Experimental Evaluation of Hybrid PWM/DPAM Dimming Control Method for Digital Color Shift Keying Using RGB-LED Array

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Abstract

In this work, we focus on digital color shift keying (DCSK), which is one of the modulation schemes of visible light communication (VLC). DCSK is an extended version of IEEE 802.15.7 color shift keying (CSK) that transmits data through the intensity ratios of red, green, and blue. Digitally controlled LED drivers of DCSK can also reduce the nonlinearity effect caused by the shift of the intensity amplitude. DCSK supports lighting functions such as flicker mitigation, target color control, and dimming control. For the dimming control method of DCSK, two schemes have been considered. One is pulse width modulation (PWM), which changes the duty cycle of optical transmit signals, and the other is digital pulse amplitude modulation (DPAM), which changes the number of red, green, and blue LEDs (RGB-LEDs) being used. In a previous analysis, a hybrid scheme of PWM and DPAM was proposed that could achieve both a wider dimming range than DPAM and a higher spectral efficiency than PWM. Unlike in theoretical analysis, with actual LED drivers, the dimming level (DL) obtained by PWM, DPAM, and hybrid PWM/DPAM may cause errors due to individual differences in the dimming method and LED drive current. In this work, we experimentally evaluate the accuracy of DL and the symbol error rate (SER) of DCSK with PWM, DPAM, and hybrid PWM/DPAM.

1. Introduction

Visible light communication (VLC) is a wireless communication system that provides both communication and lighting functions \cite{1}\cite{2}. To apply VLC to an illumination source, a VLC modulation method must consider the effects of the modulated light signal that humans perceive as well as support flicker mitigation, dimming control, color temperature control, a high color rendering index (CRI), and so on. IEEE 802.15 Task Group 7 proposed three VLC modulation methods for flicker mitigation and dimming support: on-off keying (OOK), variable pulse position modulation (VPAM), and color shift keying (CSK) \cite{3}\cite{4}. The CSK system is particularly promising because it can increase the data speed by combining the outputs of red, green, and blue in RGB-LED (i.e., trichromatic LED (TLED)). In CSK, \( M \) signal points are mapped inside the RGB constellation triangle on the CIE xy chromaticity diagram \cite{5} and are presented by the intensity ratio of red, green, and blue. When the individual intensities of red, green, and blue in a TLED are \( P_R, P_G, \) and \( P_B \), respectively, the total intensity is constant (i.e., \( P_R + P_G + P_B = \text{const.} \) for flicker mitigation. CSK can also utilize the original frequency response of the LED of MHz order, while the frequency response of the blue LED with phosphor is limited to just MHz order due to the phosphor \cite{6}\cite{7}. However, CSK systems suffer from LED nonlinearity effects when adjusting to the desired optical intensity due to the change in the current driving with a digital-to-analog converter (DAC). This analog-controlled LED causes nonlinearities of the current to voltage (I-V) characteristics and intensity to current (\( \Phi-I \)) characteristics of the LED \cite{8}. Moreover, an analog-controlled LED also causes an undesired color shift, which is the peak wavelength shift caused by changing the drive current of the LED. As a solution to these problems, Monteiro and Hranilovic proposed a linear variable current driver including predistortion to linearize the LED output intensity \cite{9}. This variable current driver allows the desired drive current \( I \) to flow into an LED linearly due to the open collector nature of an OP AMP. However, these architectures increase the system complexity and they cannot prevent the problem of an undesired color shift. Digital CSK (DCSK) has also been considered as a means of overcoming the drawbacks of CSK \cite{10}\cite{12}. In DCSK, the desired optical intensity is represented by digitally controlled LEDs in multiple RGB-LEDs (i.e., an RGB-LED array). This can reduce the system complexity and minimize the effect of LED nonlinearity.

In this work, we focus on a dimming control method for DCSK with RGB-LEDs. Generally, two dimming control schemes have been considered for CSK \cite{13}: pulse width modulation (PWM) and pulse amplitude modulation (PAM). PWM dims by changing the duty cycle of optical transmit signals, while PAM generally dims by adjusting the drive current of the LED, which increases the system complexity,
as mentioned earlier. Therefore, for DCSK, digitally controlled PAM (DPAM) is proposed, which dims by changing the number of RGB-LEDs being used in an RGB-LED array. In a previous study, a hybrid scheme of PWM and DPAM was proposed [14] that could achieve both a wider dimming range than DPAM and a higher spectral efficiency than PWM. Unlike in theoretical analysis, with actual LED drivers, the dimming level (DL) obtained by PWM, DPAM, and hybrid PWM/DPAM may cause errors due to individual differences in the dimming method and LED drive current. In this work, we experimentally evaluate the accuracy of DL and the symbol error rate (SER) of DCSK with PWM, DPAM, and hybrid PWM/DPAM.

