

A New CSK Communication System With Display and Cameras

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Abstract- Color Shift Keying (CSK) is one of the modulation schemes for Visible Light Communication (VLC) that was approved as the IEEE802.15.7-VLC standard in 2011. CSK has some advantages over conventional modulation schemes for VLC. In this paper, the principle and the performance of the basic CSK system are shown and a new CSK communication system from display to cameras on mobile devices is proposed. In experiments with non-real time test system, the proposed system achieved 240 kbps data rate using 64×64 SDM-16CSK. A real time prototype system that can send some contents from display to smart phone, achieved 6kbps data rate with 16×16SDM-4 CSK.

I. Introduction

Visible Light Communication (VLC) is one of the most attractive technologies for the next indoor or outdoor high speed and high security communication network [1]. In 2008, Color Shift Keying (CSK) was proposed to the IEEE standard association as a new modulation scheme for VLC [2-3]. In 2011, CSK was approved as one of the physical layers in the IEEE802.15.7-VLC standard [4].

CSK is a new modulation scheme that uses visible colors for data transmission. It uses VLC systems consisting of multi-color light sources and photo detectors. In such multi-color systems, a Wave-length Division Multiplexing (WDM) scheme with an On-Off Keying (OOK) modulation is generally used for VLC [5]. Each light source in a WDM system independently transmits information. On the other hand, CSK systems transmit information using mixed color generated by the multi-color light sources. Although WDM is a good solution for increasing the data rate using multi-color light sources, CSK has the following advantages over the conventional WDM-OOK system.

(1) Good Connectivity

Future VLC systems will consist of various light sources, illuminations, LED displays, LCDs, etc. Therefore, we have to consider the connectivity among these various devices, which have different color characteristics. In WDM, the connectivity is guaranteed by the wavelength matching between the light source on the transmitter and the photo detector on the receiver. Thus, the connectivity directly depends on the characteristics of the light devices. However, in CSK, information data is transformed into a mixed color that is generated by multi-color light sources. The mixed color is defined as a color point of the CSK constellation on the color coordinates plane. Therefore, the connectivity is guaranteed by the color coordinates even among different devices.

(2) High Speed and Variable Data Rate

One of the issues with VLC is that the frequency responses of light sources (LED, etc.) are generally insufficient for high speed modulation. In OOK modulation, the bit rate is decided by only the symbol rate for the optical modulation. This means the OOK bit rate is limited by the frequency response of the light source. In CSK, the bit rate is decided by not only the symbol rate, but also the number of color points in the CSK constellation. This means that the CSK bit rate is not limited by the frequency response of the light sources. If the Signal-to-Noise Ratio (SNR) is higher, the CSK system can obtain a higher bit rate.

(3) Constant Total Power

The total power of all the CSK light sources is constant although each light source may have a different instantaneous output power. Thus, there is no flicker issue associated with CSK due to amplitude variations. Also, the total power can be changed independently of the mixed color. Therefore, dimming control is simultaneously possible in CSK data communications.

In this paper, firstly, the principle and performance of the basic CSK system are shown in section II. Next, a new CSK communication system with display and cameras is proposed, and some experimental results for evaluating the proposed system are shown in section III.

II. BASIC CSK SYSTEM

A. Principle

A basic CSK system configuration consisting of multi-color (RGB) LEDs and photo detectors with RGB color filters in Figure 1. Figure 2 shows an example of CSK color symbol mapping on CIE 1931 x-y color coordinates [6]. In this figure, $R(x_R, y_R)$, $G(x_G, y_G)$, and $B(x_B, y_B)$ are the x-y color coordinates of the RGB LEDs, and (x_p, y_p) is the one for the allocated color point used as a CSK symbol.

The information data in Figure 1 are coded into x-y values by the color mapping block, according to the color mapping rule shown in Figure 2. In this example, four color points are placed in the RGB triangle as CSK symbols. This means the system can send 2 bits of data per CSK symbol. Those allocated color points are called a CSK color constellation. Moreover, the example constellation with four color points is called 4CSK. Then, the x-y values are transformed into P_R , P_G , and P_B which are the emission powers of the RGB LEDs. The color of point (x_p, y_p) is generated according to the ratio of the 3 LEDs' powers P_R , P_G , and P_B . The relation among (x_R, y_R) , (x_G, y_G) , (x_B, y_B) , (x_p, y_p) , P_R , P_G , and P_B is shown by the following simultaneous equations.

$$\begin{aligned} x_p &= P_R \cdot x_R + P_G \cdot x_G + P_B \cdot x_B \\ y_p &= P_R \cdot y_R + P_G \cdot y_G + P_B \cdot y_B \\ P_R + P_G + P_B &= 1 \end{aligned} \quad (3)$$

As the last equation shows, the total power ($P_R + P_G + P_B$) is always constant. Furthermore, those power values are normalized ones. Therefore, the actual total power can be arbitrarily set up and can be changed even during the CSK communication. The x-y values at the receiver side are calculated from the received RGB light power P_R' , P_G' , and P_B' . Then, the x-y values are decoded into the received data. As mentioned above, the CSK symbols are provided as the visible colors that are created by the RGB light sources, and the information is transmitted as the intensity ratio among the RGB light sources.

