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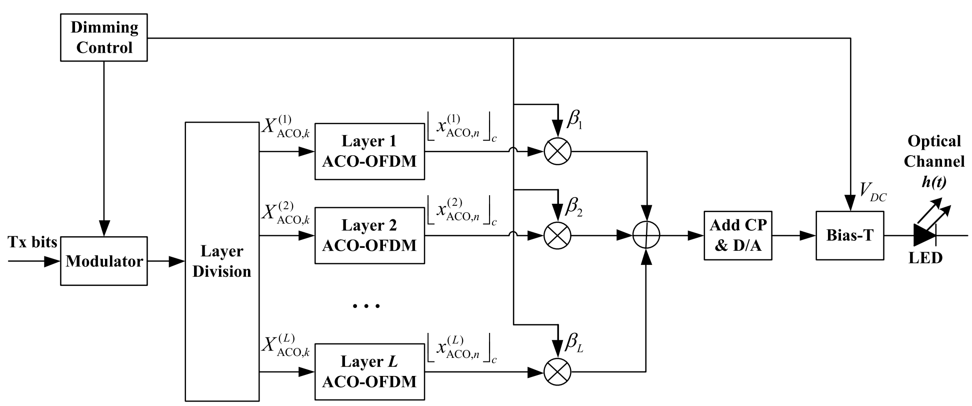

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Dimmable Visible Light Communications Based on Multilayer ACO-OFDM

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Abstract: This paper proposes a dimmable scheme for a visible light communication (VLC) system based on multilayer asymmetrically clipped optical orthogonal frequency-division multiplexing (ACO-OFDM), which is able to support a wide dimming range for different illumination requirements. In the proposed scheme, multiple layers of ACO-OFDM occupying different subcarriers are combined so that almost all of the subcarriers can be used for data transmission. The polarities of different layers of ACO-OFDM are varied to obtain flexible time-domain waveform, which can fully exploit the dynamic range of light-emitting diodes (LEDs) and achieve better performance. The scaling factor and modulation order for each layer, as well as the dc bias, are optimized for different dimming requirements to achieve improved spectral efficiency. Simulation results demonstrate that the proposed scheme can support communication over a wide dimming range and achieve higher spectral efficiency, compared with existing methods under different dimming requirements.

Index Terms: Orthogonal frequency-division multiplexing (OFDM), visible light communication (VLC), dimming control, light-emitting diode (LED).

1. Introduction

Visible light communications (VLCs) have attracted increasing attention as a promising technique to provide secure and high-speed data transmission, especially in indoor scenarios. For low-cost implementation, the information is modulated onto the intensity of light-emitting diode (LED) lamps in VLC systems, while the light is directly detected by photodiodes (PDs) at the receiver and converted to electrical signal that is proportional to its optical power, which is referred to as intensity modulation with direct detection (IM/DD) [1], [2].

In indoor VLC systems, communication and illumination should be maintained simultaneously, where the light can be dimmed to satisfy different illumination and power requirements [3]–[5].

However, the dimming operation will interfere with the communication function of VLC systems since it will alter the received optical power and signal-to-noise ratio (SNR). For the IEEE 802.15.7 Standard, single carrier pulsed modulations such as on-off keying (OOK), pulse-position modulation (PPM) and color shift keying (CSK) are utilized, whereas dimming control is usually realized by combining the existing modulation schemes with pulse amplitude modulation (PAM) or pulse width modulation (PWM) [3]. Besides, several compensation schemes have been proposed combined with various forward error correction (FEC) codes [6]–[8].

As a spectrally efficient modulation scheme, orthogonal frequency division multiplexing (OFDM) has been extensively employed in VLC systems to achieve ultra-high speed data transmission, and multi-gigabit/s experiments have been demonstrated [9]–[12]. In order to comply with intensity modulation, optical OFDM requires real and nonnegative output and various modifications to conventional OFDM have been proposed, among which DC biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM) are mostly used [13], [14]. The dimming control techniques used for single-carrier modulations can be extended to OFDM-based VLC systems. In [15], each time-domain OFDM signal is multiplied by a PWM signal to satisfy different dimming requirements. However, the required frequency of PWM signals should be at least twice the OFDM signals, which is infeasible for high-speed VLC systems. Alternatively, a much wider PWM signal is used in [16], where the time-domain OFDM signals are only modulated during the on-state of PWM, which is easy to implement but sacrifices the data rate since the time of off-state is wasted. The idea is further extended in [17] to utilize multi-PPM (MPPM) for dimming control and carrying information simultaneously, where more information bits can be transmitted but the disadvantage of wasting time is still unsolved. Reverse polarity optical-OFDM is proposed in [18], which combines the fast ACO-OFDM signal with the relatively slow PWM dimming signal to fully utilize the duty cycle and LED dynamic range. However, this scheme is not spectrally efficient since only the odd subcarriers are used for data transmission. In [19], a hybrid optical OFDM scheme combining ACO-OFDM signals occupying odd subcarriers and pulse-amplitude-modulated discrete multitone (PAM-DMT) signals modulating even subcarriers is proposed, which supports dimming control by a DC bias without PWM signals. However, its spectral efficiency is limited since the real part of the even subcarriers are not modulated in PAM-DMT.

