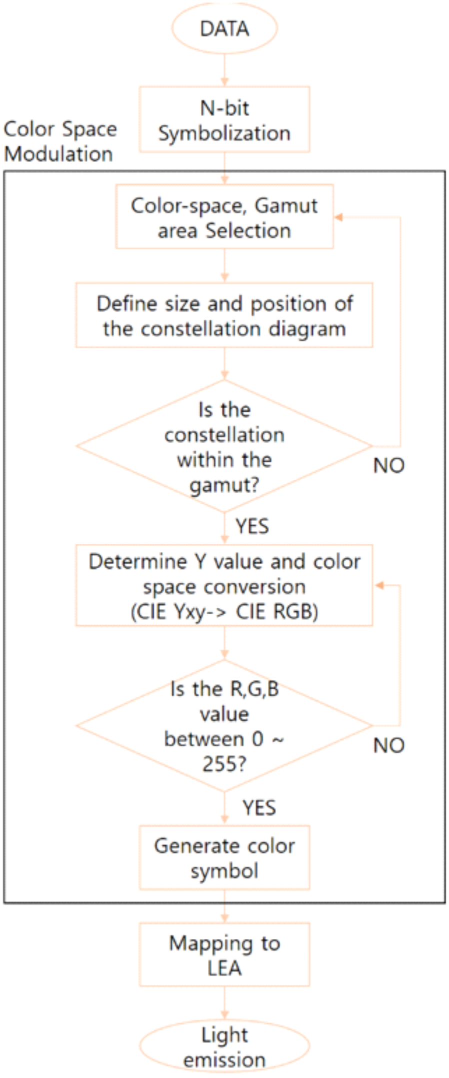


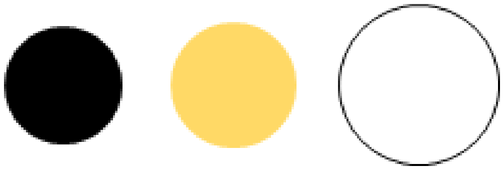
Fig. 6. Flowchart of transmitter including color-space-based modulation

Ⅲ. proposed method

We demonstrate two cases that may occur when color information is received at the luminance Y1 or Y2 as an example.

Case 1. When the dynamic range is adjusted to luminance Y1 (if you want to receive Y1):

Consider an image in which the dynamic range of the camera is set to luminance Y1. If the dynamic range is adjusted to the luminance of Y1, the color information of luminance Y2 will appear as fully saturated in the LED area. In addition, since the



(a) (b) (c)

Fig. 7. Size of LED area in the received image if the dynamic range is adjusted to the Y1 (a) Original LED area size (b) Received LED area size of luminance Y1 (c) Received LED area size of luminance Y2

luminance value of Y2 is large, it appears in the received image as a saturation area larger than the size of the original LED area. So, the luminance Y1 and the luminance Y2 can be distinguished by the size of the LED area. Here, using the circular Hough transform, we can find the circular region accurately by using the brightness value in the image. For example, in Fig. 7, we can see that the luminance Y1 and the luminance Y2 can be distinguished by the size of the LED area.

In addition, in the case of Y2, the area is saturated and it is not possible to represent the correct transmitting color. Therefore, after dividing the luminance Y1 and Y2 first by the size of the LED area, it can also be distinguished by the display color of the LED area if necessary.

Case 2. When the dynamic range is adjusted to luminance Y2 (if you want to receive Y2):

Receiving with adjusting to luminance Y2 is easier than the case 1 above. The LED area of luminance Y1 does not appear well in the image because of the lower luminance than the dynamic range of a camera. It may appear as a dark area in the image. And although it can be photographed as a region showing faint light in the image, it may not be included as a region of interest by adjusting a parameter (sensitivity to light) when performing a circular Hough transform. Therefore, only desired luminance Y2 can be filtered out.

That is, searching for frequencies in RF communication can be compared to adjusting camera dynamic range in visual-MIMO. In addition, the above filtering can be complemented in image processing. Figure 8 shows the flowchart of the

