A new image sensor communication system using Color Shift Keying

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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 image sensor communication system using CSK is proposed. In experiments with non-real time test system, the proposed system achieved 238 kbps data rate using 64×64 SDM-16CSK. A real time prototype system which can send contents from a display to a smart phone, achieved a 1.44kbps data rate at 8 meters distance using 8×8SDM-8CSK and a 12kbps data rate at 2 meters distance using 16×16SDM-16CSK.**

Keywords—CSK, color shift keying, VLC, visible light communication, OOK, on off keying, WDM, wave length division multiplexing, SDM, space division multiplexing

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. In the case of CSK, the system transmits information using mixed color generated by multi-color light sources. Although WDM is a good solution for increasing 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. However, in WDM, the connectivity is guaranteed by the wavelength matching of the light source on a transmitter and the photo detector on a 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. This mixed color is defined as a color point in 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, which means the OOK bit rate is limited by the frequency responses of the light sources. 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.

Furthermore, CSK is quite suitable for image sensor communications from displays to cameras, because it uses visible colors for its communication. All displays will be able to be transmitters and all cameras will be able to be receivers of CSK without additional hardware.

In this paper, firstly, the principle and performance of the basic CSK system are shown in section Ⅱ. Secondly, the proposal of a new image sensor communication system using CSK, and some experimental results for evaluating the proposed system are shown in section Ⅲ.

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II. BASIC CSK SYSTEM

A. Principle

The basic CSK system configuration consisting of RGB multi-color LEDs and photo detectors with RGB color filters is illustrated in Figure 1. RGB are the light's three primary colors red-green-blue (RGB). Figure 2 shows an example of a CSK color symbol mapping on CIE1931 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, this constellation example 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.

$$x_p = P_R \cdot x_R + P_G \cdot x_G + P_B \cdot x_B \qquad (1)$$

$$y_p = P_R \cdot y_R + P_G \cdot y_G + P_B \cdot y_B \qquad (2)$$

$$P_R + P_G + P_B = 1 \qquad (3)$$

As the last equation shows, the total power (P_R+P_G+P_B) is always constant. Furthermore, these power values are normalized to value of one. Therefore, the actual total power can be arbitrarily set up and can be changed even during the CSK communication. The x-y values on 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 visible colors that are created by the RGB light sources, and the information is transmitted as the intensity ratio among the RGB light sources.

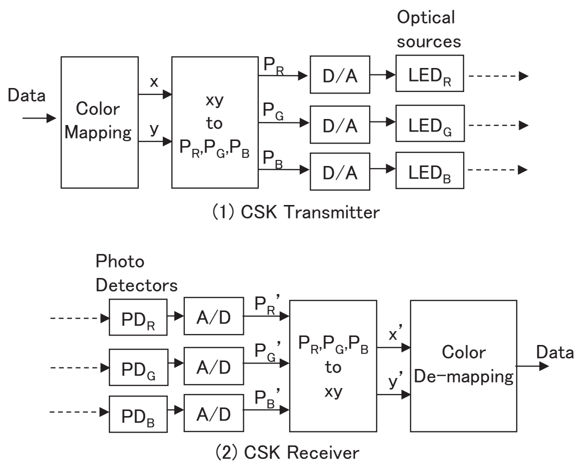

Fig. 1. CSK basic system configuration.

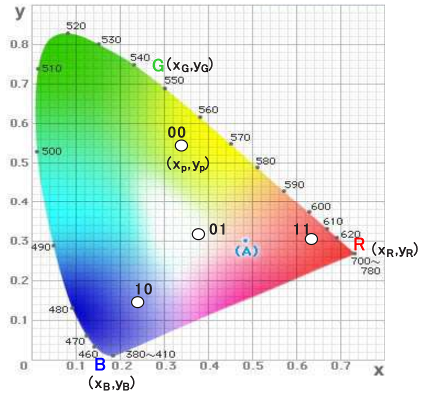

Fig. 2. CSK color symbol mapping on CIE1931 x-y color coordinates.

B. Constellation Design

The color constellations for CSK are shown in Figure 3. When the constellation has four color points, it is called 4CSK which can send 2 bits per CSK symbol. Furthermore, 8CSK with 8 color points which can send 3 bit/symbol, 16CSK with 16 color points which can send 4 bit/symbol, and 64CSK with 64 color points which can send 6 bit/symbol are shown in the figure. These CSK color constellations are designed so that every color point has the same and maximum distances from the adjacent color points.

