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Performance of dimming control scheme in visible light communication system

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Abstract: We investigate the performance of visible light communication (VLC) system with a pulse width modulation (PWM) dimming control scheme. Under this scheme, the communication quality in terms of number of transmitted bits and bit error rate (BER) of less than 10^{-3} should be guaranteed. However, for on-off-keying (OOK) signal, the required data rate becomes 10 times as high as the original data rate when the duty cycle of dimming control signal is 0.1. To make the dimming control scheme easy to be implemented in VLC system, we propose the variable M-QAM OFDM VLC system, where M is adjusted according to the brightness of LED light in terms of duty cycle. The results show that with different duty cycles the required data rates are not higher than the original value and less LED lamp power is required to guarantee the communication quality, which makes the dimming control system that satisfies both communication and illumination requirements easy to be implemented and power-saving.

OCIS codes: (230.3670) Light-emitting diodes; (060.4510) Optical communications; (060.4080) Modulation; (999.9999) Dimming control.

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1. Introduction

Visible light communication (VLC) using light-emitting diodes (LEDs) offers many advantages [1–8], including low power assumption, high data rate, safety and not being prone to be radio frequency (RF) interference [1–8], which make VLC be an attractive solution for the access of home area networks (HAN) [1, 2]. In indoor VLC system, illumination and communication are two functions of the LED. The brightness of LED light should be adjusted for the convenience of illumination for work and study. In addition, dimming the brightness of LED light is also for the consideration of saving energy [9]. Pulse width modulation (PWM) is widely used as a dimming control technique [9, 10], where the brightness of LED light is changed by adjusting the duty cycle of PWM signal without varying the LED current.

During the "on" period of the PWM dimming control signal, the optical signal is not affected; however, during the "off" period, the optical signal could not be transmitted. Hence, the total number of transmitted bits is reduced, which deteriorates the VLC system performance. In order to maintain the communication quality in terms of the number of transmitted bits under dimming control scheme, the data rate of the modulating signal should be adjusted when the duty cycle of PWM dimming control signal is changed. Consequently, the noise power in terms of data rate and therefore the bit error rate (BER) performance are affected.

In this paper, firstly we investigate the performance of on-off-keying (OOK) signal under dimming control scheme. Results show that the required data rate is inversely-proportional to the duty cycle to satisfy the communication quality in terms of number of bits and BER. When the duty cycle of PWM dimming control signal is 0.1, the required data rate has to be 10 times as high as the original data rate. Such increase in data rate is not easy to be implemented on the original circuit. In addition, our study reveals that since the LED lamp power should remain constant under the dimming control scheme, in order to achieve BER of 10^{-3} for the whole duty cycle range of 0.1 to 1, the required LED lamp power has to be increased significantly when applying dimming control, which is power-consuming. To solve this problem, we propose to use an advanced modulation format, variable multi-level quadrature amplitude modulation (M-QAM) orthogonal frequency division multiplexing (OFDM), in the VLC system, where M (number of points in each signal constellation [11]) is adjusted according to the changed duty cycle firstly, followed by the change of symbol rate. The impact of modulation index to dimming control scheme is also discussed. Note that the adjustment of modulation format and symbol rate is widely used in wireless communications [11]. The simulation results reveal that the required symbol rates of M-QAM OFDM are always not larger than the original symbol rate, but larger than the half of the original symbol rate, which makes the dimming control scheme easy to be implemented. Moreover, the corresponding required LED lamp power to achieve BER of 10^{-3} for the whole duty cycle range of 0.1 to 1 is much less than that of OOK signal, which is power-saving.

The rest of this paper is organized as follows. The principle of dimming control scheme in VLC system is described in Section 2. Section 3 describes the performance of OOK signal under the dimming control scheme. The performance of variable M-QAM OFDM signal under the dimming control scheme is given in Section 4. Section 5 gives the conclusions.

