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Volume 10, Number 5, September 2018

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DOI:10.1109/JPHOT.2018.2868485
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Manuscript received August 10, 2018; revised August 27, 2018; accepted August 30, 2018. Date of publication September 3, 2018; date of current version September 21, 2018. This work was supported in part by National Key R&D Program of China under Grant 2016YFB0800302, and in part by National Natural Science Foundation of China under Grant 61771062. Corresponding author: Yaojun Qiao (e-mail: qiao@bupt.edu.cn).

Abstract: In this paper, the efficient dimming control systems based on single-carrier frequency-division multiplexing (SCFDM) are proposed for visible light communications (VLC). By virtue of the strengths of the low peak-to-average power ratio and the inherent resistance to high-frequency distortion, the proposed SCFDM-based dimming control schemes are adaptive to the bandwidth-limited and linearity-limited VLC system, thus supporting the wide dimming range for different illumination requirements. Two SCFDM-based VLC systems with dimming control including asymmetrical hybrid optical SCFDM (AHO-SCFDM) and DC-biased optical SCFDM (DCO-SCFDM) are proposed. For AHO-SCFDM with spectral efficiency of 1.75 bit/s/Hz and DCO-SCFDM with spectral efficiency of 2 bit/s/Hz, the 20% wider dimming range can be achieved than their orthogonal frequency-division multiplexing (OFDM) based counterparts, respectively. Meanwhile, the two proposed schemes can also achieve 24.8% and 31.3% gains of average spectral efficiency under the same dimming range compared with their counterparts, respectively. For an overall analysis, SCFDM shows the feasibility and superiority for dimming control systems.

Index Terms: Visible light communication, light emitting diode, dimming control, orthogonal frequency-division multiplexing, single-carrier frequency-division multiplexing.

1. Introduction
Visible light communication (VLC) has emerged as a complementary access technology for the fifth generation (5G) and beyond wireless communication owing to its numerous advantages [1]–[3]. The enormous license-free spectrum resource can alleviate the imminent spectrum crunch.
of radio-based wireless communications. The high-level privacy and immunity to electromagnetic interference also make it attractive for some special occasions [4]. With a particular concern, VLC can support simultaneous illumination and communication, which is eco-friendly and energy-efficient [5], [6]. Therefore, the VLC technology with dimming control attracts the extensive attention from academia and industry.

Many modulation schemes, such as pulse width modulation (PWM) [6], pulse position modulation (PPM) [7] and on-off keying (OOK) [8], have been applied to provide dimming control in VLC systems straightforwardly. Recently, in order to effectively resist the inter-symbol interference (ISI) and achieve high spectral efficiency transmission, orthogonal frequency-division multiplexing (OFDM) based dimmable VLC schemes are widely investigated [9]–[14]. In [9], multi-PPM (MPPM) dimming control pulses are combined with OFDM signals to achieve efficient data transmission and alleviate the receiver sensitivity requirement. Additionally, the dimmable VLC systems are achieved by combining the industry-preferred PWM with OFDM [10]–[12]. Recently, for satisfying high spectral efficiency transmission as well as low-complexity dimming control simultaneously, Wang et al. [5] proposed the first asymmetrical hybrid optical OFDM (AHO-OFDM) scheme by combining asymmetrical clipped optical OFDM (ACO-OFDM) signal and inverted pulse-amplitude-modulated discrete multitone (PAM-DMT) signal flexibly. This scheme can achieve the efficient dimming control as well as higher spectral efficiency than ACO-OFDM scheme. Moreover, some performance-enhancement dimmable VLC systems are also proposed, such as multilayer ACO-OFDM dimmable system [13] and hybrid spacial modulation based dimmable system with multilayer ACO-OFDM [14].

However, in the existed OFDM-based dimmable VLC systems, there still are two key problems lacking adequate consideration. One is high peak-to-average power ratio (PAPR) of OFDM signal. In the linearity-limited VLC systems, the high-PAPR OFDM signals suffer serious clipping and quantization distortions [15], [16]. At the low or high dimming level, OFDM-based dimmable VLC systems are hard to support the efficient communication due to the serious clipping and quantization distortions. The other is the distortion on the high-frequency subcarriers of OFDM signal caused by bandwidth-limited devices and multi-path fading channel [17]. The high-frequency distortions severely deteriorate the performance of VLC systems. Therefore, how to effectively handle these two issues is very important for dimmable VLC systems. However, as far as we know, there are few OFDM-based dimmable schemes to effectively overcome these barriers up to now [9]–[14].