For the constellation design, the light's three primary colors red-green-blue (RGB) are assumed as the tops of the color triangle, 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.

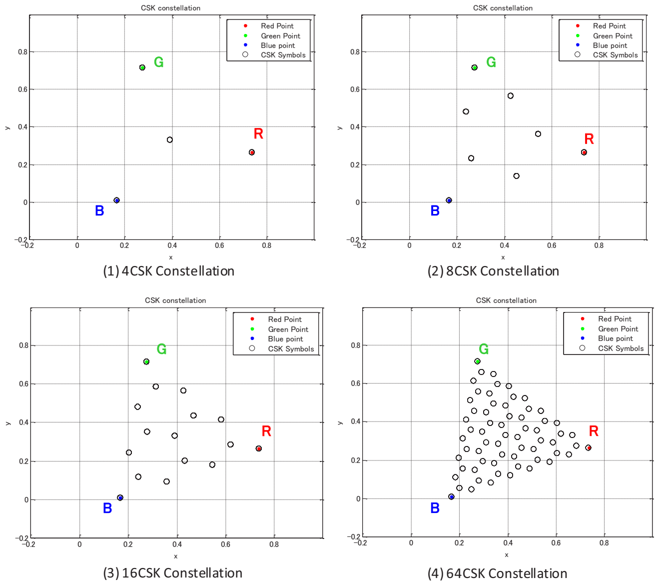

Fig. 3. CSK color constellations mapped on CIE1931 x-y color coordinates.

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.

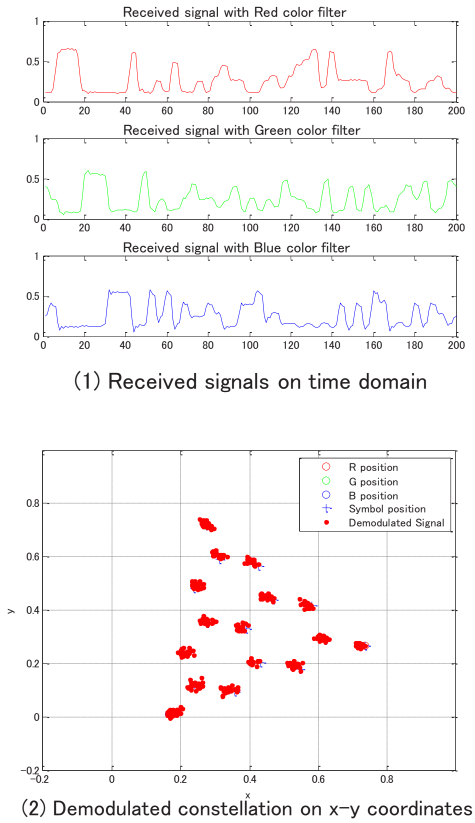

Fig. 4. Received 16CSK signals at 100Mbps bit rate.

III. PROPOSED IMAGE SENSOR COMMUNICATION SYSTEM

In this section, the proposed new image sensor communication system using CSK is illustrated and some performance evaluation results are shown.

A. *Proposed system*

The proposed 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 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 promising communication system, because it consists of displays and cameras that are already existing and it doesn't need any additional hardware. However, high data rate cannot be expected, because the symbol rate is limited by the capture frame rates of cameras. Generally, the capture 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 the most 60 bps when using 16CSK. We will present a method for increasing the bit rate in the following section.

B. Space Division Multiplex for high data rate

Color displays 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 a display to cameras. We call the scheme Space Division Multiplexing CSK (SDM-CSK). SDM-CSK is very effective for increasing the data bit rate. If we use a 16×16 cell sized CSK code for SDM-CSK, the bit rate increases 256 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.

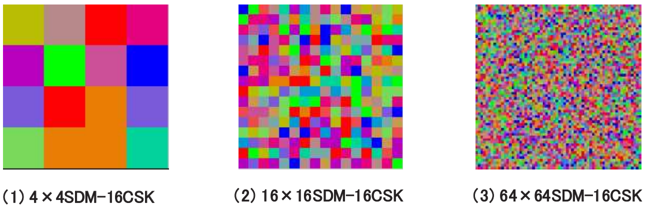

Fig. 5. Two dimensional CSK code for proposed system.

C. Color Calibration for robust communication

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 constellation 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.

