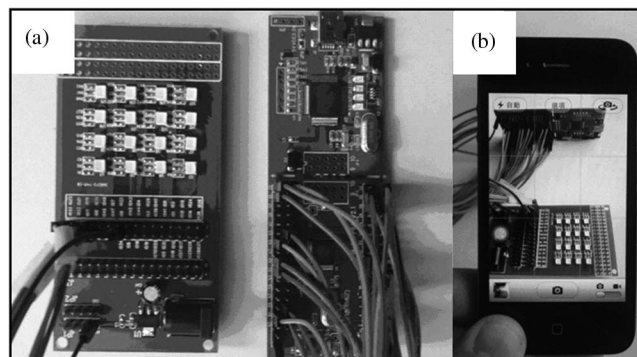# Color-Shift Keying and Code-Division Multiple-Access Transmission for RGB-LED Visible Light Communications Using Mobile Phone Camera

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Color-Shift Keying and Code-Division Multiple-Access Transmission for RGB-LED Visible Light Communications Using Mobile Phone Camera

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Abstract: Light-emitting diodes (LEDs) have been deployed for various applications in our daily lives. Similarly, image sensors or cameras integrated into mobile phones have become common. Hence, visible light communication (VLC) using LED and mobile phone cameras is attractive and provides low-cost wireless communication. In this paper, we propose and demonstrate a VLC system using color-shift-keying (CSK) modulation and code-division multiple-access (CDMA) technology simultaneously for the first time; a mobile phone camera is used as the receiver (Rx). CSK is used to enhance the VLC system capacity and to mitigate the single color light interference, whereas CDMA allows multiple users to access the network. The system design and operation mechanism of the proposed CSK–CDMA VLC system are discussed. A proof-of-concept demonstration is performed, and error-free transmission is achieved for multiple-access users. A 3-dB transmission gain is also obtained in each user when compared with the traditional on–off keying (OOK) modulation.

Index Terms: Free-space communication, optical communications, light-emitting diode (LED).

1. Introduction

Light emitting diodes (LEDs) have been deployed for various applications, such as vehicle headlights/taillights, traffic lights, signboards and general lightings. Optical wireless communication (OWC) using LED visible light [also called visible light communication (VLC)] has attracted attenuation recently in academia and industry [1]–[6]. Similarly, image sensors or cameras integrated into mobile-phones have become common. New generation mobile-phones usually equipped with embedded Complementary Metal-Oxide-Semiconductor (CMOS) cameras allowing users to capture photos and videos conveniently. Hence, VLC using LED and mobile-phone cameras is attractive and provides a low-cost wireless communication. VLC systems using CMOS camera have been reported in [7] and [8], respectively. The focus of [7] is mainly increasing the VLC transmission rate by using the rolling shutter effect of the CMOS sensor. In [8], a
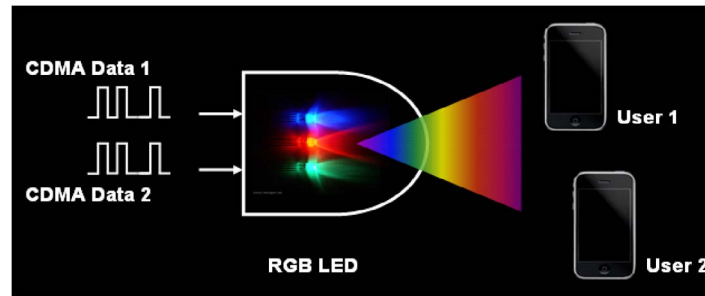
Fig. 1. Proposed CSK-CDMA VLC system.

TABLE 1

Bit map of color magnitude subsets

Bit map		Color Magnitude Subset		
		Red (R)	Green (G)	Blue (B)
$Color_1$	00	60	40	0
$Color_2$	01	40	0	40
$Color_3$	10	20	20	60
$Color_4$	11	0	60	20

tailor-made image sensor with specific pixels for imaging and photodiode (PD) for high-speed VLC is fabricated. However, this sensor is not commercially available and may increase the system costs and complexity.