Recently, several multi-layer unipolar OFDM schemes have been proposed [20]–[28]. In [21] and [22], an enhanced unipolar OFDM (eU-OFDM) is proposed which simultaneously transmits multiple unipolar data streams and achieves higher spectral efficiency compared to conventional U-OFDM. Besides, several schemes are proposed to improve the spectral efficiency of ACO-OFDM, which combine multiple layers of ACO-OFDM with different subcarriers modulated for simultaneous transmission [23]–[27]. Moreover, it has been verified by Lowery that layered ACO-OFDM offers the highest receiver sensitivity for a given optical power at spectral efficiencies above 3 bit/s/Hz [28].

Against this background, in this paper, a dimmable optical OFDM (DO-OFDM) is proposed to support dimming control for different illumination requirements in VLC. In the proposed scheme, multiple layers of ACO-OFDM occupying different subcarriers are combined for simultaneously transmission, which is able to utilize almost all the subcarriers to improve the spectral efficiency. The polarities of different layers of ACO-OFDM are varied and combined to obtain flexible time-domain waveform. Besides, the scaling factor and modulation order for each layer as well as the DC bias are optimized for different dimming requirements, so that the dynamic range of LEDs can be fully exploited to achieve improved spectral efficiency. Simulation results show that the proposed scheme can support communication over a wider dimming range and achieve higher spectral efficiency compared with existing methods under different illumination requirements.

The rest of this paper is organized as follows. In Section 2, the system model of OFDM-based VLC and illumination requirement is described, while in Section 3, our proposed DO-OFDM scheme is presented. In Section 4, the performance of the proposed scheme is presented and compared with existing methods, and our conclusions are drawn in Section 5.

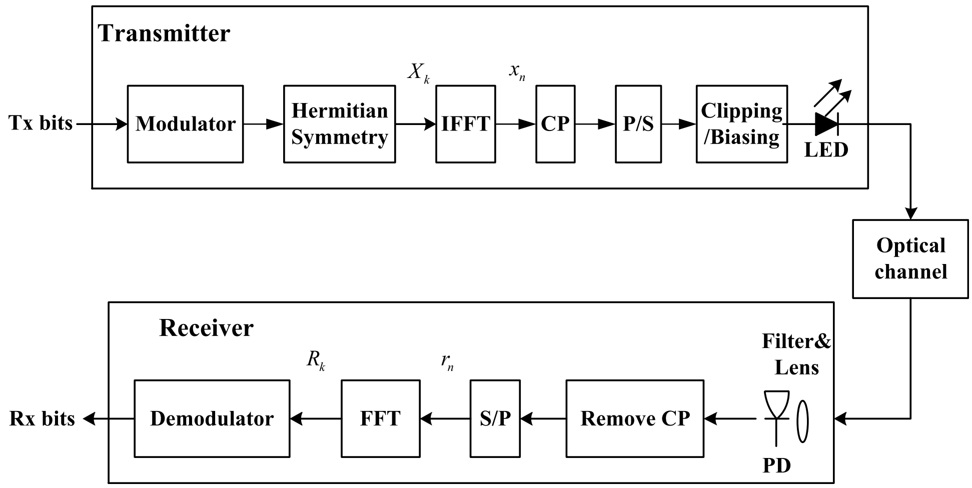

Fig. 1. OFDM-based VLC system.