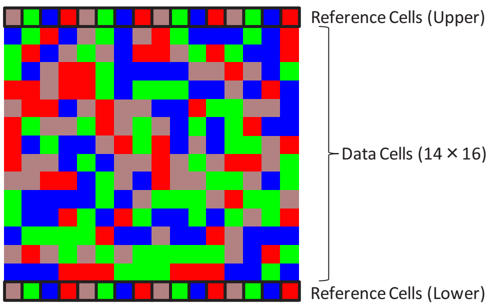

Fig. 6. Two Dimensional CSK code with Color Reference Cells.

Table I lists the expected data rate of the SDM-CSK system at 15 Hz symbol rate considering reference cells without coding. SDM-CSK can select various bit rates by choosing a SDM cell number and a CSK color constellation.

TABLE I. DATA RATE OF SDM-CSK SYSTEM AT 15HZ SYMBOL RATE.

SDM Cell number	4CSK	8CSK	16CSK	64CSK
Normal CSK 1×1	30 bps	45 bps	60 bps	90 bps
4×4	240 bps	Undefined*	Undefined*	Undefined*
16×16	6.72 kbps	10.0kbps	13.4 kbps	Undefined*
64×64	119 kbps	178 kbps	238 kbps	357 kbps

*Cannot set reference cells, because the cell number on a side is less than the CSK color point.

D. Performance Evaluation with non-real time test system

The non-real time test system consists of a display (32-inch, UHD), a camera (4mega pixels, 60fps) and a personal computer for de-modulating CSK codes. The display shows SDM-CSK test codes repeatedly with 15Hz symbol rate. The performance of the proposed CSK system is affected by various parameters, such as display size, camera capture frame rate, camera pixel size, display-camera distance, CSK symbol rate, CSK color constellation, SDM cell number and 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 SDM cell numbers are 64×64 with 16CSK, and the CSK code sizes are 5 to 20 cm square. The display-camera distance is 1 to 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. Thus, this system is available for 238kbps data transmission using 64×64SDM-16CSK at a distance of 1 meter. Table II shows other conditions of the evaluation.

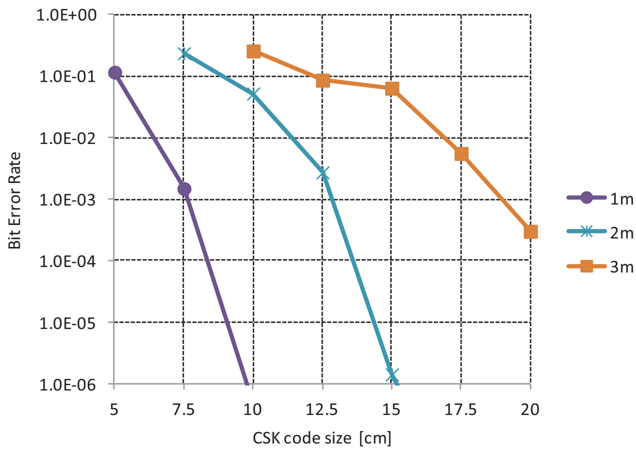

Fig. 7. BER Performance of non-real time test system with 64x64SDM-16CSK at 15Hz symbol rate. Data Rate:238kbps.

TABLE II. CONDITIONS OF NON-REAL TIME TEST SYSTEM EVALUATION.

Item	Condition
Display	32inch, UHD(4K)
Camera	60 fps, 4 mega pixels
CSK symbol rate	15Hz
CSK color constellation	16CSK
SDM sell number	64×64
CSK code size	5-20cm square
Distance	1, 2, 3 meter
Data rate	238kbps
Error correction	No coding

E. Real time prototype system

The real time prototype system consists of a display (55-inch, Full HD) and a camera (13mega pixels, 30fps) on a smart phone (Android). The display shows CSK codes repeatedly with 15Hz symbol rate. The system can send a 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.

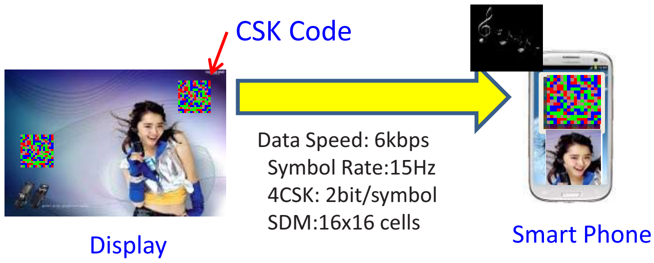

Fig. 8. Overview of the real time prototype system.

For evaluating the real time prototype system, we measured FER (Frame Error Rate) performance when the system sends a test data train repeatedly. In this evaluation, the frame means a bit train included in a CSK code which is displayed at 15Hz. FER is a ratio between number of the error frames and the number of all frames after Reed-Solomon error correction.