2. System Setup

2.1 PWM dimming control method

PWM is generally used for the dimming control in VLC. This method dims the light intensity in VLC by changing the pulse width. In a DCSK system, the duty cycle of optical transmission signals is related to the brightness of the lighting. We define the number of dimming stages of PWM, \( N'_{\text{max}} \), as

\[
N'_{\text{max}} = \frac{T_s}{T_c}
\]

(1)

where \( T_s \) is the symbol duration of the original DCSK and \( T_c \) is the chip duration for PWM dimming control. Then, the PWM DL, \( \varepsilon_{\text{PWM}} \), is represented as

\[
\varepsilon_{\text{PWM}} = \frac{N'_{\text{PWM}}}{N'_{\text{max}}} \times 100\% \quad (N'_{\text{PWM}} = 1, 2, \cdots, N'_{\text{max}})
\]

(2)

where \( N'_{\text{PWM}} \) is the PWM signal duration.

DCSK with PWM can represent a wider dimming range by decreasing the chip duration, \( T_c \); however, the spectral efficiency of DCSK with PWM is less than that of the original DCSK.

2.2 DPAM dimming control method

The PAM dimming control method generally dims by adjusting the drive current of LEDs. However, analog current control causes a color shift problem, and we also have to linearize the LED nonlinearity effects.

As a possible solution to these problems, DPAM is considered [14]. DPAM represents the DLs by changing the number of active RGB-LEDs in the RGB-LED array. Therefore, the number of dimming stages is limited by the number of RGB-LEDs in the RGB-LED array. When we define the number of RGB-LEDs for the original DCSK as \( N_{\text{min}} \) and the number of RGB-LEDs in the RGB-LED array as \( N_{\text{RGB}} \), the number of dimming stages of DPAM can be written as

\[
N_{\text{max}} = \left\lfloor \frac{N_{\text{RGB}}}{N_{\text{min}}} \right\rfloor
\]

(3)

where \( \lfloor \cdot \rfloor \) is the floor function. Then, the DPAM DL, \( \varepsilon_{\text{DPAM}} \), is represented as

\[
\varepsilon_{\text{DPAM}} = \frac{N_{\text{DPAM}}}{N_{\text{max}}} \times 100\% \quad (N_{\text{DPAM}} = 1, 2, \cdots, N_{\text{max}})
\]

(4)

The spectral efficiency of DCSK with DPAM is the same as that of the original DCSK. However, the number of RGB-LEDs in the RGB-LED array is limited, so the number of dimming stages of DCSK with DPAM is less than that of DCSK with PWM.

2.3 Hybrid PWM/DPAM dimming control method for DCSK

A hybrid PWM/DPAM system was proposed in a previous study [14]. This system combines PWM and DPAM to enable a wider dimming range than DPAM and a higher spectral efficiency than PWM by selecting the optimum combination. The number of dimming stages of hybrid PWM/DPAM, \( N \), can be written as

\[
N = N'_{\text{max}} \times N_{\text{max}}
\]

(5)

Then, the DL, \( \varepsilon \), is represented as

\[
\varepsilon = \frac{N_{\text{PWM}}}{N_{\text{max}}} \times \frac{N_{\text{DPAM}}}{N_{\text{max}}} \times 100\%
\]

(6)

However, the hybrid PWM/DPAM system cannot actually represent \( N \) DLs because they include overlapped patterns such as \( (\varepsilon_{\text{DPAM}}, \varepsilon_{\text{PWM}}) = (100\%, 33\%) = (33\%, 100\%) \), which theoretically result in \( \varepsilon = 33\% \).

Figure 1 shows an example of the transmit signal pattern model of a 4-ary DCSK with the hybrid PWM/DPAM dimming control method using nine RGB-LEDs. When \( N_{\text{min}} = \) 3, DPAM can represent three dimming stages. By combining PWM with three dimming stages, the hybrid PWM/DPAM can represent nine dimming stages including overlapped DLs.

