A New Color Space Based Constellation Diagram and Modulation Scheme for Color Independent VLC

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***Abstract*—In this paper, generation of a constellation diagram, data to light intensity mapping, and light intensity to data demapping are introduced for the visible light communication (VLC) systems. We propose a new constellation diagram and modulation scheme named generalized color modulation (GCM) based on light color space which can be uniquely applied to modulate the light signals used to deliver data information regardless of target colors of VLC signals. At first, we describe the generation of a constellation in a light color space considering the target color of VLC signals. Then we represent the data symbols as constellation points, resulting in every data symbol having a specific position and corresponding color in the light color space. After that, we determine the position of received signal points in the light color space at the receiver by manipulating the intensities of received signals from the photo detectors. Finally, we convert these received points to data symbols by matching them to the constellation points generated by the receiver. We consider both single color and multiple colors scenarios and investigate two cases to obtain the color information at the receiver. Simulation results show that our proposed scheme can be applied to the development of a more efficient VLC system.**

***Index Terms*—Constellation diagram, GCM, Light color space, Mapping and demapping, Visible light communication.**

I. Introduction

Recently, an unprecedented demand for wireless data communication has been taking place. Usually, the radio frequency (RF) is used for wireless data transmission, but it has its bandwidth (BW) constraints. Visible light communication (VLC) is the most advanced wireless communication technology using visible light sources (e.g., light-emitting diodes (LEDs)) for high speed data transmission without losing their main functionality such as illumination and visual display [1]–[5]. VLC technology has many distinctive features, such as its worldwide availability, a unique bandwidth without conventional electromagnetic interference, security, and license-free operation etc. Furthermore, high accuracy indoor positioning can also be implemented using VLC system [6], [7].

The VLC system has its own signal sources and channels. These signals and channels have unique characteristics which are different from radio signals. Variable on-off keying (VOOK), variable pulse position modulation (VPPM), multiple PPM (MPPM), pulse dual slope modulation (PDSM), OFDM, and subcarrier modulations are some of the well known modulation schemes proposed for VLC [8] – [13]. However, these modulation schemes are directly based on the intensity variation of optical signal. The first light color space based modulation scheme named color-shift keying (CSK) was proposed by the IEEE 802.15.7 task group [14], [15]. However, CSK is not suitable to communicate under varying target color condition and it did not show the superior performance compared to the conventional intensity based wavelength division multiplexing (WDM) [16]. Some constellation designs for CSK based on billiards algorithm have examined in [17]. But the constellation design solution given for color balancing could not be verified analytically. In order to overcome these limitations, we propose a new color space based generalized color modulation (GCM) scheme for target color independent VLC. Using this modulation, any data stream can be delivered regardless of target colors of VLC signals and the data is conveyed by varying (or modulating) the intensities of light signals from multiple light sources (e.g., LEDs). These light signals from multiple LEDs are combined in order to generate an intended data symbol's color signal. The color's average corresponding to entire data symbols results in the target color of VLC signal.

The most distinctive features and advantages of GCM over other modulation schemes is that it is independent on the lightning color as well as the number of LEDs at the transmitter and photo detectors (PDs) at the receiver. In addition, a fixed total light intensity over time can be maintained which ensure flicker-free operation and dimming control, whereas other intensity modulation schemes (OOK and PPM) change the light intensity to deliver the data information.

The remainder of this paper is organized as follows. In section II, the various light color spaces related to the modulation scheme are described. In section III, our proposed scheme is presented. The simulation results are discussed in section IV. Finally, the conclusion is given in section V.

II. Various Light Color Spaces

A light source (LED) or a light receiver (photo diode) can be represented by a point in a light color space. Various color spaces have been devised so far to represent colors of light sources [18]. Two of these spaces which potentially fit to the modulation scheme proposed in this paper are briefly described in the following subsections.

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A. The CIE 1931 Color Space

The tristimulus values of a color are the levels of the three primary colors in a three-component additive color model needed to generate a target color, denoted by X, Y, and Z [18], [19]:

$$X = \int S(\lambda)\bar{x}(\lambda)d\lambda,\ Y = \int S(\lambda)\bar{y}(\lambda)d\lambda,\ Z = \int S(\lambda)\bar{z}(\lambda)d\lambda \qquad (1)$$

where λ is the wavelength (nanometers) of the equivalent monochromatic light $S(\lambda)$ is the spectral power distribution of a light source and three color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are used in CIE 1931 color space. These three tristimulus values can be normalized by:

$$x = \frac{X}{X+Y+Z},\ y = \frac{Y}{X+Y+Z},\ z = \frac{Z}{X+Y+Z} \qquad (2)$$

$$x + y + z = 1 \qquad (3)$$

Using these normalized values, a chromaticity diagram, called CIE 1931 chromaticity diagram, can be drawn [18], [19]. Because of its simple derivation from eye-response functions, the CIE 1931 chromaticity diagram is not perceptually uniform. Since CSK modulation scheme is based on the CIE 1931 color space, it contains all the limitations of CIE 1931 color space.