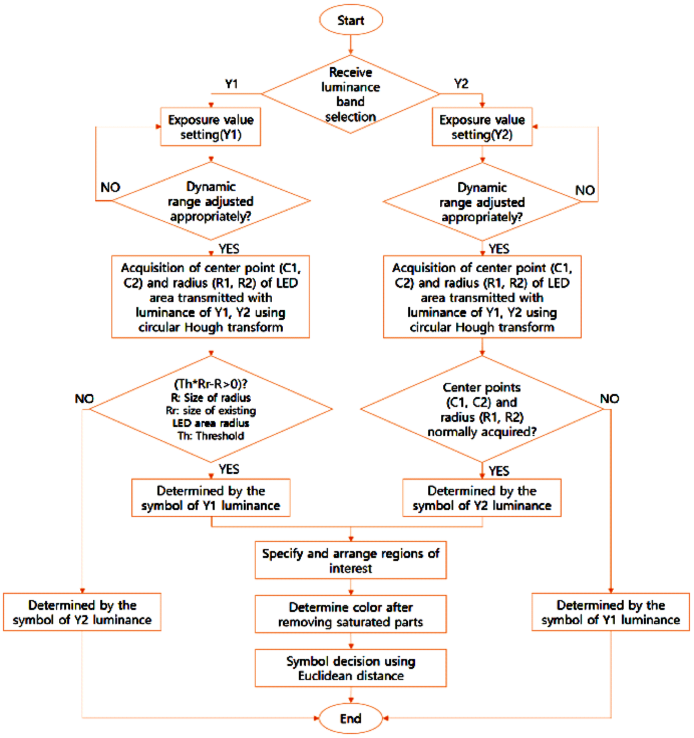


Fig. 8. Flowchart of demodulation process by adjusting the dynamic range

whole process of demodulation corresponding to Y-based modulation of Fig. 5.

Y-based visual MIMO has several advantages compared to the conventional visual MIMO system. The number of symbols can be increased in many folds in this updated system. The conventional visual MIMO can be constructed with a constellation diagram and segmenting the constellation diagram into several points designated by 2^2 symbols. This constellation diagram only depends on the color spectrum, and not the Luminosity of the light emitted. This results in limited use cases, as increasing segmentation in the constellation diagram reduces the inter-symbol distance, increasing errors in the received symbol. In this updated Y-based visual MIMO system, the Y also used to generate symbols. In this case, the 2^n symbols can be generated in several levels of Y.

For example, if the constellation diagram is segmented into $2^2 = 4$ symbols, the conventional visual MIMO could only transmit 4 symbols with one source. But in Y-based visual MIMO, if the Y-space of the source is segmented into 2 levels, the total number of symbols that could be transmitted is 2*4 = 8 symbols with each source.

The different Y-levels can also be used to differentiate among users. And having large intensity variations in Y-levels can enable data security since the receivers have low dynamic range and can only focus on a specific Y-level.

Ⅳ. Conclusion

In this paper, in color-space-based Visual-MIMO, we proposed a method for using the luminance as a carrier similar to that of RF communication. When information 1 and information 2 are transmitted with Y1 (luminance 1) and Y2 (luminance 2), respectively at the same time, we presented the method that demodulates only the information received with the Y1 value or demodulates only the information received with the Y2 value.

By demonstrating two cases that may occur when color information is received at the luminance Y1 or Y2, we showed the successful recovery of the information through the adjustment of the receiver dynamic range and the circular Hough transform at the receiving end.

References

[1] A. Ashok, M. Gruteser, N. B. Mandayam, J. Silva, K. Dana, and M. Varga, “Challenge: Mobile optical networks through visual MIMO,” *MobiCom’10*, pp. 105-112, NY, USA, 2010.

[2] A. Ashok, M. Gruteser, N. B. Mandayam, and K. Dana, “Characterizing multiplexing and diversity in visual MIMO,” *2011 45th Annu. Conf. Info. Sci. and Syst.*, pp. 1-6, Baltimore, MD, 2011, doi:10.1109/CISS.2011.5766257.

[3] J.-E. Kim, J.-W. Kim, Y. Park, and K.-D. Kim, “Color-space-based visual-MIMO for V2X communication,” *Sensors*, vol. 16, no. 4, Apr. 2016, doi:10.3390/s16040591.

[4] J.-E. Kim, J.-W. Kim, and K.-D. Kim, “LEA detection and tracking method for color-independent visual-MIMO,” *Sensors*, vol. 16, no. 7, Jul. 2016, doi:10.3390/s16071027.

[5] P. Das, B.-Y. Kim, Y. Park, and K.-D. Kim, “Color-independent VLC based on a color space without sending target color information,” *Optics Commun.*, vol. 286, pp. 69-73, Jan. 2013, doi:10.1016/j.optcom.2012.07.083.

[6] P. Das, B.-Y. Kim, Y. Park, and K.-D. Kim, “A new color space based constellation diagram and modulation scheme for color independent VLC,” *Advances in Electr. and Comput. Eng.*, vol. 12, no. 4, pp. 11-18, Nov. 2012, doi:10.4316/AECE.2012.04002.

[7] P. Banik, R. Saha, and K.-D. Kim, “Regression analysis for LED color detection of visual-MIMO system,” *Optics Commun.*, vol. 413, pp. 121-130, Apr. 2018, doi: 10.1016/j.optcom.2017.11.086.

[8] T.-H. Kwon, J.-E. Kim, Y.-H. Kim, and K.-D. Kim, “Color-independent visible light communications based on color space: State of

the art and potentials," *Electronics*, vol. 7, no. 9, 190, pp. 1-15, Sep. 2018, doi: 10.3390/electronics7090190.

[9] W. Aldhahi, J.-E. Kim, and K.-D. Kim, "Performance improvement of color-independent visual-mimo system using color quantization based palette," *J. KICS*, vol. 42, no. 12, pp. 2418-2424, Dec. 2017.

[10] P. Das, B.-Y. Kim, Y. Park, and K.-D. Kim, "Color-independent VLC based on a color space without sending target color information," *Opt. Commun.*, vol. 286, pp. 69-73, 2013.

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