2. Principle of dimming control in VLC system

The Lambertian radiation pattern is applied to model the LED radiant irradiance [6, 7]:

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$$R(\varphi)=\frac{(m+1)\cos^{m}(\varphi)}{2\pi}, \tag{1}$$

where φ is the angle of irradiance from the LED, m is the order of Lambertian emission defined by the LED's semi-angle at half power $\varphi_{1/2}$, which is $m = \ln(1/2) / \ln(\cos(\varphi_{1/2}))$. Hence the channel direct current (DC) gain is described by [5, 7]

$$H(0)=\frac{R(\varphi)\cos(\theta)A}{d^{2}}=\frac{(m+1)\cos^{m}(\varphi)A\cos(\theta)}{2\pi d^{2}}, \tag{2}$$

where d is the distance between LED and the photo-detector, A is the physical area of photo-detector, and θ is the angle of incidence. Note that in this paper the LED lamp points vertically to the plane where the photo-detector is located.

After modulation, the optical signal at the output of an LED lamp is given by $p(t)=P_t\left(1+M_{index}f(t)\right)$, where P_t is the LED lamp output power without modulation, M_{index} is the modulation index [12] and $f(t)$ is the normalized modulating signal. The modulation index is defined as the ratio of the LED's maximum current variation caused by the modulating signal to the LED bias current. The received carrier power is given by

$$P_r = H(0)P_t. \tag{3}$$

After photo-detection, considering that the DC component of the detected electrical signal is filtered out in the receiver, the output electrical signal is given by $s(t)=RP_rM_{index}f(t)+n(t)$, where R is the responsivity of the photo-detector and $n(t)$ is the additive white Gaussian noise (AWGN). Hence, the SNR of the output electrical signal is given by [7],

$$SNR=\frac{\left(RH(0)P_tM_{index}\right)^{2}\overline{f(t)^{2}}}{\sigma^{2}}, \tag{4}$$

where $\overline{f(t)^{2}}$ is the average power of normalized signal. The noise variance σ^2 consists of both shot noise and thermal noise, whose variances are given by [5],

$$\sigma_{shot}^{2}=2q\left[RP_r\left(1+\overline{\left(M_{index}f(t)\right)^{2}}\right)+I_{bg}I_2\right]B, \tag{5}$$

$$\sigma_{thermal}^{2}=8\pi kT_K\eta AB^{2}\left(\frac{I_2}{G}+\frac{2\pi\Gamma}{g_m}\eta AI_3B\right). \tag{6}$$

where $P_r\left(1+\overline{\left(M_{index}f(t)\right)^{2}}\right)$ is the total received power, q is the magnitude of electron charge [13], B is the equivalent noise bandwidth, k denotes the Boltzmann constant, and T_k represents the absolute temperature. The parameters shown in Eqs. (1-6) and other parameters in VLC system are listed in Table 1.

As shown in Fig. 1(a), the LED current is modulated by PWM signal to control its brightness by changing the 'on' duration of the whole period. So the light is dimming during the whole period of PWM signal. And then the data is modulated onto the dimming-controlled light in the 'on' duration only, and no light should be transmitted in the 'off' duration as depicted in Fig. 1(b). Since the LED current remains constant, the brightness of LED light is changed by applying PWM dimming control signal to adjust its 'on' duration of the whole period. When the duty cycle of PWM signal is 1, all the LED light will be transmitted and the light is of the highest brightness. When the duty cycle is reduced, the LED light that appears

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in the 'off' duration is blocked. Hence the light is dimming during the whole period of PWM signal, and the light is not transmitted during the 'off' period as is shown in Fig. 1(b) for the case of 0.6-duty cycle. In some situations, as shown in Fig. 1(a), the modulation format of modulating signal will be affected by the PWM dimming control signal, which will be discussed in Section 4. Note that the frequency of PWM signal should not be too low, as this would give negative impact on human healthy [14].

Table 1. Parameters of VLC system configuration.