*B. The 1976 CIE L*u*v* (CIELUV) Color Space*

The CIELUV color space is developed to get more perceptual uniformity [18], [19]. In CIELUV chromaticity diagram is that the distance between any two points is approximately proportional to the perceived color difference. Since it achieves better perceptual uniformity, the CIELUV is more appropriate as a color space for modulation schemes using the constellation diagram in a light color space. In our scheme, we have used the CIELUV color space for both the LEDs at the transmitter and the PDs at the receiver. Therefore, similar perceptual uniformity is applied at both transmitter and receiver.

III. The Proposed Scheme

A. The Basic Concept

Fig. 1 shows the block diagrams of transmitter and receiver of typical VLC system [20]. After converting the serial bit-streams into parallel bits, an m bit input is mapped to intensities of LEDs by a modulator. The light emitting module produces the desired light signal. In the receiver, outputs of the PDs are amplified by the amplifier and then demapped by the demodulator. Finally, the output of the demodulator is converted into a serial data stream that is sent to the information sink.

GCM represents a parallel m bit input (i.e., a data symbol) by a point (which is one of the 2^m constellation points) in a light color space. Then it maps the input point into the intensities of n LEDs at transmitter. The combined intensity after mapping is the sum of intensities assigned to n LEDs. That is, the light intensity for a data symbol point should be the total intensity which is constant and specified by the system requirements. At the transmitter target color is determined by "Target color information" input from outside and by this input any target color of VLC signals can be chosen from the gamut area. For any target color any data stream can be sent by choosing an appropriate constellation diagram that produces the target color. At the receiver, a set of k intensities detected by the k PDs are demapped into an m bit output. "Target color information" can be optional in receiver, because it can generate target color by averaging a fixed amount of received data symbols, as target color point is the average of transmitted data symbols. The mapping at the transmitter and the demapping at the receiver employ the inputs and outputs as shown in Fig. 2.

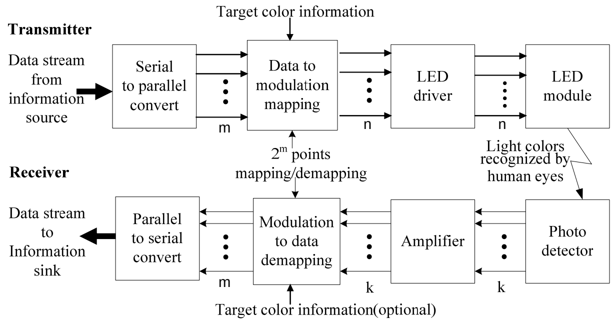

Figure 1. Block diagrams of VLC transmitter and receiver

B. Factors for Mapping and Demapping

The factors considered in the design of mapping and demapping are:

- The Suitable Target Color for Human Eyes

Only a small number of target colors are considered in simple applications. For more complicated applications, any target color can be generated by manipulating a set of n different light or color components. The mapper is informed of this target color by "Target color information" input from outside.

- Number of LEDs and PDs

n LEDs with their light intensities $(C_1, C_2, ..., C_n)$, and k PDs with their measured light intensities $(C_1', C_2', ..., C_k')$, are considered for the mapping and demapping procedure, respectively. Actually, in order to generalize the procedure, n LEDs and k PDs which have different spectral distributions are considered.

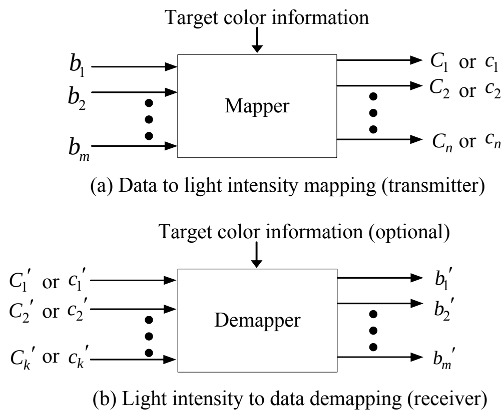

Figure 2. The VLC mapping and demapping

C. Generation of a Constellation

GCM constructs a constellation diagram in a light color space to represent data symbols. There are two assumptions applied in the generation of a constellation:

- Input data symbols equiprobable and random.
- The target color change rates are much lower than data rates.