2. System Model

2.1. VLC System With Optical OFDM

A typical VLC system with optical OFDM is illustrated in Fig. 1. The transmitted bit stream is mapped onto the complex-valued symbols, which are grouped as $\{X_0, X_1, \ldots, X_{N-1}\}$ for N subcarriers. Since intensity modulation is utilized in VLC system, the subcarriers should satisfy Hermitian symmetry to make sure that the time-domain signals after inverse fast Fourier transform (IFFT) are real-valued, where we have $X_k = X^*_{N-k}$, $k = 1, 2, \ldots, N/2 - 1$. Besides, X_0 and $X_{N/2}$ corresponding to the DC component are set to zero. The time-domain OFDM signal can be generated by IFFT as [14]

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \exp\left(j\frac{2\pi}{N}nk\right), \ n = 0, 1, \ldots, N-1. \tag{1}$$

In order to obtain nonnegative signal for intensity modulation, a DC bias can be added to x_n and this scheme is called DCO-OFDM. Alternatively, in ACO-OFDM, only the odd subcarriers are modulated so that the time-domain signals follow anti-symmetry and can be directly clipped at zero without information loss [13]. This way, DC bias is not required, which is more energy efficient compared with DCO-OFDM. It is interesting to note that the clipping distortion only falls on the even subcarriers after FFT, which is orthogonal to the useful information on the odd subcarriers. Therefore, the ACO-OFDM signals can be simply recovered at the receiver [13]. In order to eliminate the inter-symbol interference, the cyclic prefix (CP) is inserted at the beginning of each OFDM symbol. After that, the signal is parallel to serial (P/S) converted into a single stream for emission.

At the receiver, the light is filtered and focused by lens, which is then detected by PDs and converted to the electronic signal that is proportional to the received optical power. Meanwhile, the signal is disturbed by shot noise and thermal noise at the receiver, which is usually modeled as additive white Gaussian noise (AWGN) [2]. After CP removal and serial-to-parallel (S/P) conversion, the received signals are grouped as $\{r_0, r_1, \ldots, r_{N-1}\}$ and then transformed to the frequency domain by fast Fourier transform (FFT) as follows:

$$R_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} r_n \exp\left(-\frac{j2\pi kn}{N}\right), k = 0, 1, \ldots, N-1. \tag{2}$$

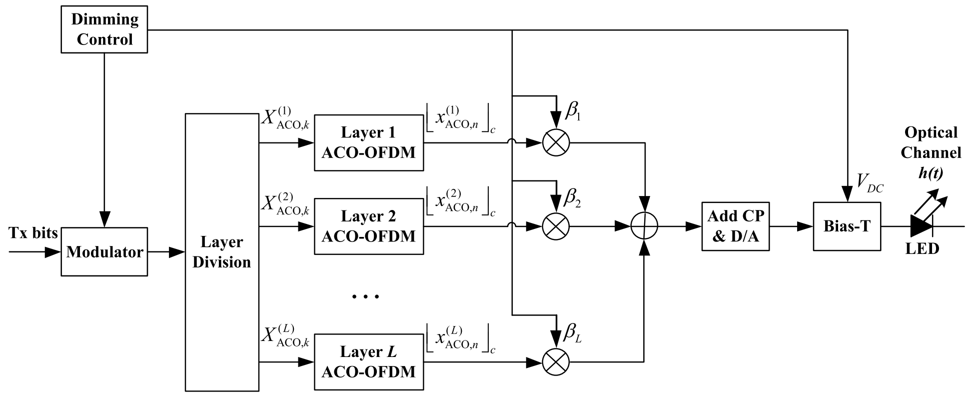

Fig. 2. Dimmable VLC transmitter based on multilayer ACO-OFDM.

2.2. Dimming Control for Illumination Requirement

In VLC systems, the inherent nonlinearity of LEDs is a challenge for OFDM implementation since OFDM has high peak-to-average power ratio (PAPR). The input of LEDs has a minimum threshold value that can generate current, which is referred to as turn-on voltage (TOV). When the input voltage is above the TOV, however, the voltage-current and current-power characteristics are still nonlinear [29]. Several algorithms have been proposed to mitigate the effect of LED nonlinearity, where the transfer characteristics of LED can be quasi-linear in a limited range after predistortion [30], [31]. Therefore, we denote $v_{\min}$ and $v_{\max}$ as the minimum and maximum allowed signals according to the voltage levels permitted by LEDs, and the transfer characteristics of LEDs between $[v_{\min}, v_{\max}]$ is assumed to be linear. Specifically, the relationship between the emitted optical power and the input voltage is given by

$$P_{\text{opt}}(t) = \begin{cases} 0, & v(t) < v_{\min} \\ \eta(v(t) - v_{\min}), & v_{\min} \leq v(t) \leq v_{\max} \\ \eta(v_{\max} - v_{\min}), & v(t) > v_{\max} \end{cases} \tag{3}$$

where η and $v(t)$ denote the voltage-power transfer coefficient and instantaneous input voltage, respectively.