Room size (length × width × height)	5 m × 5 m × 3 m
Height of desk where the receiver is located	0.85 m
Transmitter's semi-angle at half power ($\varphi_{1/2}$)	60 °
Physical area of photo-detector (A)	10^{-4} m^2
Receiver's field of view (FOV)	170 °
Responsivity of photo-detector (R)	1 A/W
Background current (I_{bg})	5100 μA
Noise bandwidth factor (I_2)	0.562
Field-effect transistor (FET) transconductance (g_m)	30 mS
FET channel noise factor (Γ)	1.5
Fixed capacitance (η)	112 pF/cm^2
Open-loop voltage gain (G)	10
I_3 [15]	0.0868
Location of LED lamp	[2.5, 2.5, 3.0]
Location of user	[3.75, 1.25, 0.85]

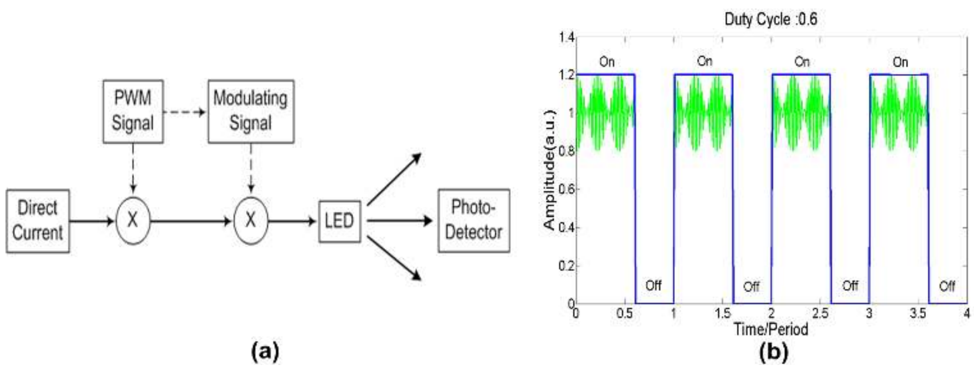

Fig. 1. (a) Schematic, (b) waveform in VLC system with dimming control.

3. Performance of bipolar OOK signal under dimming control scheme in VLC system

As described in Section 2, under the dimming control scheme the duration of data transmission in one PWM dimming control signal period (T) is reduced from 1, compared with the case without dimming control. Although the BER performance in the 'on' duration of PWM dimming control signal is not changed, in the whole PWM period the number of transmitted bits would be reduced, which actually reduces the average data rate. In order to solve this problem, the data rate should be increased accordingly when the LED light is dimming, and the number of transmitted bits should remain unchanged. Thus, we have

$$R_1 TD = R_0 T$$
$$R_1 = \frac{R_0}{D}, \tag{7}$$

where R represents the bit rate of bipolar OOK signal, and D denotes the duty cycle of PWM dimming control signal. The subscripts "0" and "1" in Eq. (7) correspond to the situations without and with dimming control, respectively. The adaptive data rate under dimming control scheme is shown in Fig. 2(a). In this section, we assume that the original data rate R_0 of OOK signal is 50 Mbit/s without dimming control. As depicted in Fig. 2(a), under the

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dimming control scheme the adaptive data rate is inversely-proportional to the duty cycle of PWM dimming control signal in order to make the number of transmitted bits constant. Hence, the adaptive data rate R_1 will be higher than the original data rate R_0 as the duty cycle becomes smaller. For example, when duty cycle is 0.1, the adaptive data rate is 10 times higher than the original data rate, which makes the system hard to be implemented on the original circuit.