We consider two parameters to choose points in the light color space for generating the constellation: (i) only colors perceivable by the human eye after modulation are used as the target color in the constellation, and (ii) the minimum distance between any two adjacent constellation points is maximized in constellation diagram. When points are detected by the PDs at the receiver, equidistance between any two adjacent points is the best choice in order to reduce the symbol error rate by minimizing the influence of interference. In addition, in order to maximize the minimum distance between any two points in a constellation, the constellation area needs to be maximized. The maximum area of a constellation is determined by two factors: (i) the point of the target color, which becomes the center of the constellation diagram, and (ii) the gamut area formed by the points of the LEDs. Considering these factors, the maximum area of a constellation is formed by plotting the largest circle inside the gamut area whose center is located at the target color point. A simple example of a constellation generation for a target color is illustrated in Fig. 3.

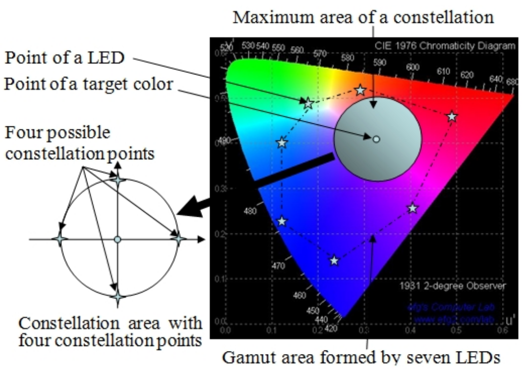

Figure 3. Generation example of a constellation diagram for a target color in CIELUV color space (example uses seven LEDs and two bit data symbols)

D. Data to Light Intensity Mapping

GCM delivers data information by using combinations of intensities of emitted visible light from multiple LEDs. The emitted light beams from the multiple LEDs are mixed together to generate light of a specific color for a specific data symbol. Here we assumed that, a data symbol's color generated by a mixture of various light signals from multiple LEDs can be uniquely represented by a point in the light color space. Therefore, this mixed light has its own color and it represents a point in the light color space constellation diagram. Consequently, equiprobable data symbols (i.e. constellation points at constellation circles periphery) will always produce the target color, which is the center of constellation diagram.

A constellation point in a light color space (x, y), can be mapped into intensities $(C_1, C_2, ..., C_n)$ of n LEDs by [21]:

$$x = \frac{\sum_i C_i x_i}{\sum_i C_i} = \frac{\sum_i \frac{C_i X_i}{X_i + Y_i + Z_i}}{\sum_i C_i} \quad (4)$$

$$y = \frac{\sum_i C_i y_i}{\sum_i C_i} = \frac{\sum_i \frac{C_i Y_i}{X_i + Y_i + Z_i}}{\sum_i C_i} \quad (5)$$

where (x_i, y_i), $i = 1, 2, ..., n$, are the chromaticity coordinates of the i^{th} LED in a light color space and are given by [19]:

$$x_i = \frac{X_i}{X_i + Y_i + Z_i}, \quad y_i = \frac{Y_i}{X_i + Y_i + Z_i} \quad (6)$$

Now, in order to determine C_i values, any set of C_i 's satisfying the relationships given by Eq. (4) and Eq. (5) is acceptable. Thus there can be numerous methods to determine these C_i values. In this paper, we have proposed an algorithm to determine C_i values as below.

Proposed Algorithm for the Determination of C_i 's

1. Determine the farthest LED point from the data symbol point A (x, y). (point H in Fig. 4)
2. Draw a line connecting the farthest point and the data symbol point.
3. Determine the closest LED point from this line on each side of the line. (points F and G in Fig. 4)
4. Draw a line connecting these two points.
5. For the point of intersection of these two lines (point B in Fig. 4), only two intensity components are nonzero values (intensities of only two LEDs at F and G in Fig. 4, C_F and C_G , respectively), such that $C_F : C_G = d_4 : d_3$ and $C_i = 0 \; (i \neq F, G)$ for point B. From this, only the relationship (or ratio) between these two intensities can be obtained. Then the light intensity of point B is: $C_B = C_F + C_G = (1 + d_4 / d_3) C_G$.
6. Now C_H for point A is determined by $C_B : C_H = d_1 : d_2$. Then $C_H = C_B d_2 / d_1 = (1 + d_4 / d_3) C_G d_2 / d_1$.
7. Finally, the total light intensity at point A is: $C_{total} = C_B + C_H = C_F + C_G + C_H$.

From the above algorithm, point A has only three nonzero intensity components C_F, C_G, and C_H.