In this paper, to the best of our knowledge, we first propose the efficient single-carrier frequency-division multiplexing (SCFDM) based dimming control systems, including asymmetrical hybrid optical SCFDM (AHO-SCFDM) and DC-biased optical SCFDM (DCO-SCFDM) for VLC. Compared to conventional OFDM-based ones, the proposed SCFDM-based dimmable VLC systems fundamentally reduce the impact of the drawbacks mentioned above owing to the advantages of lower PAPR and better resistance to the high-frequency distortions, thus supporting the wide dimming range for different illumination requirements. For AHO-SCFDM with spectral efficiency of 1.75 bit/s/Hz and DCO-SCFDM with spectral efficiency of 2 bit/s/Hz, the 20% wider dimming range can be achieved than their OFDM-based counterparts, respectively. Meanwhile, under the same dimming range, the 24.8% and 31.3% gains of average spectral efficiency for two proposed schemes can also be achieved compared with their counterparts, respectively.

The remainder of this article is organized as follows. In Section 2, the model of VLC system with dimming control is introduced. In Section 3, AHO-SCFDM based dimming control system for VLC is shown and discussed, and DCO-SCFDM based dimming control system for VLC is presented and discussed in Section 4. Finally, the article concludes in Section 5.

2. Model of VLC System With Dimming Control

Fig. 1(a) depicts the schematic diagram of VLC system with simultaneous illumination and communication. Since LEDs used in VLC system are incoherent sources, the electrical signal is modulated into the instantaneous optical power. Thus, intensity-modulation and direct-detection (IM/DD) is generally employed in VLC system, which requires the transmitted signal to be non-negative and real-valued [17]. Moreover, as the energy-saving lighting equipment, LEDs are required to
support different dimming levels as practical environment changes. However, LEDs exist the serious nonlinear characteristics restricting the communication performance of system. Fortunately, many nonlinear mitigation methods such as lookup table-based pre-distortion [18] and Volterra-based post-equalization [19], have been proposed to reduce the effect of nonlinearity. Then, the quasi-linear transfer function with double-clipped characteristic, as depicted in Fig. 1(b), is commonly employed to model the effect of LED. Then, the transmitted optical power can be given by

\[
P_{t,\text{opt}} = \begin{cases} 
P_{\text{Max, opt}}, & V_t > V_{\text{MP}}, \\ 
\gamma (V_t - V_{\text{TOV}}), & V_{\text{TOV}} < V_t \leq V_{\text{MP}}, \\ 
P_{\text{Min, opt}}, & V_t \leq V_{\text{TOV}} 
\end{cases}
\]

where \(P_{\text{Min, opt}}\) and \(P_{\text{Max, opt}}\) are the minimum and maximum output optical powers, respectively. \(V_t\) is the instantaneous input voltage and \(\gamma\) represents the electrical-to-optical (E/O) conversion coefficient. \(V_{\text{TOV}}\) and \(V_{\text{MP}}\) are the turn-on voltage and the maximum permissible voltage of LED, respectively. Then, the dynamic input range of LED is denoted as \([V_{\text{TOV}}, V_{\text{MP}}]\). Beyond the range, the amplitude of signal will be clipped. Generally, the illumination level depends on the average transmitted optical power [5]. For simplification, the normalized dimming level is defined as

\[
\eta = \frac{E(P_{t,\text{opt}}) - P_{\text{Min, opt}}}{P_{\text{Max, opt}} - P_{\text{Min, opt}}}
\]

where \(E(\cdot)\) is statistical expectation.

3. AHO-SCFDM Based Dimming Control System for VLC

Fig. 2 depicts the transmitter structure of AHO-SCFDM based dimming control system for VLC. The AHO-SCFDM scheme is achieved by combining two asymmetrical clipped optical SCFDM (ACO-SCFDM) encoding layers with opposite polarity. It is divided into encoding unit and dimming control unit. In the encoding unit, the incoming pseudo random bit sequence is separately mapped into gray-coded \(M\)-PAM symbols for upper and lower encoding layers.