The BER performance of bipolar OOK signal is given by [16],

$$BER = Q\left(\sqrt{2SNR}\right), \tag{8}$$

where $Q(\cdot)$ is the Q-function. As described above, the signal power is not affected by the changing of duty cycle; however, the noise power in Eqs. (5)-(6) will be increased as the data rate grows when the duty cycle decreases, which deteriorates the BER performance in terms of SNR as shown in Eq. (8). Under dimming control scheme, the BER of less than 10^{-3} should be guaranteed, since the error-free transmission could be achieved by applying forward error correction (FEC) code [17] under this BER benchmark. The required LED lamp power without applying dimming control to achieve BER of 10^{-3} is derived by substituting Eq. (4) into Eq. (8),

$$\begin{aligned} BER = Q\left(\sqrt{2SNR}\right) &= Q\left(\sqrt{\frac{2\left(RH(0)P_t M_{index}\right)^2}{\sigma^2(P_t)}}\right) \\ &= Q\left(\frac{\sqrt{2}RH(0)P_t M_{index}}{\sigma(P_t)}\right). \end{aligned} \tag{9}$$

Note that the average power $\overline{f(t)^2}$ of bipolar OOK signal in Eq. (4) is unity and the noise variance σ^2 is related to the total received optical power P_r in terms of the LED lamp power P_t. Hence, by solving Eq. (9) the required LED lamp power without applying dimming control can be obtained, which is associated with both modulation index M_{index} and the noise variance, when the locations of LED lamp and receiver are fixed. Note that the required LED lamp power to achieve BER of 10^{-3} could not be changed under the dimming control scheme.

Figure 2(b) shows the required LED lamp power to achieve BER of 10^{-3} without applying dimming control versus the duty cycle. As shown in Fig. 2(b), when the duty cycle is reduced from 1 to 0.3, i.e., the illuminance of LED light is reduced to 30% of the original illuminance, the required LED lamp powers without applying dimming control increase slowly to 2.0 W and 1.3 W for the modulation indices of 0.2 and 0.3, respectively. However, as the duty cycle is further reduced from 0.3 to 0.1, i.e., the illuminace of LED light is only 10% of the original illuminance, the required LED lamp power without applying dimming control grows drastically from 2.0 W to 7.8 W when the modulation index is 0.2 and grows from 1.3 W to 5.2 W when the modulation index is 0.3. Since the LED lamp power should remain constant under the dimming control scheme, in order to achieve BER of 10^{-3} for the whole duty cycle range of 0.1 to 1, the required LED lamp power should be set at as high as 7.8 W if the modulation index is 0.2, and at 5.2 W if the modulation index is 0.3. In this way, when the dimming control scheme is applied, the LED lamp power would remain constant and the BER of 10^{-3} can be guaranteed. The above results reveal that the OOK VLC system with dimming control scheme is power-consuming if communication quality should be guaranteed for the whole duty cycle range of 0.1 to 1.

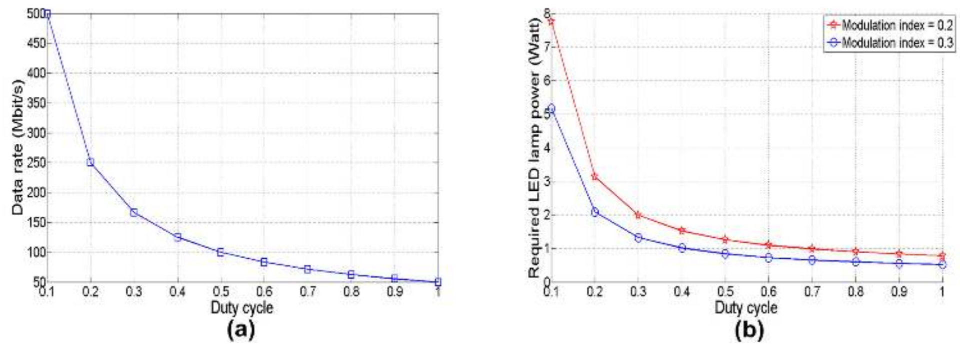

Fig. 2. (a) Adaptive data rate versus the duty cycle, (b) the required LED lamp power to achieve BER of 10^{-3} without applying dimming control in OOK VLC system versus the duty cycle.