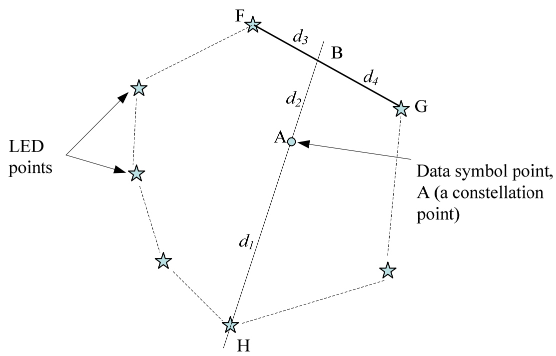

Figure 4. The calculation of LED intensities for a data symbol point

A Numerical Example:

Let $d_1 = 5,\ d_2 = 3,\ d_3 = 1,\ d_4 = 3,\ and\ C_{total} = 32.$ Then $C_F : C_G = 3:1$. The light intensity of point B is: $C_B = C_F + C_G = 4C_G$. After that, C_H is determined by $C_H = 3C_B / 5 = 12C_G / 5$. Finally, the total intensity is given by: $C_{total} = C_F + C_G + C_H = 3C_G + C_G + 12C_G / 5 = 32C_G / 5 = 32.$

The total intensity $C_{total} = \sum_i C_i$, should be equal to system brightness (or illuminance) required. For the above example, since C_{total} is 32, the real intensities of the LEDs at points F, G, and H are 15, 5, and 12 respectively, whereas the other LEDs do not emit light. As a result, at most, only three C_i 's among n values are nonzero values for each information point of a constellation, whereas the other values are all zero, which allows simpler system implementation.

Let the relationship between C_i and c_i be:

$$C_i / c_i = K,\ \ i = 1,\ 2,\ ...,\ n \tag{7}$$

where c_i is the normalized intensity, such that $\sum c_i = 1$ and K is constant for a symbol period. This means that the ratio of C_i to c_i is fixed for a symbol period for all LEDs. Hence, the similar equations as for the non-normalized intensities can be applied and same results can be obtained for the normalized intensities $(c_1,\ c_2,\ ...,\ c_n)$.

As in the above explanation, two steps are necessary for the mapping procedure:

Step 1: An m bit input is matched to a point, (x, y) in a light color space constellation diagram so that, (x, y) is a constellation point for the m bit input.

Step 2: (x, y) is transformed (i.e., mapped) to intensities of n LEDs $(C_1,\ C_2,\ ...,\ C_n)$, or $(c_1,\ c_2,\ ...,\ c_n)$, using the proposed algorithm and $(x_i, y_i),\ i = 1,\ 2,\ ...,\ n.$

E. Light Intensity to Data Demapping

At first, the receiver generates the constellation diagram by using target color information. Then, through the demapping procedure, a set of received intensities of k PDs, $(C_1',\ C_2',\ ...,\ C_k')$ or $(c_1',\ c_2',\ ...,\ c_k')$, are converted to a point (x_r', y_r'), in the applied light color space. After that, the nearest constellation point from (x_r', y_r') is the recovered data symbol point (x', y'). The nearest constellation point is determined by the minimum Euclidian distance from the received points.

$(C_1',\ C_2',\ ...,\ C_k')$ can be normalized to $(c_1',\ c_2',\ ...,\ c_k')$, so that:

$$c_i' = \frac{C_i'}{\sum_{i=1}^{k} C_i'},\quad \sum_{i=1}^{k} c_i' = 1 \tag{8}$$

The measured PD intensities $(C_1',\ C_2',\ ...,\ C_k')$ can be demapped into a corresponding point (x_r', y_r') in a light color space by:

$$x_r' = \frac{\sum_i C_i' x_i'}{\sum_i C_i'} = \frac{\sum_i \frac{C_i' X_i'}{X_i' + Y_i' + Z_i'}}{\sum_i C_i'} \tag{9}$$

$$y_r' = \frac{\sum_i C_i' y_i'}{\sum_i C_i'} = \frac{\sum_i \frac{C_i' Y_i'}{X_i' + Y_i' + Z_i'}}{\sum_i C_i'} \tag{10}$$

where $(x_i', y_i'),\ i = 1,\ 2,\ ...,\ k,$ are the chromaticity coordinates of the i^{th} PD in a light color space and can be obtained by Eq. (6).

In summary, there are two steps applied to match an m bit output for the demapping procedure:

Step 1: $(C_1',\ C_2',\ ...,\ C_k')$ or $(c_1',\ c_2',\ ...,\ c_k')$, are converted to a point in the light color space (x_r', y_r'), by using Eq. (9) and Eq. (10).