3.1 Principle and Basic Properties of AHO-SCFDM

For generating real-valued ACO-SCFDM at the upper encoding layer, conventional encoding processes include \(N/2\)-point discrete Hartley transform (DHT) spread, odd-subcarrier mapping, \(N\)-point DHT-based multiplexing and zero-clipping operations. It has high computational complexity.
of $O(N \log_2 N)$, which is a challenge for cost- and energy-sensitive VLC systems. Fortunately, the simplified ACO-SCFDM encoding method has been proposed in our previous work [20], [21]. The real-valued output after $N$-point DHT can be simplified as

$$X_{SCFDM,R}(i) = \begin{cases} \frac{[X(i)C(i) + X(N/2 - i)S(i)]}{\sqrt{2}}, & 0 \leq i \leq N/2 - 1, \\ \frac{[X(i - N/2)C(i) + X(N - i)S(i)]}{\sqrt{2}}, & N/2 \leq i \leq N - 1 \end{cases}$$  \tag{3}$$

where $X(i)$ is the input $M$-PAM symbol of upper layer, $C(i) = \cos(2\pi i/N)$ and $S(i) = \sin(2\pi i/N)$. Moreover, anti-symmetrical property can be found for $X_{SCFDM,R}$. Thus, the ACO-SCFDM encoding processes are equivalent to a $N/2$-point simplified encoding, that is $X_{U1}(i) = X_{SCFDM,R}(i)$, $(0 \leq i \leq N/2 - 1)$, plus an anti-symmetric operation and zero-clipping for generating non-negative signals with length of $N$-point.

At the lower ACO-SCFDM encoding layer, the similar principle as the upper layer is used. Notably, $M$-PAM symbols in the lower layer are assigned to the subcarriers with sequence numbers of $2(2i + 1)$, $(i = 0, 1, \ldots, N/4 - 1)$, while symbols at the upper layer are arranged to the subcarriers with the number of $i$, $(i = 1, 3, \ldots, N - 1)$. One can observe that an additional quarter of subcarriers are used for carrying the information, which increases the spectral efficiency of system. Moreover, the resultant clipping signal at the lower layer is repeated two times for ensuring the same length of signal as that at the upper layer.

After inserting cyclic prefixes (CPs) at two ACO-SCFDM encoding layers, the resultant signals, $X_{U2}$ and $X_{L2}$, are normalized and suitably scaled to $X_U$ and $X_L$, respectively. Then, subtraction operation of $X_U$ and $X_L$ is implemented for taking full advantage of the dynamic range of LED and achieving the effective dimming control of VLC system. The output signal of the dimming control unit is denoted as AHO-SCFDM. Eventually, the AHO-SCFDM signal is superimposed to DC voltage via Bias-tee to yield:

$$X_S = X_U - X_L + V_{DC} \tag{4}$$

where $X_U$ and $X_L$ are defined as

$$X_U = \frac{X_{U2}}{\sigma_{RMS,X_{U2}}} \times \frac{V_U - V_{DC}}{\beta_U}, \quad X_L = \frac{X_{L2}}{\sigma_{RMS,X_{L2}}} \times \frac{V_{DC} - V_L}{\beta_L} \tag{5}$$

where $\sigma_{RMS,X_{U2}}$ and $\sigma_{RMS,X_{L2}}$ are the root mean square (RMS) values of $X_{U2}$ and $X_{L2}$, respectively. $V_L$ and $V_U$ are the lower and upper bounds in dynamic range of LED. $V_{DC}$ is DC-bias voltage. $\beta_U$ and $\beta_L$ are the scaling factors of $X_{U2}$ and $X_{L2}$, respectively. Substituting Eq. (4) and (5) into (2), the normalized dimming level can be revised as