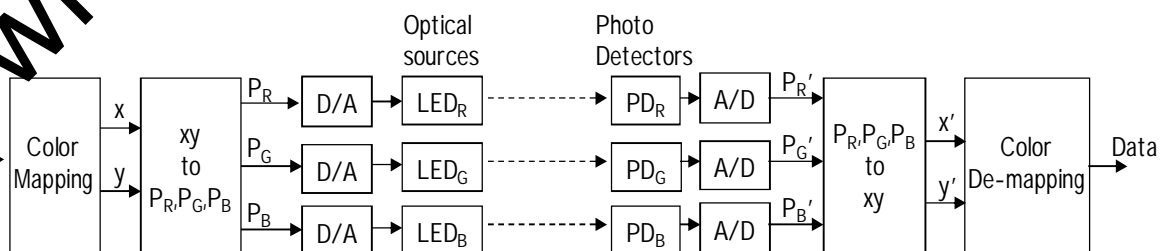


Figure 1. CSK basic system configuration.

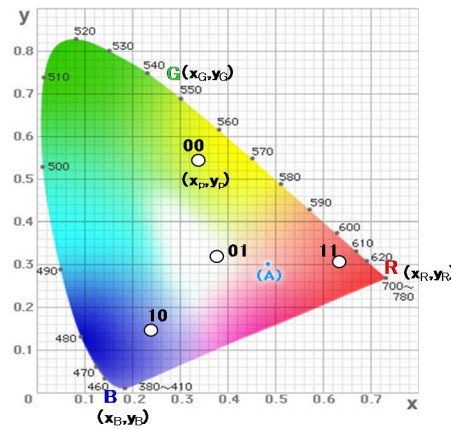


Figure 2. CSK color symbol mapping on CIE1931 x-y color coordinates.

B. Constellation Design

Some color constellations for CSK are proposed as shown in Figure 3. For the constellation design, RGB three colors as the tops of the color triangle are assumed, because of the following reasons.

- (1) RGB LEDs are the most popular commercial multi-color LEDs.
- (2) The RGB colors can provide a large triangular area in the x-y color coordinates for a CSK color constellation.
- (3) Although the CSK systems with over three color light sources require more complex hardware, they do not provide effective performance gain.

In practice, they can use arbitrary three colors for the tops of the color triangle, if they can accept to degrade the performance of the system. In IEEE802.15.7-VLC standard, they can choose three colors out of the seven color bands that are defined as the wave length band plan.

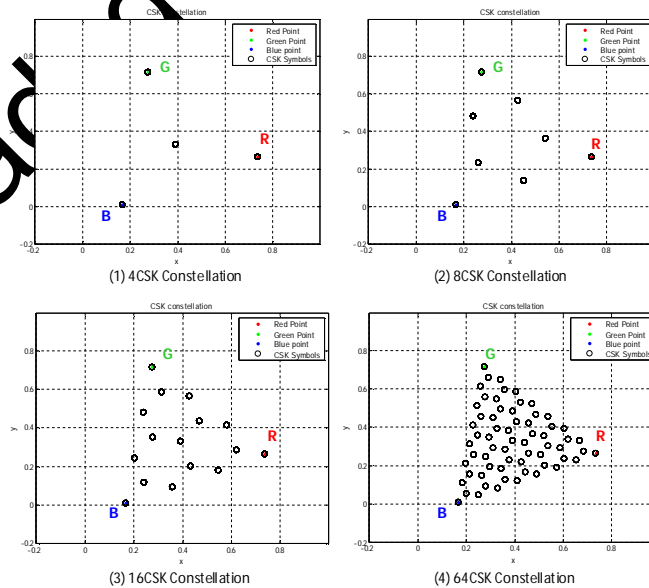
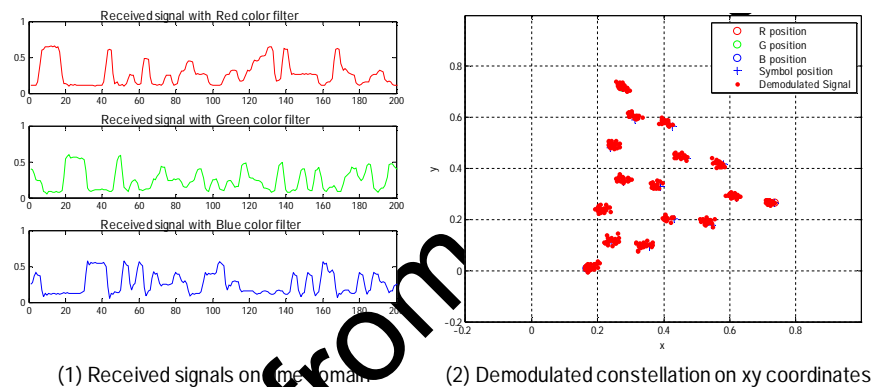