Step 2: (x_r', y_r') is matched to a point (x', y'), which is the nearest constellation point from (x_r', y_r') in the generated constellation diagram at receiver. The resultant constellation point (x', y'), is demapped to an m bit data output.

In order to get an m bit data output by demapping, it is assumed that the receiver obtains enough information (e.g., the target color point and the number of data symbol points in a constellation) to generate the constellation diagram.

IV. Simulation Results

Table I lists the applied simulation parameters. The channel noise is assumed to be additive white and Gaussian noise (AWGN). Sunlight, incandescent, fluorescent, and other background lights can interfere with VLC signals. Although these noises can be minimized by optical filtering, still they can add shot noise in a well-designed receiver. Due to its high intensity, this shot noise can be modeled as white Gaussian [22] and independent of VLC signals. Furthermore, when little or no ambient light is present, the dominant noise source is receiver preamplifier noise, which is also signal-independent and Gaussian (though often nonwhite). Because of these reasons we modeled the noise as signal-independent AWGN. At the receiver, three PDs with different spectral distribution followed by optical concentrators and three RGB filters are used for light detection. Different responsivity problem of PDs for different colors can be compensated by LED driver circuit.

TABLE I. THE SIMULATION PARAMETERS

Parameter	Value
Number of LEDs and PDs	3
Number of constellation points (2 bit data symbol is assumed)	4
Total intensity	3 A. U.
Total number of data bits transmitted	120000
Three arbitrary target color point coordinates in the CIELUV color space	(0.22,0.3);(0.29,0.36); (0.5,0.44)
3 LED positions (or points) at the transmitter and the PDs at the receiver in the CIELUV color space	R: (0.6,0.5) G: (0.02,0.56) B: (0.25,0.02)

Moreover, in VLC, the information carrier is a light wave whose frequency is about 10^{14} Hz and typical detector areas are in the order of thousands of wavelengths, leading to spatial diversity that prevents multipath fading. Therefore, multipath fading can be neglected [23], [24]. In addition, a VLC system model described in [25] concluded that the signal-to-noise ratio (SNRs) ≥ *40dB* and BWs ≥ *90MHz* are available at all positions in a typical room. Therefore, the VLC channel has much greater modulation BW and typical illumination levels results in very high SNR at the receiver. Since the BW is not critical factor in VLC, we did not consider in our simulation any BW limitation seriously. Finally, for proper lighting and reliable high-speed data transmission, a certain brightness of the illuminated surface is required and sufficient optical power is needed. These conditions need to be considered in the VLC system design.

Since the target color is a very important parameter for VLC, our scheme focuses mainly on the target color information. We assumed that the transmitter sends the target color information. Generally, two types of color illumination scenario can be assumed for real application:

- The first type is a single color with no change of color, such as the colors from lighting illumination, e.g., office and house lighting.
- The second type is multiple colors with slow or fast color changes, such as the colors from simple sign boards, sign boards with moving images, and TVs.

Fig. 5 shows the simulation scenarios. For the single color scenario, only one target color will remain unchanged for the whole data transmission period. Various single colors from the gamut area can be seen in real situation. In our simulation, we have used three target colors, whose coordinates inside the gamut area are given in Table I. In addition, for the multiple colors scenario, we assumed two different color changing rates, "slow and periodic" and "fast and random". For the slow and periodic color change rate, one target color may remain unchanged for long time (e.g., traffic light remains unchanged for a reasonable amount of time), i.e., target colors are changing very slowly and periodically. Therefore, transmitter can transmit many data bits within one target color duration. We assumed 40000 data bits (i.e., 20000 data symbols) are transmitted within one target color duration. On the other hand, for the fast and random color change rate, one target color changes to another randomly and target colors change very frequently compared to the slow color change rate. As a result, the transmitter may be able to send small number of data symbols within one target color duration.

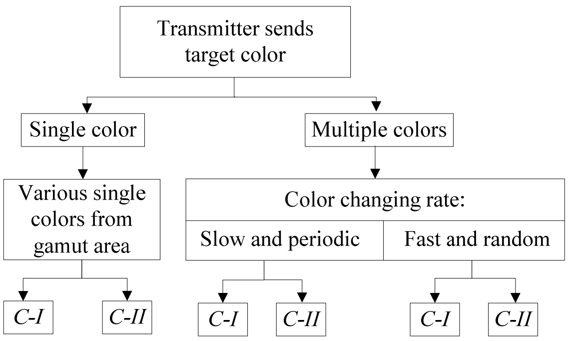

Figure 5. The simulation scenario

Target color information is needed to form a constellation at the receiver because it is assumed that the target color point is the center of the constellation circle. We considered two cases to obtain the transmitted target color information at the receiver.