$$\eta = \frac{1}{V_U - V_L} \left[ 1 - \frac{E(X_{U2})}{\sigma_{RMS,X_{U2}}\beta_U} - \frac{E(X_{L2})}{\sigma_{RMS,X_{L2}}\beta_L} \right] \cdot V_{DC} + \frac{E(X_{U2})V_U}{\sigma_{RMS,X_{U2}}\beta_U} + \frac{E(X_{L2}V_L)}{\sigma_{RMS,X_{L2}}\beta_L} \right]. \tag{6}$$
It can be found that the different $\eta$ can be achieved by jointly adjusting the signal amplitudes and bias voltage. Furthermore, a certain communication quality should also be guaranteed besides ensuring the primary illumination function in LED-based VLC systems. The spectral efficiency of AHO-SCFDM can be calculated by

$$\xi_{SC} = \frac{\log_2 M_{U,SC}}{2} + \frac{\log_2 M_{L,SC}}{2 \times 2} = \frac{2\log_2 M_{U,SC} + \log_2 M_{L,SC}}{4}$$ (7)

where $M_{U,SC}$ and $M_{L,SC}$ are the modulation orders of PAM constellation at the upper and lower layers of AHO-SCFDM scheme, respectively.

In comparison, AHO-OFDM scheme combines $M$-QAM modulated ACO-OFDM at the upper layer and $M$-PAM modulated PAM-DMT at the lower layer [5]. It demonstrates that the dimmable scheme can achieve a wide dimming range with a small throughput fluctuation compared to DCO-OFDM and ACO-OFDM schemes. Its spectral efficiency can be calculated by

$$\xi_{O} = \frac{\log_2 M_{U,O}}{2 \times 2} + \frac{\log_2 M_{L,O}}{2 \times 2} = \frac{\log_2 M_{U,O} + \log_2 M_{L,O}}{4}$$ (8)

where $M_{U,O}$-QAM and $M_{L,O}$-PAM constellations are modulated at the upper and lower layers of AHO-OFDM scheme, respectively. Therefore, when $M_{U,O} = M_{U,SC}^2$, that is $M_{U,SC}$-PAM is used at the upper layer for AHO-SCFDM scheme and $M_{U,SC}^2$-QAM is used at the upper layer for AHO-OFDM scheme, the same spectral efficiency of system can be achieved where the same PAM modulation order is employed at the lower layer for the two schemes.

### 3.2 Simulation Results and Discussion

In this part, simulation results and discussion for AHO-SCFDM and AHO-OFDM dimmable VLC schemes are present.

According to [22], the PAPR is calculated by the ratio between the maximum instantaneous power and the average power of the discrete signals, that is:

$$\text{PAPR} = 10 \times \log_{10} \left[ \frac{\max(|X_S(i)|^2)}{E(|X_S(i)|^2)} \right] (\text{dB}).$$ (9)

The cumulative distribution function (CDF) is commonly used for characterizing the PAPR of signals. It is defined as the probability of PAPR lower than a threshold value, that is, $\text{CDF} = P_r(\text{PAPR} < \text{PAPR}_t)$. 

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**Fig. 3.** (a) Comparison of PAPR performance for AHO-SCFDM and AHO-OFDM with different spectral efficiencies; (b) Time-domain signal waveforms with the normalized power ($\xi = 2$ bit/s/Hz).
Fig. 3(a) shows the comparison of PAPR performance for AHO-SCFDM and AHO-OFDM when the spectral efficiencies are set to 2 and 3 bit/s/Hz, respectively. The subcarrier number is 256, and the number of symbols is $10^4$ in the simulation. Compared with AHO-OFDM, the PAPR of AHO-SCFDM has an improvement of $\sim 5.8$ dB when the spectral efficiency is 2 bit/s/Hz, and an improvement of $\sim 4.8$ dB when the spectral efficiency is 3 bit/s/Hz. Taking the two schemes with spectral efficiency of 2 bit/s/Hz as an example, the time-domain signal waveforms with the normalized power are illustrated in Fig. 3(b). The AHO-OFDM scheme has a wider amplitude range compared with the AHO-SCFDM scheme. Therefore, for both schemes with the same spectral efficiency, the low-PAPR AHO-SCFDM scheme will be more immune to the amplitude clipping from LED, thus ensuring the effective communication.