Since the illumination level is proportional to the average optical power, dimming control can be achieved by adjusting the average optical power of LEDs. Thus, we can define the dimming level d as

$$d = \frac{E\left(P_{\text{opt}}(t)\right)}{(\eta(v_{\max} - v_{\min}))} \tag{4}$$

which obviously falls in the interval [0, 1]. When the required dimming level is adjusted, the received optical power and effective SNR are changed, which will vary the achievable data rate for a given bit error rate (BER) requirement. Therefore, we aim to design an efficient modulation scheme which can support high data rate under different dimming targets.

3. Proposed Dimmable VLC System Based on Multi-Layer ACO-OFDM

The block diagram of proposed transmitter is depicted in Fig. 2, where L layers of ACO-OFDM occupying different subcarriers are combined for transmission. The transmitted bit stream is firstly mapped onto the complex-valued symbols, which are then divided into different groups for layered modulation. In Layer l ($l = 1, 2, \ldots, L$) ACO-OFDM, an OFDM symbol which only modulates the

$2^{l-1}k$-th subcarriers are considered and is denoted as $X^{(l)}_{\text{ACO},k}$ for $k = 0, 1, \ldots, N/2^{l-1} - 1$. After N-point IFFT, the time-domain signals are given by [25]

$$
\begin{aligned}
x^{(l)}_{\text{ACO},n} &= \frac{1}{\sqrt{N}} \sum_{k=0}^{N/2^{l-1}-1} X^{(l)}_{\text{ACO},k} \exp\left(j\frac{2\pi}{N} n \cdot 2^{l-1}k\right) \\
&= \frac{1}{\sqrt{2^{l-1}}} \frac{1}{\sqrt{\frac{N}{2}^{l-1}}} \sum_{k=0}^{N/2^{l-1}-1} X^{(l)}_{\text{ACO},k} \exp\left(j\frac{2\pi}{\frac{N}{2}^{l-1}} nk\right) \\
&= \frac{1}{\sqrt{2^{l-1}}} x^{(l)}_{\text{mod}\left(n, \frac{N}{2}^{l-1}\right)}, \; n = 0, 1, \ldots, N-1
\end{aligned} \tag{5}
$$

where $x^{(l)}_n$ denotes the $N/2^{l-1}$-point IFFT result of $X^{(l)}_{\text{ACO},k}$. It can be seen that $x^{(l)}_{\text{ACO},n}$ is periodic and can be obtained with the $N/2^{l-1}$-length signal $x^{(l)}_n$. In order to obtain real signals after IFFT operation, the subcarriers should satisfy Hermitian symmetry, i.e., $X^{(l)}_{\text{ACO},k} = \left(X^{(l)}_{\text{ACO},N/2^{l-1}-k}\right)^*$ for $k = 0, 1, \ldots, N/2^{l-1} - 1$. Furthermore, similar to conventional ACO-OFDM, only the subcarriers with odd indices of $X^{(l)}_{\text{ACO},k}$ are modulated, while the subcarriers with even indices of $X^{(l)}_{\text{ACO},k}$ remain empty.

After IFFT, the time-domain signals of Layer l ACO-OFDM follows anti-symmetry that $x^{(l)}_n = -x^{(l)}_{n+N/2^l}$, which can be directly clipped at zero without any information loss [25]. The clipped Layer l ACO-OFDM signals are denoted as

$$
\left\lfloor x^{(l)}_{\text{ACO},n} \right\rfloor_c = x^{(l)}_{\text{ACO},n} + i^{(l)}_{\text{ACO},n} = \begin{cases} x^{(l)}_{\text{ACO},n}, & x^{(l)}_{\text{ACO},n} \geq 0 \\ 0, & x^{(l)}_{\text{ACO},n} < 0 \end{cases} \tag{6}
$$

for $n = 0, 1, \ldots, N-1$, where $i^{(l)}_{\text{ACO},n}$ denotes the negative clipping distortion of Layer l ACO-OFDM, which is orthogonal to the useful information when transformed to the frequency domain.

Therefore, in Layer l ACO-OFDM, $N/2^{l+1}$ useful symbols are actually transmitted, and different layers of ACO-OFDM occupy different subcarriers. Inspired by the multi-layer structure proposed in [20]–[28], a dimmable optical OFDM (DO-OFDM) scheme based on multi-layer ACO-OFDM is proposed in this paper, which transmits multiple layers of ACO-OFDM simultaneously and supports different dimming levels.