4. Performance of variable M-QAM OFDM signal under dimming control scheme in VLC system

As discussed in Section 3, the adaptive data rate of OOK signal is inversely-proportional to the duty cycle of PWM dimming control signal which makes the system hard to be implemented on the original circuit when the duty cycle is small. In addition, there is a large difference between the required LED lamp powers to achieve BER of 10^{-3} without applying dimming control under different duty cycles, which makes the dimming control scheme not power-saving. In order to solve these problems, we here propose to use an advanced modulation format, M-QAM, where M represents the number of points in each signal constellation [11], and apply OFDM with Hermitian symmetry to carry the M-QAM signal [18]. Since one symbol of M-QAM signal carries $\log_2(M)$ bits, the total number of transmitted bits could remain the same without increasing the original symbol rate, when higher level M-QAM is used. Under dimming control scheme when the duty cycle decreases, the value of M should be adjusted, followed by the changing of symbol rate to make sure that (*i*) the number of transmitted bits is constant and (*ii*) the adaptive symbol rate R_1 is not larger than the original symbol rate R_0. Let M_0 be the initial number of points in each signal constellation, which is 4 in this section and M_1 be the adaptive number of points in each signal constellation. Hence, we have

$$M_1 R_1 T D = M_0 R_0 T$$
$$R_1 = \frac{M_0 R_0}{M_1 D}. \tag{10}$$

In this section, the original symbol rate R_0 of M-QAM signal is also assumed to be 50 Msymbol/s without dimming control.

The BER performance of M-QAM is given by [11],

$$BER \le 0.2\exp\left(-1.5\overline{\gamma}/\left(M-1\right)\right). \tag{11}$$

where $\overline{\gamma}$ denotes the average SNR per symbol, Eq. (11) is a tighter bound good to within 1 dB [11], which is valid when

$$\begin{cases} 0 \le \overline{\gamma} \le 30\, dB, \\ M \ge 4. \end{cases} \tag{12}$$

The required LED lamp power without applying dimming control for M-QAM is obtained by substituting Eq. (4) in to Eq. (11),

$$BER \le 0.2\exp\left(\frac{-1.5\left(RH\left(0\right)P_t M_{index}\right)^2}{\left(M-1\right)\sigma^2\left(P_t\right)}\right). \tag{13}$$

Note that the average power $\overline{f\left(t\right)^2}$ of M-QAM signal in Eq. (4) is also unity. Hence the required LED lamp power to achieve BER of 10^{-3} without applying dimming control of M-QAM signal is obtained by solving Eq. (13). According to the relationship between the adaptive symbol rate R_1 and the original symbol rate R_0 in Eq. (10), the values of M_1 in Eq. (10) under different duty cycles are listed in Table 2. As shown in Fig. 3(a), all the adaptive symbol rates are in the range between half of R_0 (25 Msymbol/s) and R_0 (50 Msymbol/s), i.e., if the value of M_1 in Table 2 is halved, the adaptive symbol rate will be larger than the original rate (50 Msymbol/s). Hence, we see that with the variable M-QAM OFDM scheme, when the light is dimming, the adaptive symbol rate only decreases within 50% of the original symbol rate, which is much easier to be implemented on the original circuit than that of OOK signal.

Table 2. Relationship between M_1 and duty cycle for variable M-QAM with dimming control

Duty cycle	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
M_1	64	32	16	16	8	8	8	8	8	4

