

Visible Light Communication with Color and Brightness Control of RGB LEDs

Kyungmook Choi, Yunseon Jang, MinChul Ju, and Youngil Park

We propose a visible light communication system in which the color and brightness are controllable. Pulse width modulation and variable pulse position modulation (VPPM) schemes are used to control the color and brightness, respectively. A digital algorithm to decode VPPM signals is suggested and implemented. A seamless transmission is observed in a testbed experiment under various environmental conditions. The proposed scheme can be applied to emotional-lighting-based wireless optical communication.

Keywords: Visible light communication, VLC, light-emitting diode, LED, pulse width modulation, PWM, variable pulse position modulation, VPPM, dimming control.

I. Introduction

As more LED lamps are installed in stores and offices, interest in wireless optical communications using visible light is increasing. The first standard on LED-based visible light communication (VLC) is approved, which provides the MAC and PHY protocol of VLC [1]. Many modulation schemes are introduced to enhance the data rate of visible LEDs [2]-[6]. One of the advantages of LEDs is that their color and brightness are easily changed by controlling the input current. However, most of the studies on VLC have used a white color [2]-[5] since it is the most popular type. However, VLC with diverse colors will find many useful applications as emotional lighting becomes a prominent illumination method. Emotional lighting is an illumination scheme that changes the color

according to factors relative to the surrounding environment, such as mood, music, food, temperature, energy saving, or ecological benefits. A color-independent VLC scheme was studied in [7], but without showing color control. Several modulation schemes for dimming control, which is another essential part of emotional lighting, have been suggested [8], [9]. In this letter, we suggest a way to control both the color and brightness of LEDs during data transmission. We use pulse width modulation (PWM) to control color and variable pulse position modulation (VPPM) to control dimming while transmitting data [10]. The conventional PWM scheme is modified to fit the data transmission. The VPPM scheme is included in the IEEE VLC standard [1], and we suggest a way to implement it. By merging them in an appropriate way, data transmission with color and dimming control is possible. The binary output waveform of the proposed scheme makes its implementation simple. A testbed is implemented, and its transmission performance is provided.

II. Principles of Proposed System

Red, green, and blue (RGB) LEDs are used to present colors because the color combination can produce any color according to such chromaticity diagrams as the CIE 1931. The color perceived by the human eye is decided by the intensity ratio of each LED color, which can be controlled by the on/off period of each LED. Therefore, the PWM signals shown in Fig. 1 can generate any color by displaying RGB colors in turn in a time sequence; the PWM period, T_w , should be short enough to avoid flickering perceived by the human eye. For example, the RGB display time ratio of 1:1:1 generates white, whereas that of 1:0.6:0 produces orange. PWM represented in Fig. 1(a) has a fixed time slot for each color, but the actual

Manuscript received Sept. 21, 2012; revised Mar. 10, 2013; accepted Mar. 21, 2013.

This work was supported by Broadcasting-Communications R&D Program of KCC/KCA Korea (11-911-01-111) and ITRC support program of MKE Korea (NIPA-2012-H0301-12-2007).

Kyungmook Choi (phone: +82 2 910 5074, ckooks@naver.com), Yunseon Jang (thdusc1020@hanmail.net), MinChul Ju (mcju@kookmin.ac.kr), and Youngil Park (corresponding author, ypark@kookmin.ac.kr) are with the School of Electrical Engineering, Kookmin University, Seoul, Rep. of Korea.

<http://dx.doi.org/10.4218/etrij.13.0212.0425>

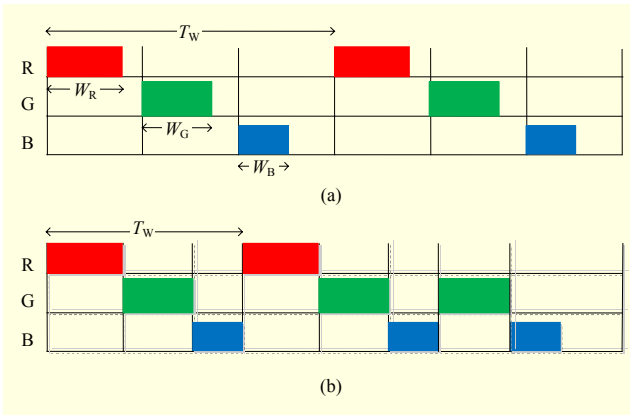


Fig. 1. Color control of LEDs using PWM coding scheme: (a) with fixed PWM period and (b) with variable PWM period.