In DO-OFDM scheme, multiple layers of ACO-OFDM with different polarities are combined in the time domain for simultaneous transmission, whose time-domain signals are written as

$$
x_n = \sum_{l=1}^{L} \beta_l \left\lfloor x^{(l)}_{\text{ACO},n} \right\rfloor_c + v_{\text{bias}}, n = 0, 1, \ldots, N-1 \tag{7}
$$

where L is the number of layers. β_l denotes the scaling factor for the Layer l ACO-OFDM, which can be either negative or positive, while v_{bias} represents the DC bias to satisfy the dimming target. In this way, almost all the subcarriers can be used for carrying information since different layers occupy different subcarriers, which improve its spectral efficiency. The spectral efficiency of DO-OFDM is calculated as

$$
SE = \sum_{l=1}^{L} 2^{-(l+1)} \log_2(M_l) \tag{8}
$$

where M_l denotes the modulation order of Layer l for $l = 1, 2, \ldots, L$. Moreover, the waveform of DO-OFDM can be very flexible to fit in the dynamic range of LEDs by adjusting the scaling factors of different layers when different DC bias is utilized.

At the receiver, the symbols on different layers are detected successively. Symbols on the lower layers are firstly detected by simple FFT. After that, the corresponding clipping distortion is reconstructed and eliminated from the received signals so that symbols on the higher layers can be detected.

In order to fully exploit the dynamic range of LEDs and improve the effective SNR at the receiver, the coefficients β_l and v_{bias} should be carefully selected for different dimming levels. Besides, it can be seen in (3) that the signals outside the interval $[v_{\min},\ v_{\max}]$ need to be clipped, which results in undesired clipping distortion and degrades the performance. Therefore, we need to make sure most of the signals are within the interval $[v_{\min},\ v_{\max}]$. In the following, the derivation for β_l and v_{bias} is given for different dimming levels.

We assume the variance of modulated symbol $X_{\text{ACO},k}^{(l)}$ to be uniform as σ^2 for all the L layers of ACO-OFDM. After IFFT, the time-domain OFDM signal in (5) approximates a Gaussian distribution when $N \geq 64$ according to the central limit theorem [14]. Since $N/2^{l+1}$ symbols are modulated in Layer l ACO-OFDM and another $N/2^{l+1}$ subcarriers are occupied for Hermitian symmetry, the variance of the unclipped signal $x_{\text{ACO},n}^{(l)}$ is equal to $\sigma^2/2^l$ according to the Parseval's theorem, while the expectation of $x_{\text{ACO},n}^{(l)}$ is zero. Therefore, the probability density function of Layer l $(l = 1, 2, \ldots, L)$ ACO-OFDM signals $\lfloor x_{\text{ACO},n}^{(l)} \rfloor_c$ is given by

$$p\left(\left\lfloor x_{\text{ACO},n}^{(l)}\right\rfloor_c\right) = \begin{cases} \frac{1}{2}, & \left\lfloor x_{\text{ACO},n}^{(l)}\right\rfloor_c = 0 \\ \frac{1}{\sqrt{\frac{\pi}{2^{l-1}}}\sigma}\exp\left(-\frac{\left\lfloor x_{\text{ACO},n}^{(l)}\right\rfloor_c^2}{\frac{\sigma^2}{2^{l-1}}}\right), & \left\lfloor x_{\text{ACO},n}^{(l)}\right\rfloor_c > 0 \end{cases} \tag{9}$$

and the expectation of $\lfloor x_{\text{ACO},n}^{(l)} \rfloor_c$ is then calculated by [32]

$$E\left\{\left\lfloor x_{\text{ACO},n}^{(l)}\right\rfloor_c\right\} = 2^{-(l+1)/2}\pi^{-1/2}\sigma. \tag{10}$$

Therefore, the expectation of x_n can be calculated as

$$E\{x_n\} = \sum_{l=1}^{L}\beta_l E\left\{\left\lfloor x_{\text{ACO},n}^{(l)}\right\rfloor_c\right\} + v_{\text{bias}} = \sum_{l=1}^{L} 2^{-l/2}\pi^{-1/2}\beta_l\sigma + v_{\text{bias}}. \tag{11}$$

For a given dimming level d_t, the required average optical power can be calculated according to (4) as

$$E\left(P_{\text{opt}}(t)\right) = d_t\eta(v_{\max} - v_{\min}) \tag{12}$$

which is nonlinear in terms of instantaneous input voltage according to (3). It is worth noting that most of the modulated signals are within the linear range of LEDs in practical implementation to avoid clipping distortion, so that we can only consider the signals within the dynamic range and neglect the clipping distortion in the calculation of average optical power. Therefore, the expectation of x_n should be approximate to

$$E\{x_n\} \approx d_t v_{\max} + (1 - d_t)v_{\min} \tag{13}$$

and the coefficients β_l $(l = 1, 2, \ldots, L)$ and v_{bias} for dimming control can be solved by (11) and (13), where we have

$$\sum_{l=1}^{L} 2^{-l/2}\pi^{-1/2}\beta_l\sigma + v_{\text{bias}} = d_t v_{\max} + (1 - d_t)v_{\min}. \tag{14}$$