Figure 3. CSK color constellations. They are CSK constellations mapped on CIE1931 xy color coordinates.

C. Performance

Basic CSK system consists of a transmitter with multi-color LED light sources, and a receiver with a color sensor that has high speed photo detectors with RGB color filters. It is assumed that high speed CSK systems communicate from illuminations, digital signage boards, traffic lights or other light sources with multi-color LEDs, to mobile terminals or other receivers with color sensors. The main feature of this system is its high speed data bit rate. The bit rate of CSK is not limited by the frequency response of the LEDs based on this principle. However, a faster bit rate requires a higher SNR, because the distance between the color points on the x-y coordinates is shorter. Therefore, CSK can expect a faster bit rate within a higher SNR environment. In any case, the CSK data communication of the basic CSK system is unrecognizable to humans. The light in CSK communication is sighted as the center color of the color triangle on the x-y color coordinates.

In experiments, we confirmed that 100Mbps is available using commercial devices with 16CSK at 25MHz symbol rate. Figure 4 shows the received 16CSK signals at 25 MHz symbol rate with 100 Mbps bit rate. Figure 4 (1) is the three colors' signals within the given time domain that are received by the color sensors. Figure 4 (2) is the demodulated color constellations on the x-y color coordinates.



(1) Received signals on time domain (2) Demodulated constellation on xy coordinates

Figure 4. Received 16CSK signals at 100Mbps bit rate.

- (1) Three filtered color signals on time domain that are received by color sensors.
 (2) Demodulated color constellations on x-y color coordinates

III. Proposed CSK Communication System

A. Proposed System

Proposed new CSK communication system consists of a transmitter with a Liquid Crystal Display, Plasma Display, OLED or other color display, and a receiver with a color image sensor, i.e., a digital camera. It is assumed that the CSK systems communicate from TVs, PC displays, digital signage boards, displays on mobile terminals or other color displays, to mobile terminals or other receivers with digital cameras. The main feature of the system is that it can be created by using commercial hardware devices such as smart phones. Another feature of the system is its visibility. The CSK codes displayed as animations on displays are recognizable by humans. Therefore, when a user points a camera towards a CSK code, he or she can acquire the presented information.

CSK is a very suitable communication method from a display to cameras, because it uses visible colors for the communication. However, a high data rate cannot be expected, because the symbol rate is limited by the frame rates of cameras. Generally, the frame rate of common cameras is 30 fps. In this case, the symbol rate of CSK should be 15 Hz when considering it should be two times over sampling. Therefore, the data bit

rate would be at most 60 bps when using 16CSK. We present and discuss a method for increasing the bit rate in the following section.

B. Space Division Multiplex for the Proposed System

A color display can display animations of two-dimensional images, and digital cameras can take them. Therefore, we can adopt two-dimensional CSK codes for the communication from displays to cameras. We call the scheme Space Division Multiplex CSK (SDM-CSK). SDM-CSK is very effective for increasing the data bit rate. If we use a 4×4 cell sized CSK code for SDM-CSK, the bit rate increases 16 times compared with normal CSK.

The proposed two-dimensional CSK codes at 16CSK are shown in Figure 5. Each cell of the two-dimensional CSK code in this figure transmits each data sequence. Although the data sequences are independent of each other, the symbol rate is the same. The cameras on the receiver side accept the CSK code in movie mode, recognize it, and demodulate the data in each cell.

C. Color Calibration for the Proposed System

In the proposed CSK system, the color calibration is more important than basic CSK system, because the color characteristics of displays and cameras are complex and dynamic. Therefore, we propose another color calibration method that uses color reference cells. Figure 6 shows a proposed CSK code with reference cells. It is an example for 4CSK-16x16SDM. The top and end of lines of the CSK code are color reference cells. Reference cells include all colors of the CSK color symbols mapped on the x-y color coordinates. The receiver demodulates data cells by comparing the colors with the color reference cells. Because the color reference cells are included in all CSK codes, it is highly effective against dynamic change of the optical environment.