Case I (C-I): The target color information is accurately received from the transmitter. One possibility is that the target color information is delivered to the receiver through a separate channel such as a control channel. The other possibility is that there can be an agreement (protocol) between the transmitter and the receiver regarding the target color such that the receiver knows which target color will be transmitted. Therefore, for both assumptions, the receiver can generate and maintain the same constellation diagram as the transmitter.

Case II (C-II): The target color information is received from transmitter, but distorted by AWGN as other types of data signals are. The target color information is delivered using LED intensities (RGB) like other data bits. We have added header information so that the target color intensities can be differentiated from the data symbol's intensities. As the target color is affected by AWGN, receiver may not be able to generate the exact target color which is transmitted by the transmitter. As a result, the constellation diagram generated by the receiver may not be exactly similar to the transmitter constellation diagram.

Fig. 6 shows the generation of constellation for the three target colors. For each target color, constellation circle is generated with possible maximum radius within the gamut area. Here, three target colors are chosen in such a way so that the constellation radius of target color 1 and 3 is half and one fourth of the radius of target color 2 respectively. Target color is the center of constellation circle and four constellation points arranged like simple RF communication constellation. Any diametrically opposing points maintain target color as do any points whose "centre of mass" is at the target color coordinate. Therefore, there can be many arranging positions of constellation points around the constellation circle and proper constellation point's average will results in the target color at center. Here, there are 4 constellation points positioned at 0º, 90º, 180º, 270º on constellation circle's periphery, as an example. This diametrically opposing four constellation point's average results in the target color at center.

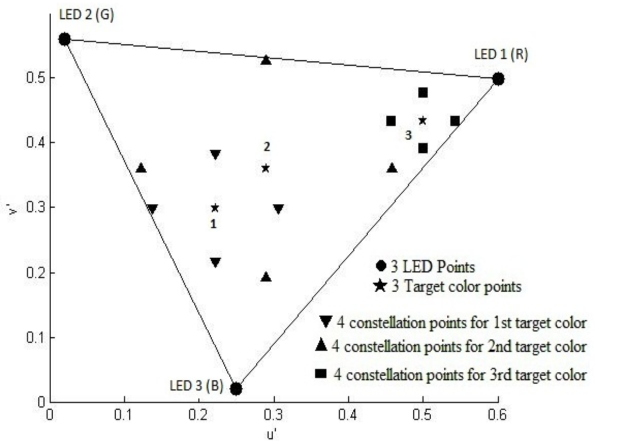

Figure 6. Generation of 4 points constellations for the three target colors in the CIELUV light color space

Furthermore, we maximized the minimum distance between any two points in the constellation by using equidistance between any two adjacent points. We also used Gray coding to represent equiprobable data symbols to constellation points. Needless to say, equiprobable data symbols will always produce the target color (which is the center of constellation). Practically, each target color has its own constellation diagram and constellation diagram changes depending on the target color. Therefore, only one target color and corresponding four constellation points should be presented in the light color space for one target color period. To save space, we show the three constellation diagrams for three target color together in one figure.

In our simulation, data symbols are arranged as a QPSK constellation. Therefore, the exact bit-error probability, P_b for M-PSK signaling can be given by [22]:

$$P_b \approx \frac{2}{b} Q\left(\sqrt{\frac{2bE_b}{N_0}}\sin\frac{\pi}{M}\right) \qquad (11)$$

where $b = \log_2|M|$, is the number of bits per symbol, $E_b = E_s / b$, is the amount of received bit energy, and N_0 is noise power spectral density. Using simulation parameters assumed in Table I, the minimum achievable bit error rate (BER) is 8.33×10^{-6}. Therefore, at $P_b = 8.33\times10^{-6}$ and $b = 2$, the required SNR (E_b / N_0) approximated by Eq. (11) is 9.6 *dB*.

Fig. 7 shows the effect of radius of constellation circle on the BER performance. Here for one target color, as the radius of constellation circle is increasing, BER is decreasing rapidly. The reason is that a larger radius results in a larger constellation area and therefore the minimum distance between adjacent symbols becomes large. As a result, the interference effect between adjacent symbols is minimized and demapping becomes more flexible and accurate in receiver side.