However, (14) is underdetermined since it includes $L + 1$ variables. Besides, the chosen coefficients should satisfy the following three requirements. First, the combined signals should use as much the dynamic range of LEDs as possible, which can achieve higher effective SNR at the receiver. Secondly, the clipped distortion of the signals should be small. At last, the BER performance of the DO-OFDM containing all different layers of ACO-OFDM signals should stratify the BER target, which is related to both the modulation order and the optical power of each layer. Therefore, some constraints are added to simplify this problem:

$$\begin{cases} 1-2\varepsilon \leq P(v_{\min} \leq x_n \leq v_{\max}) \leq 1-\varepsilon \\ \dfrac{\sum_{l=1}^{L} P_b(l) 2^{-(l+1)} \log_2(M_l)}{\sum_{l=1}^{L} 2^{-(l+1)} \log_2(M_l)} \leq \tau, \ \ l=1,2,\ldots,L \\ |\beta_1| = |\beta_2| = \cdots = |\beta_L| \end{cases} \tag{15}$$

where 2ε denotes maximum probability that x_n is clipped, and τ is the BER target. $P(\cdot)$ is the probability mass function, which can be calculated by the probability density functions of L layers of ACO-OFDM signals in (9). It should be noted that the second inequality in the first line of (15) is used to satisfy the first requirement. However, it cannot always hold when the dimming level is too low or too high. The higher layers suffer from interference from lower layers due to successive demodulation, which require higher power to achieve the same BER performance. However, it has been shown in [25] that the BER performances of different layers converge when the BER decreases since the estimation accuracy of interference from lower layers improves. Therefore, we simply assume all the layers have the same absolute beta values as in (15). $P_b(l)$ is the BER of the Layer l ACO-OFDM signals in the DO-OFDM, which can be approximated by [33]

$$P_b(l) \approx \frac{4(\sqrt{M_l}-1)}{\sqrt{M_l}\log_2(M_l)} Q\left(\sqrt{\frac{3}{M_l-1}\frac{\beta_l^2\sigma^2}{4N_0}}\right) \tag{16}$$

for M_l-ary quadrature amplitude modulation (QAM), where N_0 denotes the power spectral density of the noise, and the interference from lower layers is neglected in (16) since its influence would be very small at high SNRs as shown in [25].

The optimal coefficients to maximize the spectral efficiency in (8) can be obtained by traversing different values of β_l to satisfy (15), while the DC bias v_{bias} can be calculated by (14) when β_l $(l=1,2,\ldots,L)$ are given. In practical implementation, these parameters for various dimming levels and channel conditions can be stored in advance.

4. Numerical Results

Numerical simulations were conducted to evaluate the performance of the proposed DO-OFDM scheme. The minimum and maximum allowed voltages of LEDs within linear range were set as $v_{\min}=1$ V and $v_{\max}=5$ V, respectively, and the voltage-power transfer coefficient was assumed to be $\eta=0.25$ W/V. The clipping probability was set to $\varepsilon=0.003$ to avoid clipping distortion [34]. The BER target was set to $\tau=2\times10^{-3}$, which is within the FEC limit. Four layers of ACO-OFDM signals are combined to generate the DO-OFDM signals for transmission, and the coefficients for dimming control are acquired by (14)–(16). Fig. 3 depicts the achievable spectral efficiency of each layer of ACO-OFDM signals in DO-OFDM under different dimming requirements, where the noise power at the receiver is −10 dBm. Different orders of QAM are utilized for different layers of ACO-OFDM and dimming requirements. It can seen that different layers of ACO-OFDM can provide data transmission at the same time and contribute to the overall spectral efficiency. Therefore, better performance can be achieved. When the required dimming level is too low or too high, the achievable spectral efficiency decreases since the effective range of signals is limited to satisfy the extreme average optical power requirement.