D. Performance Evaluation with Non-Real Time Test System

The non-real time test system consists of a display(32-inch, Full HD) , a camera(4M pixels, 60fps) and a personal computer for de-modulating CSK codes. The display shows CSK test codes repeatedly with 15Hz symbol rate. The performance of the proposed CSK system is affected by various parameters, such as the display refresh rate, display pixel size, camera frame rate, camera pixel size, display-camera distance, CSK color point number, CSK cell number, and the CSK code size. Figure 7 shows the Bit Error Rate (BER) performance along with the display-camera distance and CSK code size without error correction. The CSK cell numbers for SDM are 64×64 with 16CSK, and the CSK cell sizes are 5-20 cm square. The display-camera distance is 1-3 meters. The bit error rate is under 10^{-6} , if the CSK cell size is more than 10×10 cm square of the code size at 1 meter. Therefore, this system is available for 240kbps data transmission using 64×64SDM-16CSK.

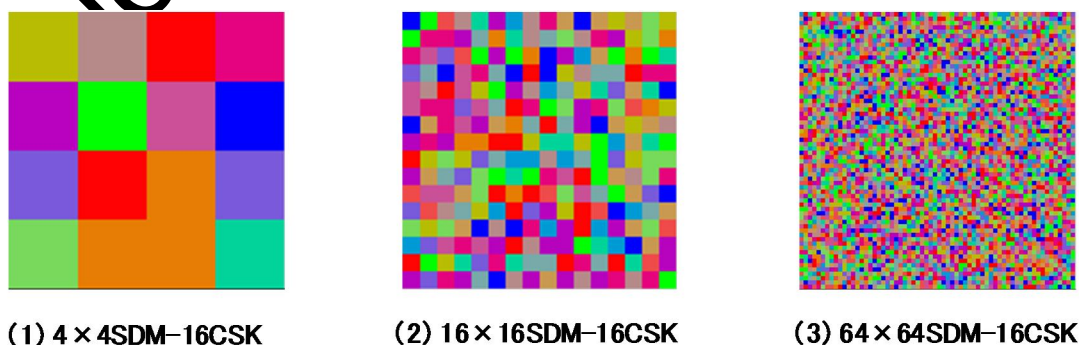


Figure 5. Two dimensional CSK code for proposed CSK system.

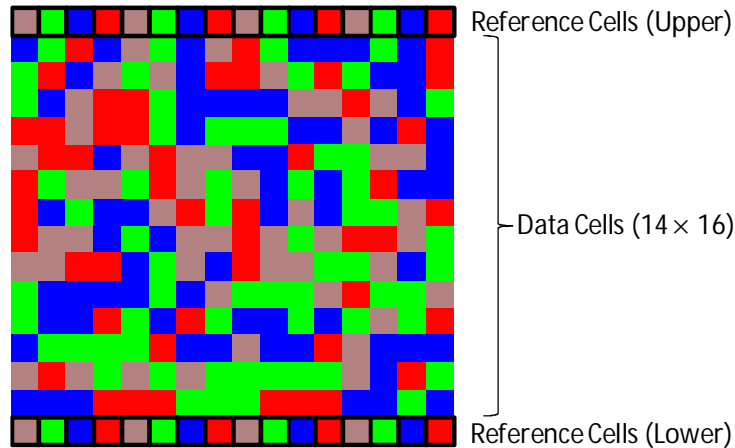


Figure 6. Two Dimensional CSK code with Color Reference Cells. It is an example for 4CSK-16x16SDM.

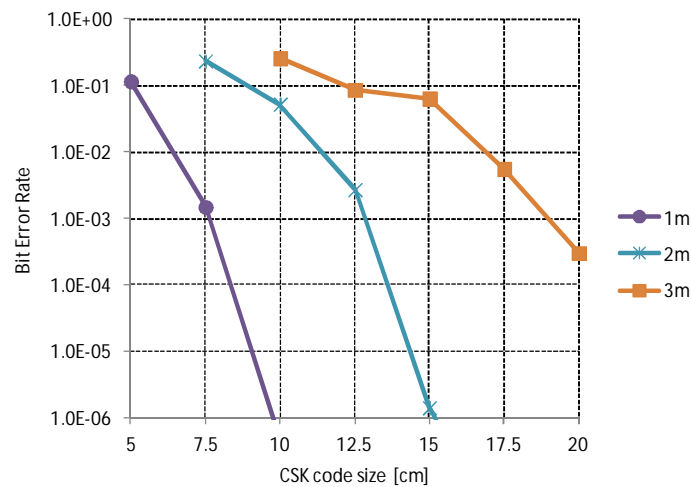


Figure 7. BER Performance of Proposed CSK system with 64x64SDM-16CSK at 15Hz symbol rate. Data Rate:240kbps.