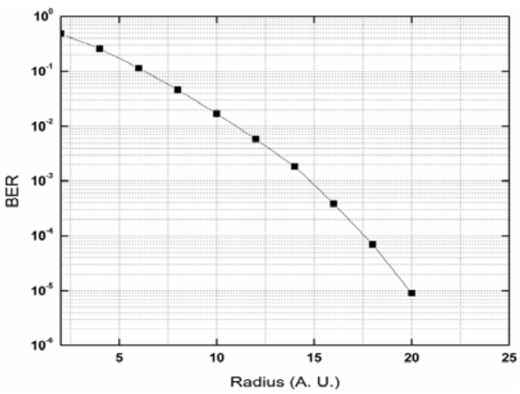

Figure 7. BER vs. Radius of constellation area

Fig. 8 shows the BER performance of three single target colors for *C-I*. Here, different target colors have different BER performances, because three target colors have different constellation radius thus different minimum intersymbol distance. The BER drops gradually with respect to the SNR for the three target colors. We can see that the target color 2 gives best BER performance because it has the largest constellation radius (area). For target color 2, when the SNR is greater than *10 dB*, BER becomes zero. That is, above this value of SNR, all of the transmitted symbols are demapped correctly at the receiver side. Therefore, for target color 2, BER is almost similar to the BER given by Eq. (11).

In addition, as observed from the Fig. 8, at any BER, the required SNR for the target color 1 and 3 is more than that for target color 2; but the SNR difference between three target colors is not similar and fixed as it is for RF communication. The reason is that, for any target color BER depends not only on radius of the constellation circle, but also on its position inside gamut area and LED (RGB) intensities.

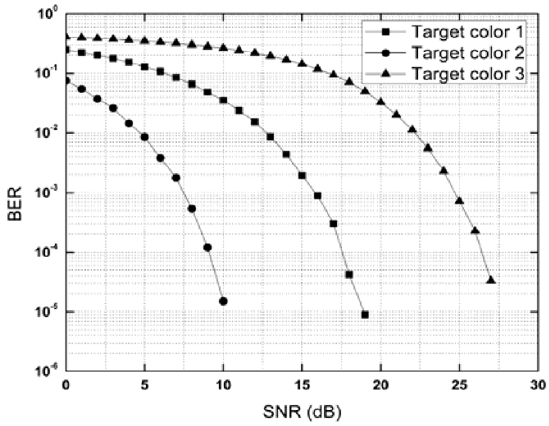

Figure 8. BER vs. SNR for three single target colors (*C-I*)

Fig. 9 shows the BER performance of the single color scenario for *C-II*. The BER performance is not as good as found for *C-I* and it shows an irregular decreasing pattern with respect to SNR. Since the transmitted target color's intensity is affected by the AWGN, the received target color is not as accurate as found in *C-I*. Further, the AWGN is a random noise, so the received target color becomes more arbitrary. Since the BER is strongly dependent on the target color, the BER performance becomes random. Therefore, we can say that the target color variation caused by noise has a great impact on the BER performance of the system.

Fig. 10 shows the BER performance of the slow and periodic color change for *C-I* and *C-II*. Again, for the same reasons stated above, the BER performance is better, smooth for *C-I* and random for *C-II*. We considered those three target colors which were used for single color scenario and changed one color to another color periodically. Therefore, the resultant BER is almost the average BER of three single target colors.

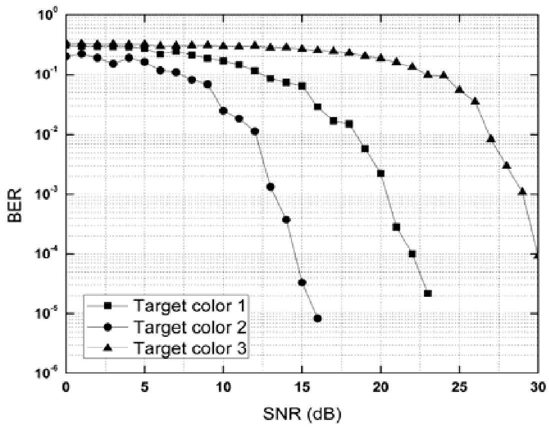

Figure 9. BER vs. SNR for three single target colors (*C-II*)