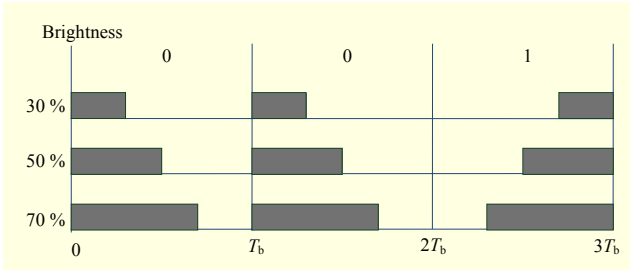


Fig. 2. Brightness control of LEDs using VPPM coding scheme [3].

pulse width (PW) within each slot is variable, which is suitable to control the brightness and color by changing the PW of each color W_{RGB} but is not adequate for continuous data transmission due to the empty time slot inserted between consecutive PWM signals. If the pulses of each color are arranged as in Fig. 1(b), data transmission will not be interrupted since each LED is turned on consecutively without any empty slots. However, this scheme cannot control the brightness alone. Since the amplitude of each pulse should be controlled to change the brightness, it requires such additional electronic circuits as serial-to-parallel converters and digital-to-analog converters. Thus, we present VPPM in combination with PWM to control both color and brightness. The pulse position of VPPM changes with incoming data, and the PW changes with brightness, as shown in Fig. 2.

Since the average turn on time of an LED does not change with the input data type (“0” or “1”), neither lamp flickering nor a color change problem is found with VPPM coding. The output signals of combined PWM and VPPM of (1) through (3) are illustrated in Fig. 3, in which the ratio of colors in PWM determines the perceivable color and the PW of VPPM controls the brightness:

$$p(t) = p_W(t) \cdot p_V(t), \quad (1)$$

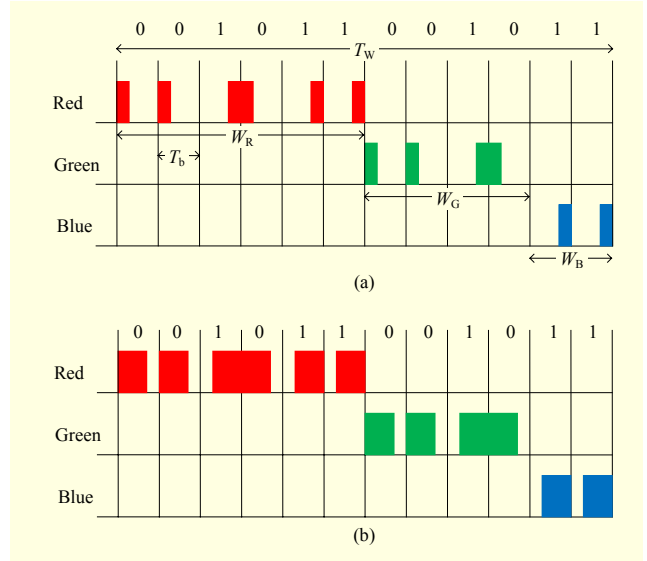


Fig. 3. Combined PWM and VPPM for color and brightness control: (a) 30% brightness and (b) 70% brightness.

where $p_W(t)$ is the PWM signal and $p_V(t)$ is the VPPM signal.

$$p_W(t) = \sum_{i=1}^{\infty} \Pi \left(\frac{t - (i-1)T_W - t_{RGB} - W_{RGB} / 2}{W_{RGB}} \right), \quad (2)$$

where Π is a rectangular function, T_W is the PWM period, t_{RGB} is the position of RGB inside a PWM window, and W_{RGB} is the PW of RGB.

$$p_V(t) = \sum_{j=1}^{\infty} \Pi \left(\frac{t - (j-1 + m_j)T_b + (2m_j - 1)V_j / 2}{V_j} \right), \quad (3)$$

where data m_j is 0 or 1, T_b is the bit period, and V_j is the PW of the VPPM signal.