E. Real Time Prototype System

The real time prototype system consists of a display(32-inch, Full HD) and a camera(13M pixels, 30fps) on a smart phone(Android). The display shows CSK codes repeatedly with 15Hz symbol rate. The system can send test data for evaluation or some content data such as pictures or sounds for demonstration. Figure 8 shows the prototype system overview. Some CSK codes are displayed, which send different content to each other. When a user points a camera towards a CSK code, he or she can acquire the presented information.

Figure 9 shows the BER performance along with the display-camera distance and CSK code size without error correction. The CSK cell numbers for SDM are 16x16 with 4CSK, and the CSK cell sizes are 3,5,10 cm square. The display-camera distance is 1-3 meters. The BER of 16x16SDM-4CSK is under 10^{-3} , when the CSK cell size is more than 5x5 cm square at 1meter. Although BER performance is lower than the non-real time test system, it is available to communicate for short content data which is displayed repeatedly. Furthermore, we can expect to improve BER performance after error correction. Figure 10 shows captured CSK code by camera and demodulated constellation on x-y color coordinates.

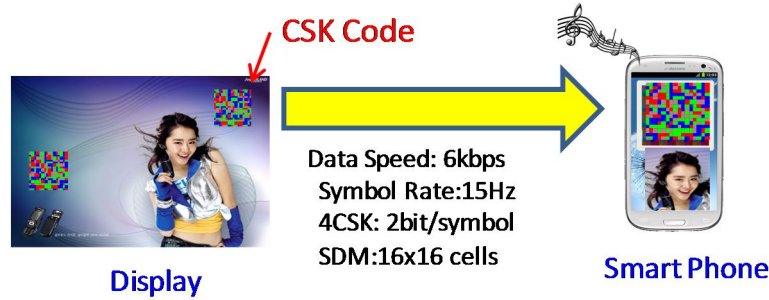


Figure 8. Overview of the real time prototype system.

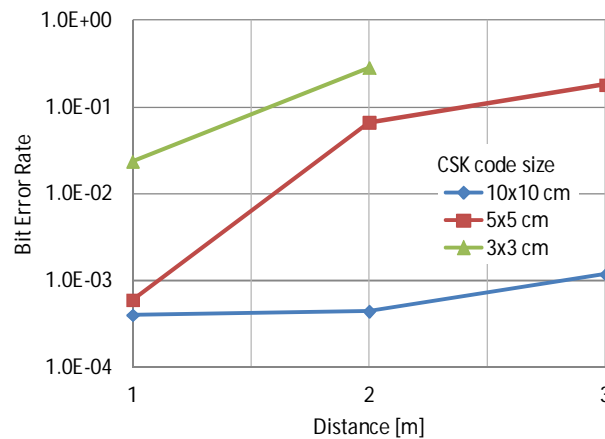


Figure 9. BER Performance of Proposed CSK system with 16x16SDM-4CSK at 15Hz symbol rate. Data Rate: 6kbps.

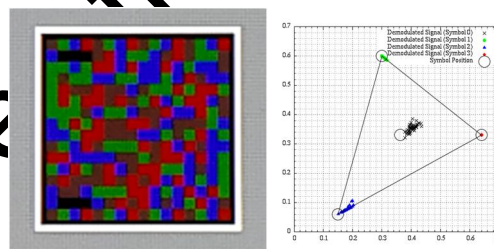


Figure 10. Captured CSK code and demodulated constellation on xy coordinates. 16x16SDM-4CSK at 15Hz symbol rate. Data Rate: 6kbps.

IV. Conclusion

CSK is one of the modulation schemes for Visible Light Communications that was approved and included in the IEEE802.15.7-VLC standard in 2011. In this paper, a new CSK communication system with display and cameras is proposed and evaluated. In experiments, the CSK test system achieved 240kbps data transmission with 64x64SDM-16CSK. The prototype system using smart phone achieved 6kbps data transmission. CSK is a unique and useful scheme for personal area communication. Especially, the proposed CSK system can expect various service models, because the system consists of displays and cameras that have already existed. Furthermore, we will improve the SDM-CSK scheme for increasing the data bit rate.

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