Color-shift keying (CSK) [9] is one of the promising modulation formats specifically for red-green-blue (RGB) light-emitting-diode (LED) VLC system. CSK can improve the VLC throughput by increasing the bit per symbol rate, and avoiding the single color interference. In addition, code division multiple access (CDMA) is a promising technology to make multiple users to access to the network simultaneously [10]. In this work, we first propose and demonstrate a VLC system using CSK modulation and CDMA technology simultaneously; mobile-phone camera is used as the receiver (Rx). CSK is used to enhance the VLC system capacity and to mitigate the single color light interference; while CDMA allows multiple users to access to the network. The system design and operation mechanism of the proposed CSK-CDMA VLC system are discussed. Bit-error rate (BER) measurement is performed, and the experiment result shows the proposed system can be operated in low error (BER $< 10^{-6}$) transmission with a 3-dB transmission gain in each multiple-access user when comparing with the traditional on–off keying (OOK) modulation.

2. System Design and Operation Mechanism

Fig. 1 shows the proposed scenario of VLC using CSK and CDMA. The CDMA $Data_1$ combines with the CDMA $Data_2$ to produce the CSK signal. The CSK signal is transmitted by an array of RGB-LED. $User_1$ and $user_2$ receive the CSK signal by mobile-phone $camera_1$ and mobile-phone $camera_2$ respectively. Each user then decodes the individual data by its own CDMA spreading code. As shown on Table 1, the CSK scheme used in this proposed system is consisted by 4 color magnitude subsets. Since the number of bit used for each color [red (R), green (G), and blue (B)] is 8 bits (color depth), the magnitude levels represented by of the R, G, and B color are within the range of 0-255. As RGB is used, the total color depth is 24 bits, and it represents 16 777 216 colors or magnitude levels. For example, the first row of Table 1 shows the $Color_1$
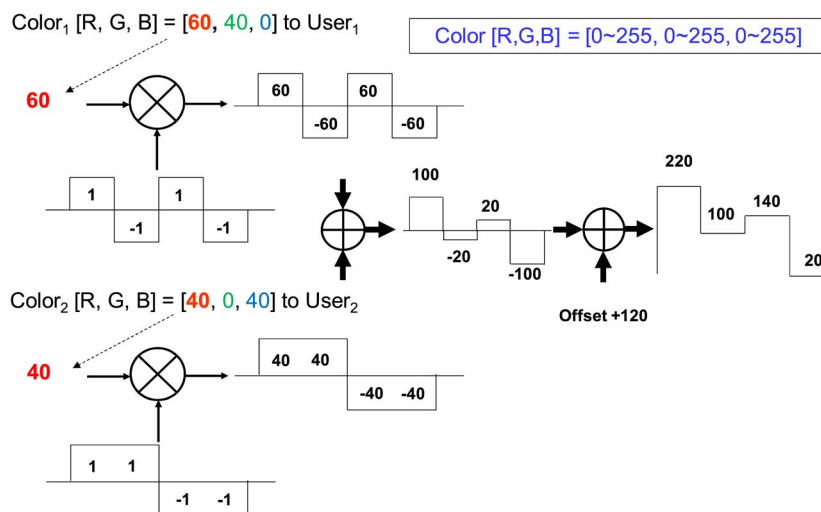
Color$_1$ [R, G, B] = [60, 40, 0] to User$_1$

Color [R,G,B] = [0~255, 0~255, 0~255]

Fig. 2. Tx of the proposed CSK-CDMA VLC system using red as an example.

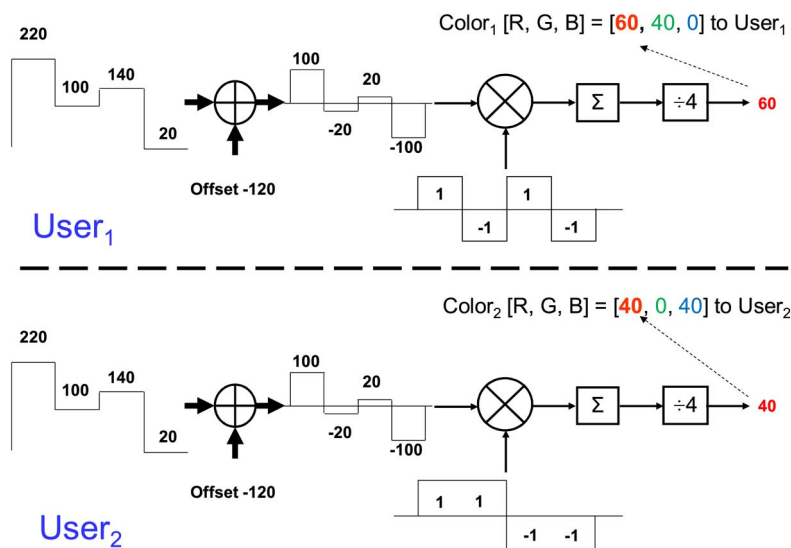Color$_2$ [R, G, B] = [40, 0, 40] to User$_2$

Fig. 3. Rx of the proposed CSK-CDMA VLC system using red as an example.