To investigate the communication performance of dimmable AHO-SCFDM scheme, simulations are conducted with the following parameters. The subcarrier number is set to 256, and the CP length is 16 for resisting the ISI. One frame consists of 1024 payload symbols and ten training symbols for channel estimation. The bandwidth of signal is set to 100 MHz. The dominate line-of-sight optical propagation link of VLC is considered. A low-pass filter with a 3-dB bandwidth of 10 MHz is used to model the typical low-pass response of VLC system, which is a rational approximation of the experimental result in [2]. The additive white Gaussian noise (AWGN) is employed to simulate the link noise including thermal noise and shot noise [23]. The noise figure is set to 0.0023. At the receiver side, direct detection and iterative reception [3] are adopted to decode the signals in two encoding layers. The decoding process is opposite to the encoding one where one-tap frequency-domain equalization is employed to compensate the channel distortion.

Note that like AHO-OFDM scheme, when the normalized dimming level, $\eta$, is greater than 50%, the polarity of signals at the upper and lower layers can be exchanged to ensure the effective communication, that is, $X_S = X_L - X_U + V_{DC}$. Owing to the quasi-linear dynamic range of LED, the symmetrical spectral efficiency can be achieved in the whole range of $\eta$. Thus, only half of dimming level range is discussed in the following.

For a target BER of $10^{-3}$, the achievable spectral efficiency versus the normalized dimming level for AHO-SCFDM and AHO-OFDM is depicted in Fig. 4. One can observe that, for each dimming level, AHO-SCFDM scheme can support the communication with higher spectral efficiency compared to AHO-OFDM. In the whole dimming range, the achievable average spectral efficiency gain can be calculated by $\sum_{\ell=1}^{L} (\xi^\ell_{SC} - \xi^\ell_{O}) / \sum_{\ell=1}^{L} \xi^\ell_{O}$, where $\xi^\ell_{SC}$ and $\xi^\ell_{O}$ are the achievable spectral efficiencies under the $\ell$-th dimming level for AHO-SCFDM and AHO-OFDM, respectively. $L$ is the total number of dimming levels. Compared with AHO-OFDM, the achievable average spectral efficiency gain of AHO-SCFDM is 24.8%. One reason is that the low-PAPR AHO-SCFDM signals

![Fig. 4. The achievable spectral efficiency versus the normalized dimming level for AHO-SCFDM and AHO-OFDM.](image-url)
are not susceptible to the clipped distortion, thus achieving a higher effective signal-to-noise ratio (SNR). The effective SNR is defined as $\text{SNR}_e = P_{CS}/(P_{AWGN} + P_{CN})$ where $P_{CS}$ is the power of clipped signal, $P_{AWGN}$ and $P_{CN}$ are the power of AWGN and the clipping noise, respectively. Another reason is that, AHO-SCFDM inherits the advantage of SCFDM in resisting the high-frequency distortions caused by the low-pass VLC channel characteristics [24]. Thus, AHO-SCFDM scheme is advantageous for the bandwidth-limited VLC. Furthermore, when modulation formats with certain modulation order are determined (i.e., $\xi$ is fixed), a wider adjustable illumination range can also be achieved for AHO-SCFDM by only changing the signal amplitudes and bias voltage conveniently. Fig. 4 shows that a 20% $(2 \times 10\%)$ wider adjustable brightness range for AHO-SCFDM can be obtained compared to AHO-OFDM when $\xi = 1.75$ bit/s/Hz.

To investigate the transmission performance of the proposed dimmable VLC scheme under the condition of certain bias voltage, BER performance versus different scaling factors $\beta_U$ and $\beta_L$ is compared for AHO-SCFDM and AHO-OFDM under the same spectral efficiencies in Fig. 5. Bias voltage is set to 0.15 and 0.45 to simulate the lower and higher bias conditions, respectively. Fig. 5(a) and (b) depict, when $V_{DC} = 0.15$ and $\xi = 1.75$ bit/s/Hz, our proposed AHO-SCFDM can achieve the FEC limit in a certain range of signal amplitudes while AHO-OFDM never reaches the limit. When $V_{DC} = 0.45$ and $\xi = 2$ bit/s/Hz, the same conclusions can be obtained as shown in Fig. 5(c) and (d). Thus, the proposed AHO-SCFDM based dimmable VLC scheme has a significant advantage compared to its counterpart.