Manchester coding or 2-PPM can easily recover clocks at the receiver since the signal changes at the center of each bit regardless of data type. However, VPPM coding has difficulty in clock recovery since the signal transition does not occur at the center but rather varies with brightness. To recover clock in this condition, algorithms are proposed in (4) and (5). The pulse durations, ΔL and ΔH , are measured in the beginning of the procedure to determine the best decision time, which comes at the center of the narrower part of the signal, as shown in Fig. 4.

Therefore, recovery procedures are classified according to the brightness and the data value. A decision time of (4) or (5), depending on whether the brightness is more or less than 50%, is applied in the measurement. The rising time, $t_r(n)$, is obtained by the transition of the VPPM signal following the previous decision time, $t_d(n)$.

$$t_d(n+1) = \begin{cases} t_r(n) + \Delta H + 0.5\Delta L & \text{if } D(n) = 1 \\ t_r(n) + \Delta L + 0.5\Delta L & \text{if } D(n) = 0 \end{cases} \text{ for } \Delta H \geq \Delta L, \quad (4)$$

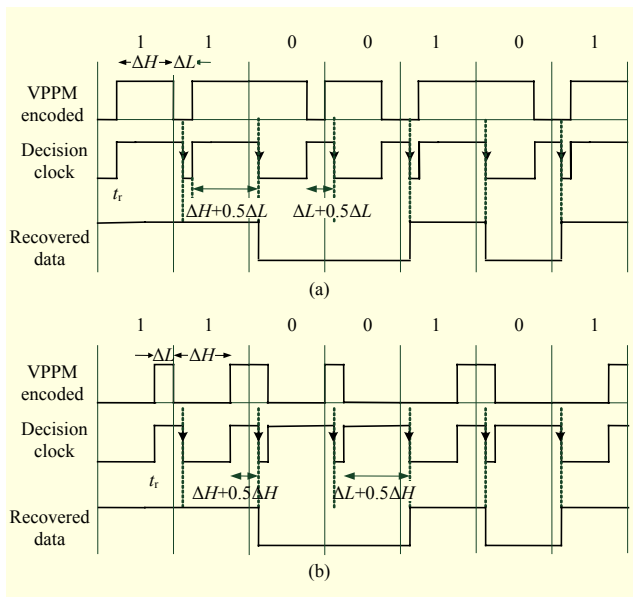


Fig. 4. Clock and data recovery from VPPM decoded signal: (a) brightness more than 50% and (b) brightness less than 50%.

$$t_d(n+1) = \begin{cases} t_r(n) + \Delta H + 0.5\Delta H & \text{if } D(n) = 1 \\ t_r(n) + \Delta L + 0.5\Delta H & \text{if } D(n) = 0 \end{cases} \text{ for } \Delta H < \Delta L. \quad (5)$$

Examples of the clock and data recovery for different degrees of brightness are shown in Fig. 4, in which Figs. 4(a) and 4(b) show 70% brightness ($\Delta H \geq \Delta L$) and 30% brightness ($\Delta H < \Delta L$), respectively. The decision signals in Fig. 4 provide the data decision times of the received VPPM encoded signal.

III. Experiment Results

The proposed VLC scheme is tested using the experimental setup shown in Fig. 5. The experiment is done in a wide open area, and both the LED lamp and photodiode (PD) are positioned vertically so that they face each other. Information data is VPPM coded and PWM coded in sequence, then provided to an LED driver circuit. Among three transistors at the driver circuit (one per color LED for driving), only one transistor is operating at any given time, as decided by the PWM pulse. An LED lamp composed of 36 LED modules (F50360) is used; each module includes separate 0.5-W RGB LED chips. The LED lamp's luminous flux is 105 lm, and the viewing angle is 120 degrees. The current level of each driving circuit is adjusted so that it can compensate for the difference in responsivity of a PD with colors. The transmitted LED light is received at the PD (FDS100), of which the spectral response is 350 nm to 1,100 nm and active area is 13.0 mm × 13.0 mm. Finally, a VPPM decoder recovers the data. PWM decoding is