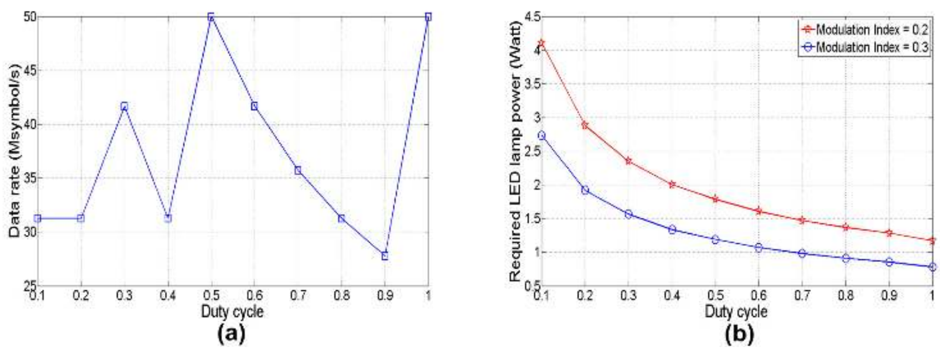

Fig. 3. (a) Adaptive symbol rate of MQAM signal versus the duty cycle, (b) the required LED lamp power to achieve BER of 10^{-3} without applying dimming control versus the duty cycle.

Figure 3(b) shows that the required LED lamp power to achieve BER of 10^{-3} for M-QAM OFDM signal without applying dimming control versus the duty cycle. As shown in Fig. 3 (b), the required LED lamp power grows smoothly as the duty cycle decreases. For example, when the duty cycle is 0.1, the required LED lamp powers without applying dimming control are 4.1 W and 2.7 W for the modulation indices of 0.2 and 0.3, respectively, which are 3.7 W and 2.5 W smaller than the corresponding LED lamp powers of the bipolar OOK signal shown in Fig. 2(b). Since the LED lamp power should remain constant under the dimming control scheme, in order to achieve BER of 10^{-3} for the whole duty cycle range of 0.1 to 1, the required LED lamp power should be set at 4.1 W if the modulation index is 0.2, and at 2.7 W if the modulation index is 0.3. In this way, when the dimming control scheme is applied, the LED lamp power would remain constant and the BER of 10^{-3} can be guaranteed. As lower LED lamp power is required, the variable M-QAM VLC system with dimming control scheme is much more power-efficient than the OOK VLC system. From (12) we know that all the SNRs should be in the range between 0 dB and 30 dB. As depicted in Fig. 4, the required SNR to achieve BER of 10^{-3} varies from 10.3 dB to 23.5 dB, when the duty cycle decreases from 1 to 0.1. Hence, the result in Fig. 3(b) can meet the requirement.

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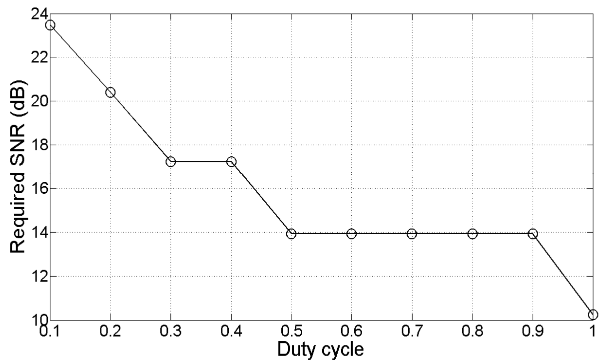

Fig. 4. Required SNR to achieve BER of 10^{-3} in variable M-QAM VLC system under dimming control scheme.

5. Conclusion

We have investigated and analyzed the performance of VLC system under dimming control scheme. To maintain the communication quality in terms of number of transmitted bits and a BER of less than 10^{-3}, the data rate has to be increased when the duty cycle of PWM dimming control signal is reduced, i.e., the LED light is dimming. In the OOK VLC system, when the duty cycle is smaller than 0.3, on the one hand the data rate has to be increased largely, which makes it difficult to be implemented on the original circuit; on the other hand, the required LED lamp power to achieve BER of 10^{-3} for the whole range of duty cycle also has to be increased significantly, which is power-consuming. To solve the problem, we have proposed to apply the variable M-QAM OFDM to VLC systems, where the *M* is changed firstly according to the duty cycle, followed by adjusting the symbol rate. Results have shown that the required symbol rates are always not larger than the original symbol rate and larger than half of the original symbol rate, which guarantees the communication quality as well as makes the dimming control scheme easy to be implemented in the real VLC system. In addition, the required LED lamp power to achieve BER of 10^{-3} is much less than that of OOK signal, which is power-saving.

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