4. DCO-SCFDM Based Dimming Control System for VLC
4.1 Principle and Basic Properties of DCO-SCFDM
Fig. 6 depicts the transmitter structure of DCO-SCFDM based dimming control system for VLC including DCO-SCFDM encoding unit and dimming control unit. In conventional low-PAPR
DCO-SCFDM encoding scheme, \( N/2 \)-point discrete Fourier transform (DFT) spread, odd-subcarrier mapping and \( N \)-point inverse DFT (IDFT) based multiplexing operations are used to generate complex-valued SCFDM signal. The processes have high computational complexity of \( O(N \log_2 N) \), which impedes the practical application in cost- and energy-sensitive VLC systems. To solve the difficulty of complexity, the simplified encoding algorithm is deduced in [25]. The complex-valued output after \( N \)-point IDFT is given by

\[
X_{\text{SCFDM},C}(k) = \begin{cases} 
X(k) \exp(j2\pi k/N)/2, & 0 \leq k \leq N/2 - 1, \\
X(k - N/2) \exp(j2\pi k/N)/2, & N/2 \leq k \leq N - 1 
\end{cases}
\]

(10)

where \( X(k) \) is the input \( M \)-QAM symbol. \( X_{\text{SCFDM},C} \) is anti-symmetric. Accordingly, extraction operation can be used to get the first-half of \( X_{\text{SCFDM},C} \) which contains all useful information. Therefore, the output of \( N/2 \)-point simplified encoding module \( X_C(k) \) is equivalent to \( X_{\text{SCFDM},C}(k) \) where \( 0 \leq k \leq N/2 - 1 \). The complexity of the module is only \( O(N) \), much lower than that of unsimplified one.

Consequently, complex-to-real transform (C2RT) operation is employed to transform the complex-valued signal to real-valued one, that is \( \text{C2RT}(\cdot) = [\mathbb{R}(\cdot), \mathbb{I}(\cdot)] \), where \( \mathbb{R}(\cdot) \) and \( \mathbb{I}(\cdot) \) are taking real and imaginary operations, respectively. The length of \( X_R \) is the same as that of \( X_{\text{SCFDM},C} \). Then, in the dimming control unit, the real-valued DCO-SCFDM signal \( X_R \) is normalized and scaled with the scaling factor of \( \beta \) to obtain \( X_1 \) as

\[
X_1 = \frac{X_R}{\sigma_{\text{RMS},X_R}} \times \frac{V_U - V_L}{\beta} 
\]

(11)

where \( \sigma_{\text{RMS},X_R} \) is the RMS value of \( X_R \). Then, \( X_1 \) is combined with DC bias by bias-tee to generate \( X_S \) for further E/O conversion. Substituting Eq. (11) into (2), the normalized dimming level of DCO-SCFDM scheme is revised as

\[
\eta = \frac{1}{V_U - V_L} \left[ \frac{V_U - V_L}{\sigma_{\text{RMS},X_R}} \cdot E(X_R) + V_{\text{DC}} - V_L \right].
\]

(12)

For DCO-SCFDM based dimming control system, only the odd subcarriers are employed for data transmission. Notably, Hermitian symmetry is not needed for real-valued DCO-SCFDM scheme owing to C2RT operation. Thus, the spectral efficiency of \( M \)-QAM modulated DCO-SCFDM can be calculated by

\[
\xi_{\text{SC}} = \log_2 M_{\text{SC}}/2
\]

(13)

where \( M_{\text{SC}} \) is the modulation order of QAM constellation in DCO-SCFDM scheme. Meanwhile, in DCO-OFDM scheme, Hermitian symmetry is needed for achieving the real-valued signals. Therefore, the spectral efficiency of \( M \)-QAM modulated DCO-OFDM is given by

\[
\xi_{\text{O}} = \log_2 M_{\text{O}}/2
\]

(14)
where $M_0$ is the modulation order of QAM constellation in DCO-OFDM scheme. That is, when the same modulation order of QAM symbol is set, the same spectral efficiency can be obtained for the two schemes.

### 4.2 Simulation Results and Discussion

In this part, we present simulation results and discussion for DCO-SCFDM and DCO-OFDM dimmable VLC systems.