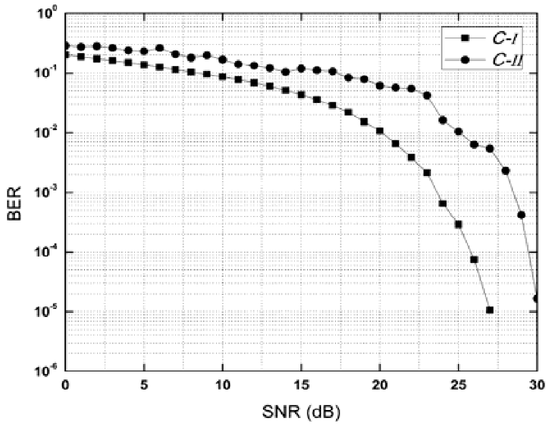

Figure 10. BER vs. SNR for slow and periodic color change

Fig. 11 shows the BER performance of fast and random color change for different fixed target color duration. This scenario is a special case of fast and random color scenario. Here receiver assumed that the received target color will change after a fixed symbol's duration but the transmitted target color can change anytime. This means that the receiver assumes fixed target color duration and the transmitter assumes variable target color duration. In this scenario, it is very easy to handle the delay and queue requirements in receiver and receiver design is also very easy. However, if the receiver assumes fixed target color duration then the BER performance becomes very bad. Because, practically target colors can be changed anytime at the transmitter side as the target colors are changing very fast and randomly. As a result, after the sudden change of a target color almost all the received data symbols within fixed target color duration will be demapped incorrectly. Different fixed target color durations at the receiver result in different BER. If the target color duration is short, then it can easily adapt to various color change rates. Therefore, short target color duration gives better BER performance than long target color duration. Since the BER performance of this scenario is not satisfactory, this scenario may not be applicable in real application.

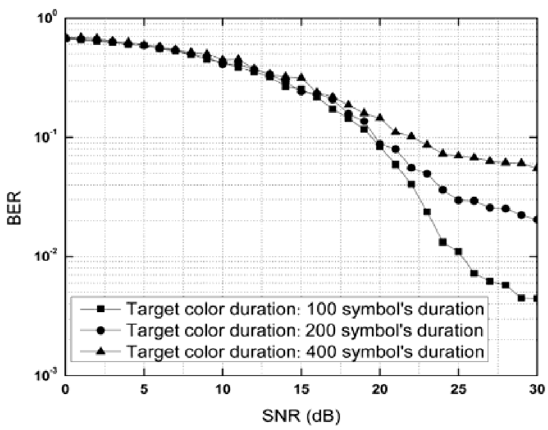

Figure 11. BER vs. SNR for fast and random color change for different fixed target color durations (*C-II*)

In order to overcome the limitation of fixed target color duration, we assumed variable target color duration at both transmitter and receiver for the fast and random color change scenario. Practically, target color of VLC signals may change anytime during transmission and reception of data; therefore, this assumption is more realistic for VLC systems. Here, as soon as a target color will have changed from one to another at the transmitter, receiver will adapt to that changed target color. Consequently, BER performance becomes very good as shown in Fig. 12. The BER performance is almost similar to the BER of the slow and periodic color change in Fig. 10. Delay and queue requirements of receiver are more sophisticated in this scenario.

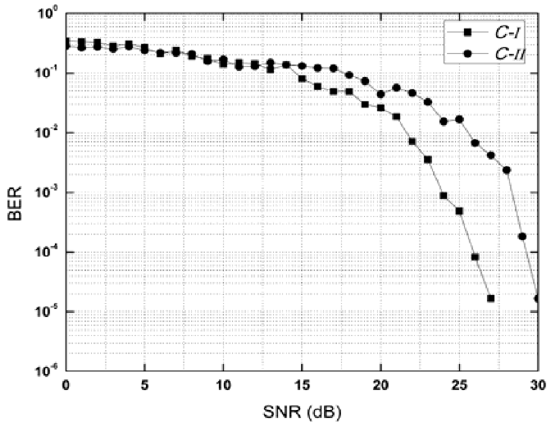

Figure 12. BER vs. SNR for fast and random color change for variable target color duration

V. Conclusion

This paper developed a modulation scheme (GCM) along with a constellation diagram in order to transmit and receive the data symbols through multiple LEDs and PDs, respectively. The proposed scheme includes a mapping procedure used to map the data by the LED intensities and a demapping procedure to demap received PD intensities to data. Moreover, the target color input makes the proposed modulation scheme color independent. Basically, the BER is decreasing almost sharply as the radius of constellation circle corresponding to the target color is increasing. The simulation results under the scenario of Fig. 5 showed that, the BER performances for all of the cases was satisfactory as shown in Fig. 7–12. Although in order to get the exact BER 8.33×10^{-6} , the required SNR is higher than the approximate SNR given by Eq. (11), but still the achieved SNR is much lower than the *40 dB* (which is minimum SNR for VLC in a typical room) for all cases. Further, for simple hardware implementation, our proposed mapping algorithm considers only three LEDs along with the farthest points and closest points to determine the LED intensities. However, more than three LEDs with any point instead of the farthest or closest can be chosen and the scheme can be applied after simple modifications.

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