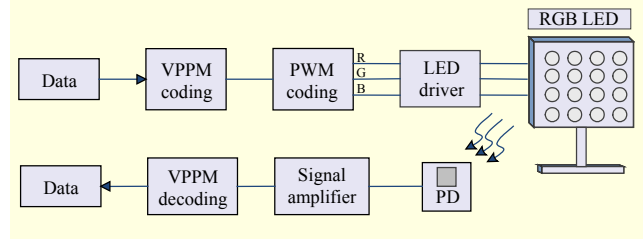


Fig. 5. Experimental setup of proposed scheme.

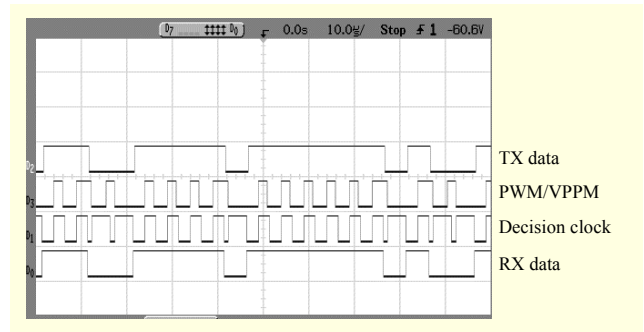


Fig. 6. Experiment results for 30% brightness.

not required since it is used only for selecting LED colors. The light of all three colors is received by a single PD. Coding and decoding functions are implemented in two FPGA devices.

A data rate of 200 kbps is used in the experiment to carry two voice channels and text messages according to PHY Type I in the VLC standard. A pseudorandom number (PN) with a period of $2^8 - 1$ is used in the transmission to measure the bit error rate (BER) at the receiver. The same PN sequence is generated at the receiver and then compared with the transmitted data, measuring the BER. Thirty-six LED modules are classified into six parallel groups, and each group comprises six LEDs connected in series; all 36 LEDs are driven by a single power field effect transistor (IRF530A). Figure 6 shows the encoded signal with 30% brightness. Transmitted data, PWM/VPPM encoded data, and decision clock and recovered data is displayed in sequence. The decision clock shown in Fig. 6 is achieved from the algorithm explained in Fig. 4. As reflected in Fig. 6, the transmitted data is recovered regardless of the brightness.

Figure 7 shows the performance of the transmission. Figure 7(a) corresponds to the BER of transmissions using different colors. The brightness is fixed at 50% in this experiment. A BER of 10^{-6} is measured with red or blue at 290 cm, while the same BER is found at 270 cm with green, which is attributed to the colors having different PD responsivity. Transmission with varying colors is also successfully demonstrated. An example of a mixed color is white, which is achieved by making the PWs of RGB LEDs nearly equal. Figure 7(b) shows the BER of white light