The performance of DO-OFDM is also compared with DCO-OFDM and AHO-OFDM with the same simulation parameters. In DCO-OFDM scheme, dimming control is realized by adaptively

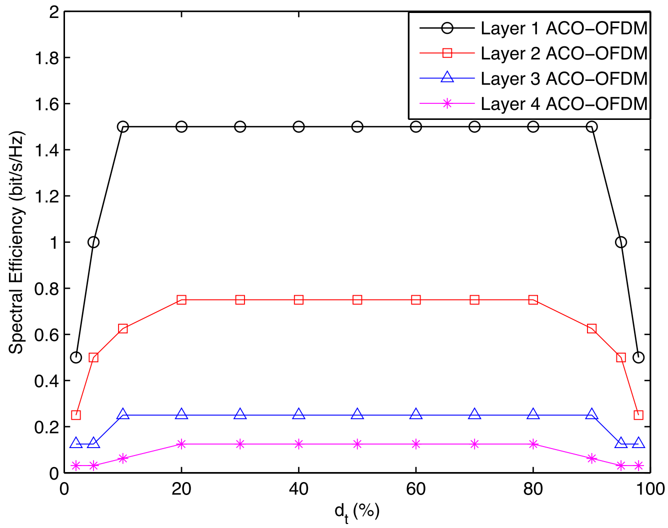

Fig. 3. Achievable spectral efficiency of each layer of ACO-OFDM in DO-OFDM under different dimming requirements, where the noise power at the receiver is −10 dBm.

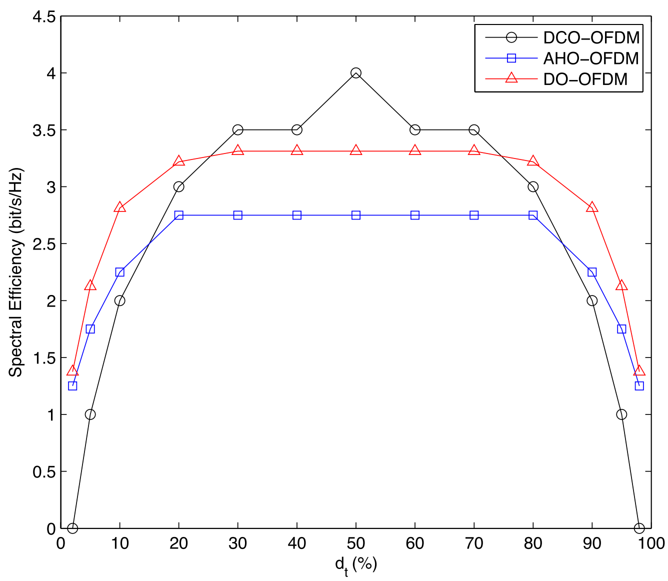

Fig. 4. Achievable spectral efficiency comparison of DCO-OFDM, AHO-OFDM, and DO-OFDM under different dimming requirements, where the noise power at the receiver is −15 dBm.

adjusting the DC bias and scaling factors, which does not require PWM signals for fair comparison. In AHO-OFDM, ACO-OFDM signals modulating odd subcarriers and PAM-DMT signals occupying even subcarriers are combined and one of them is inverted to generate asymmetrical waveform [19]. The achievable spectral efficiency comparisons of DCO-OFDM, AHO-OFDM and the proposed DO-OFDM under different dimming requirements are shown in Figs. 4–6, where the noise power at the receiver is assumed be −15 dBm, −10 dBm, and −5 dBm for low, medium, and high noise environments, respectively. It can be seen that the proposed DO-OFDM can support a much wider dimming range compared with DCO-OFDM in all the three noise environments, and its achievable spectral efficiency is relatively stable when the dimming level varies since its waveform is flexible to fully utilize the dynamic range of LEDs. Besides, it achieves higher spectral efficiency for most of the dimming requirements. Moreover, DO-OFDM is always

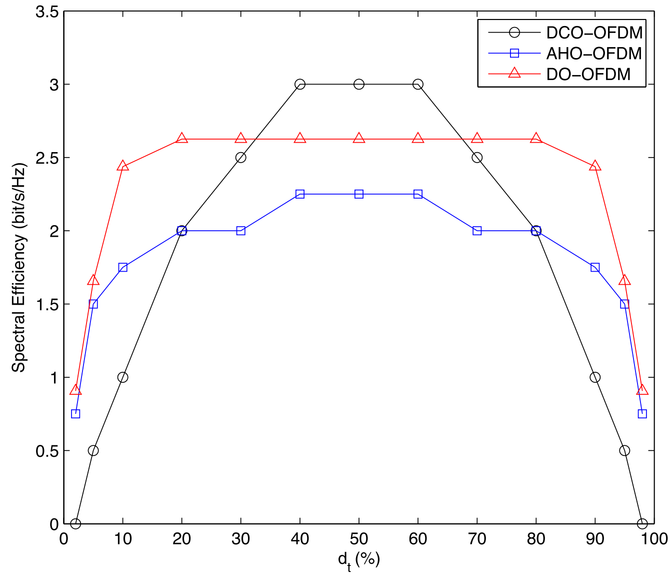

Fig. 5. Achievable spectral efficiency comparison of DCO-OFDM, AHO-OFDM, and DO-OFDM under different dimming requirements, where the noise power at the receiver is −10 dBm.