2.4 Experimental setup

The experimental setup of DCSK is shown in figure 2. Transmission data is generated from a field-programmable gate array (FPGA : Xilinx virtex-6). We programmed a pseudorandom binary sequence (PRBS) generator, DCSK modulator, and hybrid PWM/DPAM dimming controller into the FPGA. The generated DCSK signal is applied to an LED driver, and the signal data are converted into an optical signal.
The transmit signal pattern model of 4-ary DCSK with hybrid PWM/DPAM dimming control using nine RGB-LEDs is shown in Figure 1.

Figure 1: Transmit signal pattern model of 4-ary DCSK with hybrid PWM/DPAM dimming control using nine RGB-LEDs.

The experimental setup of 4-ary DCSK using nine RGB-LEDs with hybrid PWM/DPAM dimming control is shown in Figure 2.

Figure 2: Experimental setup of 4-ary DCSK using nine RGB-LEDs with hybrid PWM/DPAM dimming control.

The geometry of the DCSK system is shown in Figure 3.

Figure 3: (a) Geometry of transmitter and receiver of the DCSK system, (b) Transmitter layout with nine RGB-LEDs, (c) Receiver layout with color filters and PDs.

The experimental conditions are listed in Table 1.

The dimming accuracy of each DL is shown in Table 2. The designed DL, $\varepsilon_d$, is written as

$$\varepsilon_d = \varepsilon_{PWM} \times \varepsilon_{DPAM}$$

The measured DL, $\varepsilon_m$, is normalized by the maximum irradiance, which is measured at $\varepsilon_d = 100\%$. The relative error, $e$, is written as

$$e = \frac{\varepsilon_m - \varepsilon_d}{\varepsilon_d} \times 100[\%]$$

3. Results

The dimming accuracy of each DL is shown in Table 2. The designed DL, $\varepsilon_d$, is written as

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transmitter and receiver, D is high because the optical power of the received signal increased.

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4. Conclusions

We experimentally evaluated the dimming accuracy and SER of DCSK with hybrid PWM/DPAM dimming control. When there were several combinations representing the same DL, the PWM scheme had greater dimming accuracy than the DPAM scheme due to the individual differences among RGB-LEDs. Moreover, the SER increased when the measured DL $\varepsilon_m$ was high because the optical power of the received signal increased.

Table 2: Dimming accuracy of each DL

| Designed dimming level $\varepsilon_d$ [%] | Measured dimming level $\varepsilon_m$ [%] | Relative error $\varepsilon$ [%] |
|---------------------------------------|--------------------------------------|-------------------------------|
| 100.0 (100.0 x 100.0)                | 100.0                                 | -                             |
| 66.7 (66.7 x 66.7)                    | 68.2                                  | 2.25                           |
| 67.0 (67.0 x 100.0)                   | 66.1                                  | -1.34                          |
| 44.7 (67.0 x 66.7)                    | 45.1                                  | 0.89                           |
| 33.3 (100.0 x 33.3)                   | 34.1                                  | 2.40                           |
| 33.0 (33.0 x 100.0)                   | 33.2                                  | 0.61                           |
| 22.2 (67.0 x 33.3)                    | 22.7                                  | 2.25                           |
| 22.0 (33.0 x 66.7)                    | 22.5                                  | 2.27                           |
| 11.0 (33.0 x 33.3)                    | 11.6                                  | 5.45                           |

Figure 4: SER versus distance between transmitter and receiver, D.

From Table 2, PWM achieves high DL accuracies compared with those of DPAM. For example, when $\varepsilon_d$ is about 67%, PWM can achieve a relative error of -1.34, while the relative error of DPAM is 2.25. Similarly, when $\varepsilon_d$ is about 33%, PWM can achieve a relative error of 0.61, while the relative error of DPAM is 2.40. This is because multiple RGB-LEDs in DPAM increase the effect of individual differences in the LED drive current. Z 9110:2011 of JIS (Japanese industrial standards) defines that the minimum difference in illuminance which can be perceived is about 1.5 times [21]. The practical tolerance of the relative error is therefore about 50%.

Figure 4 shows the SER versus the distance between the transmitter and receiver, D. When $\varepsilon_d$ is high, the SER decreases because the optical power is proportional to $\varepsilon_m$.

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