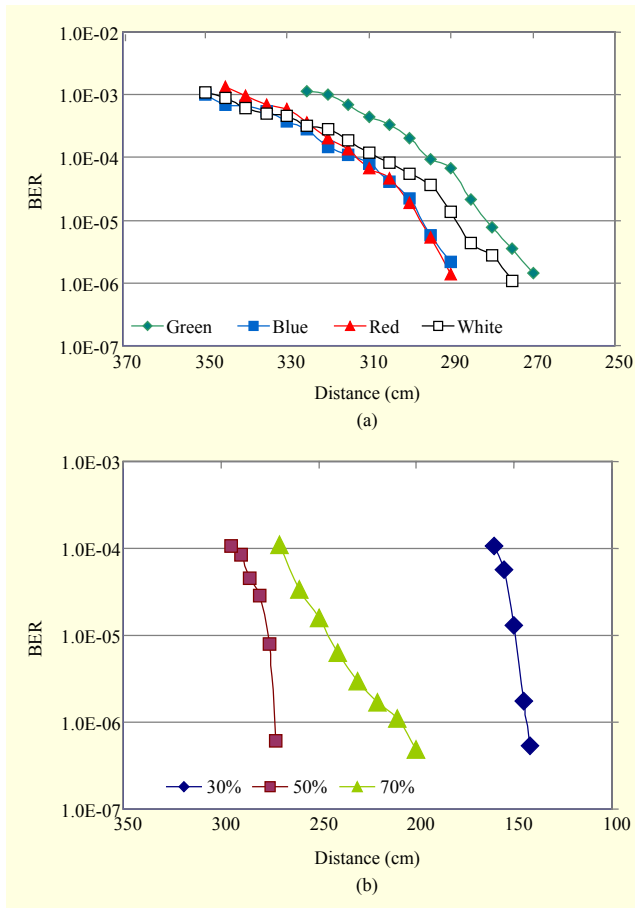


Fig. 7. BER of proposed scheme with different colors and degrees of brightness: (a) colors and (b) brightness.

achieved by PWM of RGB LEDs, but with different degrees of brightness. In this experiment, a transmission with 50% brightness shows the best result, close to that of the white light, shown in Fig. 7(a). A transmission with 70% brightness shows a worse BER. At a BER of 10^{-6} , the possible transmission distance is 60 cm shorter than that of the transmission with 50% brightness, which is due to narrow PW in VPPM for signal “0.” The worst BER is observed with 30% LED brightness, which is attributed to a narrow PW in VPPM for signal “1” and low optical power.

It is found that both pulse symmetry and intensity affect the BER. Since a data decision is made at a specific time for each bit, a symmetric pulse, such as 50% brightness, can provide better stability. Less brightness means a lower level in a bit period, which leads to a lower SNR. An increased data rate results in degradation of the performance of the VPPM signal because the lower level in the bit period causes a lower SNR. Although the transmission is not disconnected during the dimming control, a variation in performance is seen. The performance gap for different degrees of brightness is lessened by adopting an appropriate filter at the receiver, which is a topic

for further study.

IV. Conclusion

We successfully demonstrated visible light wireless optical communication while controlling color and brightness of LEDs by using PWM coding and VPPM coding. Seamless transmission was achieved against continuous change of color and brightness. Variance in transmission performance was monitored due to the alteration of received optical power and pulse shape. The difference can be compensated for by adjusting the data rate via dimming. With the wide application of emotional lighting, the proposed scheme is a notable candidate for delivering data using LED light.

References

- [1] IEEE 802.15.7, IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specification for Visible Light Wireless Personal Area Networks (WPANs), IEEE, 2011.
- [2] S. Haruyama, “Visible Light Communications,” *Proc. ECOC*, 2010, pp. 1-22.
- [3] H. Sugiyama, S. Haruyama, and M. Nagagawa, “Experimental Investigation of Modulation Method for Visible-Light Communications,” *IEICE Trans. Commun.*, vol. E89-B, no. 12, Dec. 2006, pp. 3393-3400.
- [4] J. Vucic and K.-D. Langer, “High-Speed Visible Light Communications: State-of-the-Art,” *Proc. OPC*, Mar. 2012, OTh3G.3.
- [5] H.L. Minh et al., “High-Speed Visible Light Communications Using Multiple-Resonant Equalization,” *IEEE Photon. Tech. Lett.*, vol. 20, no. 14, 2008, pp. 1243-1245.
- [6] D. Lee et al., “Visible Light Wireless Communications Based on Predistorted OFDM,” *Opt. Commun.*, vol. 285, Apr. 2012, pp. 1767-1770.
- [7] P. Das et al., “Color-Independent VLC Based on a Color Space without Sending Target Color Information,” *Opt. Commun.*, vol. 286, Jan. 2012, pp. 69-73.
- [8] M. Dyble et al., “Impact of Dimming White LEDs: Chromaticity Shifts Due to Different Dimming Methods,” *Proc. SPIE*, vol. 5941, Sept. 2005, pp. 1H1-1H9.
- [9] K. Lee and H. Park, “Modulations for Visible Light Communications with Dimming Control,” *IEEE Photon. Tech. Lett.*, vol. 23, no. 16, 2008, pp. 1136-1138.
- [10] K. Choi et al., “Visible Light Communications with Color and Dimming Control by Employing VPPM Coding,” *Proc. ICUFN*, July 2012, pp. 10-12.