Fig. 7(a) illustrates the comparison of PAPR performance for DCO-SCFDM and DCO-OFDM with different spectral efficiencies. The same simulation parameters are set with the AHO-SCFDM scheme in Section 3.2. For 16-QAM modulated DCO-SCFDM or DCO-OFDM schemes, the spectral efficiency is 2 bit/s/Hz. When 64-QAM is employed, the spectral efficiency is 3 bit/s/Hz. For DCO-SCFDM scheme, when $\xi = 2$ bit/s/Hz, a PAPR reduction of $\sim 7.8$ dB can be achieved compared to DCO-OFDM scheme. As well, a PAPR reduction of $\sim 6.8$ dB can be achieved when $\xi = 3$ bit/s/Hz. According to the definition of PAPR in Eq. (9), when the same average power of signal is adopted, the low-PAPR DCO-SCFDM has the smaller peak power. Taking 16-QAM modulated scheme as an example, the time-domain signal waveforms with the normalized power are depicted in Fig. 7(b). DCO-OFDM has a much wider range of signal amplitude than DCO-SCFDM when the same spectral efficiency is adopted. It means that DCO-OFDM is more vulnerable to the amplitude clipping than DCO-SCFDM in VLC system with limited linearity.

Besides the advantage of low PAPR, DCO-SCFDM also inherits the single-carrier characteristics of SCFDM for resisting high-frequency distortion in bandwidth-limited VLC systems. To investigate the performance of dimming control and communication for DCO-SCFDM and DCO-OFDM schemes, simulations are conducted with the same parameters in Section 3.2. We compare the achievable spectral efficiency for DCO-SCFDM and DCO-OFDM under different dimming levels when the target BER is set to $10^{-3}$. As shown in Fig. 8, the higher spectral efficiency can be achieved for DCO-SCFDM in almost the entire dimming range than DCO-OFDM. After calculation, for the proposed DCO-SCFDM based dimming control scheme, the achievable average spectral efficiency gain is 31.3% compared to DCO-OFDM based scheme under the same dimming range. For considering a simpler dimmable scheme by only adjusting the signal amplitude and bias voltage, the adjustable illumination range of DCO-SCFDM is 20% ($2 \times 10\%$) wider than DCO-OFDM when spectral efficiency is fixed at 2 bit/s/Hz.

Under the condition of certain bias voltage, numerical results of BER performance versus the scaling factor $\beta$ for DCO-SCFDM and DCO-OFDM are illustrated in Fig. 9. Bias voltage is set to 0.15 and 0.45 to simulate the lower and higher bias conditions, respectively. Fig. 9(a) depicts that,
when $\xi = 2$ bit/s/Hz and $V_{DC} = 0.15$, the 16-QAM modulated DCO-SCFDM scheme can reach the FEC limit in a wide range of signal amplitude while the corresponding DCO-OFDM counterpart never reaches the limit. When the higher bias of 0.45 and the spectral efficiency of 3 bit/s/Hz are set, one can find that DCO-SCFDM with 64-QAM modulation can achieve the target BER of $10^{-3}$, whereas the DCO-OFDM counterpart can not support the effective communication, as shown in Fig. 9(b). Therefore, the proposed DCO-SCFDM based dimming control scheme can outperform its counterpart apparently.

5. Conclusion

In this paper, for the first time, we proposed the efficient SCFDM-based dimming control systems including AHO-SCFDM and DCO-SCFDM for VLC. Owing to the strengths of the low PAPR and the inherent resistance to high-frequency distortion, the proposed SCFDM-based dimming control schemes are adaptive to the bandwidth-limited and linearity-limited VLC system, thus supporting the wide dimming range for different illumination requirements. Comprehensive numerical results show that, for AHO-SCFDM with spectral efficiency of 1.75 bit/s/Hz and DCO-SCFDM with spectral efficiency of 2 bit/s/Hz, the 20% wider dimming range can be achieved than their OFDM-based counterparts, respectively. Meanwhile, under the same dimming range, the 24.8% and 31.3% gains...
of average spectral efficiency can also be achieved compared with their counterparts with full considering the limited dynamic range of LED and bandwidth constraint of system. All that matters is, the SCFDM-based dimmable VLC system can be combined with other dimming control schemes, which will be considered in our future work.

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