Figure 9 shows measured FER along with the display-camera at distance from 1 to 10 meters. Variable parameters are CSK color constellation and SDM cell number. We chose three CSK color constellations, 4CSK, 8CSK and 16CSK, and two SDM cell numbers, 8×8 and 16×16. CSK code size is fixed at 10×10 cm square in all cases. As mentioned above, SDM-CSK data rate is determined by the CSK color constellation and the SDM cell number. The variable parameters and data rates are shown in Table Ⅲ. Other conditions of the real time prototype evaluation is shown in Table Ⅳ.

We assumed that the maximum FER for successful communication of the proposed system is less than 1%. This is a reasonable assumption for transmitting a short content. According to this assumption in figure 9, the maximum transmitting distances are shown as 'Max Distance' in TableⅢ.

We found that 1.44kbps data communication is available at a distance of 8.0meters using 8×8SDM-8CSK, and 12.0kbps data communication can be available at a distance of 2.0 meters using 16×16SDM-16CSK.

TABLE III. PARAMETRS AND PERFORMANCE OF REAL TIME PROTOTYPE

CSK color constellation	SDM Cell	Data size /frame*1	Reed Solomon	Data Rate*2	Max Distance*3
4CSK	8×8	8byte	-	960bps	9.0m
8CSK	8×8	12byte	2byte	1.44kbps	8.0m
4CSK	16×16	50byte	2byte	6.0kbps	4.5m
8CSK	16×16	76byte	4byte	9.12kbps	3.5m
16CSK	16×16	100byte	8byte	12.0kbps	2.0m

*1 Data size in a CSK code, *2 Actual data rate at 15Hz symbol rate.

*3 Maximum distance for successful communication

TABLE IV. CONDITIONS OF REAL TIME PROTOTYPE SYSTEM EVALUATION.

Item	Condition
Display	55inch, Full HD
Camera on smart phone	30 fps, 13 mega pixels
CSK symbol rate	15Hz
CSK code size	10cm square
Distance	1 - 10 meter

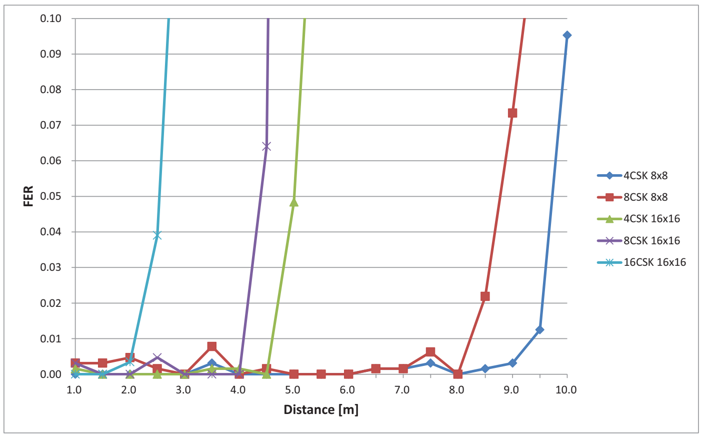

Fig. 9. FER Performance of real time prototype system with 15Hz frame rate.

Figure 10 shows a captured CSK code by the camera and a demodulated constellation on x-y color coordinates with 16×16SDM-4CSK.

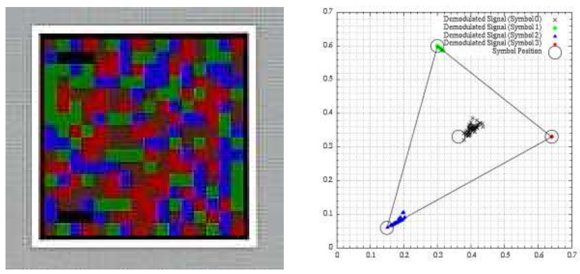

Fig. 10. Captured CSK code and demodulated constellation on xy coordinates. 16x16SDM-4CSK at 15Hz symbol rate. Data Rate:6kbps

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 image sensor communication system using CSK is proposed and evaluated. In non-real time experiments, the CSK test system achieved 238kbps data transmission with 64×64SDM-16CSK. The prototype system using a smart phone achieved 1.44kbps data transmission at a distance of 8 meters, and 12.0kbps data transmission at a distance 2 meters. CSK is a unique and useful scheme for personal area communication. Especially, the proposed 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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