(red, green, blue) with magnitudes of (60, 40, 0). When transmitter (Tx) emits Color$_1$ magnitude subset (R: 60, G: 40, B: 0), data logic bits of 00 are transmitted.

Figs. 2 and 3 show the architectures of the proposed Tx and Rx in our CSK-CDMA VLC system. An example is provided to illustrate the mechanism of the proposed scheme. Tx sends Color$_1$ to User$_1$ and Color$_2$ to User$_2$ simultaneously. In other words, Tx sends bits "00" to User$_1$ and bits "01" to User$_2$. Since the RGB colors are processed independently in the Rx, we explain the process of red color as an example. Green and blue colors are processed in the similar manner. In Fig. 2, red magnitude of Color$_1$ is 60. The value 60 is spread by Spreading-code$_1$ [+1, −1, +1, −1] and the Spread-signal$_1$ becomes [60, −60, 60, −60]. Meanwhile, red magnitude of Color$_2$ is 40 and spread by Spreading-code$_2$ [+1, +1, −1, −1]. Hence the Spread-signal$_2$ is [40, 40, −40, −40]. Spreading-code$_1$ and Spreading-code$_2$ are orthogonal to one another. The property shows that the inner product of Spreading-code$_1$ and Spreading-code$_2$ is zero. Color$_1$ and Color$_2$ are transmitted in orthogonal code basis and can be recovered by the de-spread process
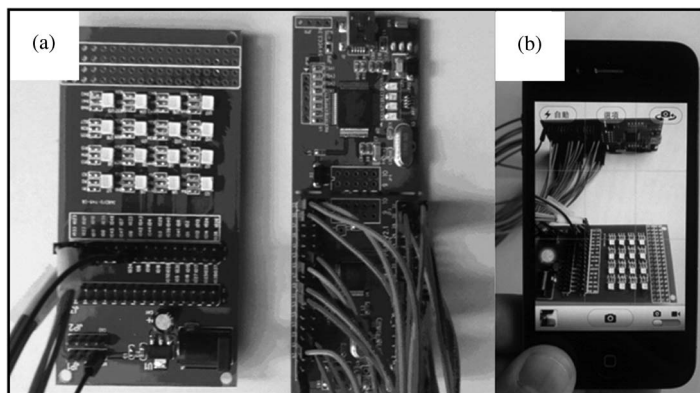
Fig. 4. (a) Tx and (b) Rx (mobile-phone camera).

in Rx. In the Tx as shown in Fig. 2, the magnitude of Spread-signal$_1$ and Spread-signal$_2$ are added to produce the total red magnitude signal. The signal level is adjusted to the level 0–255 by adding the offset $+120$. That is for fitting the 8-bit data depth (0–255). Finally, the output of Tx is [220, 100, 140, 20].

In the Rx, the red color filter separates the red color from received RGB signal. As mentioned, the Tx signal is [220, 100, 140, 20], which contains the red magnitude of Color$_1$ to User$_1$ and the red magnitude of Color$_2$ to User$_2$. In Fig. 3, the received signal is de-spread by Spreading-code$_1$ in User$_1$ mobile-phone and the received signal is de-spread by Spreading-code$_2$ in User$_2$ mobile-phone simultaneously. For User$_1$, the received signal subtracts offset of 120 before it is de-spread by Spreading-code$_1$. Then, the inner product of [100, -20, 20, -100] and [$+1$, -1, $+1$, -1] is 240, which is divided by 4 (the length of the spreading code). Hence User$_1$ obtains the value 60 of the red magnitude of Color$_1$. User2 receives red magnitude of Color$_2$ in the similar process. User$_1$ can use the same manner to retrieve the green magnitude of Color$_1$ and the blue magnitude of Color$_1$. Once Rx can recover Color$_1$ from RGB color domains, Rx can use Table 1 to de-map the two data bits emitted from the Tx.

3. Experiment of the CSK-CDMA VLC System, Results, and Discussion

A proof-of-concept experiment of the CSK-CDMA VLC system is performed. The RGB LED array size is 4×4 as shown in Fig. 4(a), and each LED package consists of RGB chips. Fig. 4(a) also shows the self-designed controller board for the CSK-CDMA Tx. It consists of power control function to select proper power level of the LED array. The Rx is based on an iPhone 4S mobile-phone camera as shown in Fig. 4(b). The frame rate of the received image is 30 frames per second and the measurement distance is 50 cm.

Fig. 5 shows the experiment result of the CSK-CDMA VLC system and the comparison with OOK modulation. The system serves two users simultaneously in this proof-of-concept demonstration; however more users can be supported by using different orthogonal spreading-codes. As shown in the BER measurement in Fig. 5, low error transmission (BER $< 10^{-6}$) for both users can be achieved. Each user has a 3-dB gain comparing with the OOK modulation. Since we use spreading-code with spreading factor $= 4$, a coding gain of 6-dB is excepted theoretically. The reduced coding gain may due to the quantization error and sensor noise from mobile-phone camera; hence, the property of orthogonality in the received signals decreases.

Since the mobile-phone CMOS camera already equips with three color (RGB) sub-pixel sensors to capture each image pixel, no extra color filter is needed to separate the red, blue and green channels. The frame rate of mobile phone is 30 frames per second, the spreading factor is 4 and there are two bits per symbol. Hence the data rate is 15 bits per second. The Tx equips with 16 LEDs, therefore the total data rate is 240 bits per second. In order to measure BER of
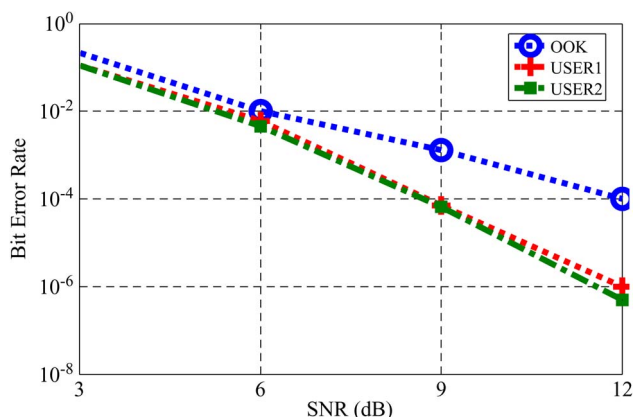
Fig. 5. Experiment BER results of the CSK-CDMA VLC system vs. OOK modulation.

10^{-6}, about 4200 s (1.2 hr) is needed. The data rate of the OOK signal is also 15 bits per second for comparison. Lower BER can be estimated by Q function. In order to save the signal processing time, we use our self-developed MATLAB program in computer to process the received images, decode the data and generate the BER curves.

Commercial mobile-phone camera usually captures video at about 30 frames per second, and this is the frame rate of the iPhone 4S used in the experiment. If iPhone 6 plus is used as the Rx, 240 frame per second can be used in the slow motion video capture function. The data rate can be 8 times larger. The limitation of mobile-phone camera recording frame rate is the key issue of the data rate in the proposed system. We can use rolling-shutter effect of CMOS sensor to further increase the data rate [7]. When the number of user terminals is increased, the most important system complexity is the color depth of the proposed system. Since the signal from each CSK-CDMA data link are added together. 24 bits color depth is shared by all users. As the number of user terminals is increased, 24 bits color depth may not enough to serve all the users in good transmission quality. In our experiment, each designed color was separated by at least 20 color depths. (i.e., 0, 20, 40, and 60). In our experiment, we have enough color depth separation to tolerate the quantization errors. For example, we can set color depth threshold = 10 to discriminate whether color depth is 0 or 20. The system performance will be degraded when the distance between Tx and Rx is increased. The performance is significantly affected if the transmission distance is > 1 m. This is because the ambient light from the environment will become as strong as the signal light, and the ambient light will interfere the received color. Since the experiment is performed in typical in-home lighting environment to emulate the practical working conditions, the received color cannot be identified easily due to the wideband ambient light when the transmission distance is > 1 m. The transmission distance can be increased by increasing the output power of the LED or dimming the environment.

4. Conclusion

A novel CSK-CDMA VLC system was proposed and a proof-of-concept experiment using RGB-LED and mobile-phone camera was demonstrated. CSK scheme enhanced the system throughput and avoid the single color interference; while CDMA allowed multiple users to access to the network. The system design and operation mechanism of the proposed CSK-CDMA VLC system were discussed. A proof-of-concept demonstration having two users to receive data in CSK simultaneously was preformed, and the proposed scheme can support more users simultaneously by using more orthogonal spreading-codes. BER measurement was performed, and the experiment result showed the proposed system can be operated in low error $(BER < 10^{-6})$ transmission with a 3-dB transmission gain compared with the traditional OOK modulation.

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