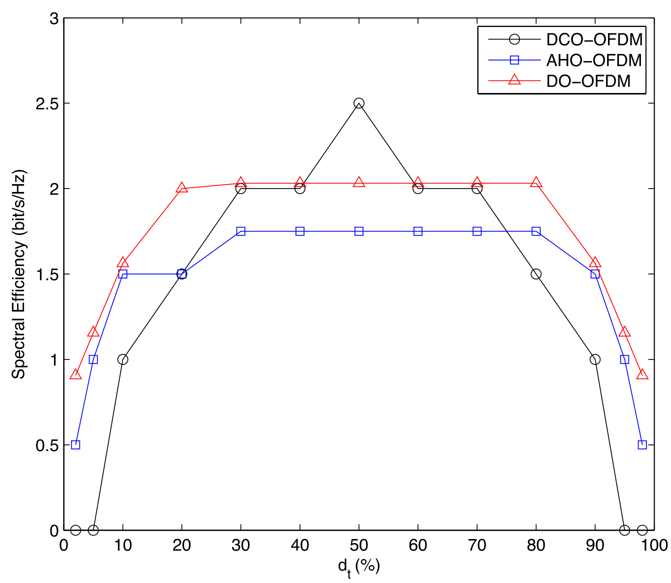

Fig. 6. Achievable spectral efficiency comparison of DCO-OFDM, AHO-OFDM, and DO-OFDM under different dimming requirements, where the noise power at the receiver is −5 dBm.

superior to AHO-OFDM under all dimming requirements. Even though AHO-OFDM has utilized all the subcarriers for carrying information, the real part of even subcarriers are still empty, while the proposed DO-OFDM is able to exploit more frequency resources for transmission by multi-layer ACO-OFDM. Therefore, the proposed scheme is proved to be a better candidate for dimmable VLC systems.

5. Conclusion

DO-OFDM is proposed in this paper for illumination and communication at the same time, whereby the polarities of multiple layers of ACO-OFDM are varied to obtain flexible time-domain waveform so that both the subcarriers and the dynamic range of LEDs can be fully exploited to achieve better performance. The scaling factor and modulation order for each layer as well as the DC bias are optimized for different dimming requirements to achieve maximum spectral efficiency. Simulation results have verified that the proposed scheme can support a wide dimming range for illumination and achieves higher spectral efficiency, compared with existing methods under different illumination requirements.

References

[1] R. Zhang, J. Wang, Z. Wang, Z. Xu, C. Zhao, and L. Hanzo, "Visible light communications in heterogeneous networks: Pave the way for user-centric design," *IEEE Wireless Commun.*, vol. 22, no. 2, pp. 8–16, Apr. 2015.

[2] S. Dimitrov and H. Haas, *Principles of LED Light Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2015.

[3] *Part 15.7: Short-Range Wireless Optical Communication Using Visible Light*, IEEE Std. 802.15.7-2011, Sep. 2011.

[4] C. Gong, S. Li, Q. Gao, and Z. Xu, "Power and rate optimization for visible light communication system with lighting constraints," *IEEE Trans. Signal Process.*, vol. 63, no. 16, pp. 4245–4256, Aug. 2015.

[5] S. H. Lee, S.-Y. Jung, and J. K. Kwon, "Modulations and coding for dimmable visible light communication," *IEEE Commun. Mag.*, vol. 53, no. 2, pp. 136–143, Feb. 2015.

[6] S. Kim and S.-Y. Jung, "Novel FEC coding scheme for dimmable visible light communication based on the modified ReedCMuller codes," *IEEE Photon. Technol. Lett.*, vol. 23, no. 20, pp. 1514–1516, Oct. 2011.

[7] S. H. Lee and J. K. Kwon, "Turbo code-based error correction scheme for dimmable visible light communication systems," *IEEE Photon. Technol. Lett.*, vol. 24, no. 17, pp. 1463–1465, Sep. 2012.

[8] J. Kim and H. Park, "A coding scheme for visible light communication with wide dimming range," *IEEE Photon. Technol. Lett.*, vol. 26, no. 5, pp. 465–468, Mar. 2014.

[9] Y.-C. Chi *et al.,* "450-nm GaN laser diode enables high-speed visible light communication with 9-Gbps QAM-OFDM," *Opt. Exp.*, vol. 23, no. 10, pp. 13 051–13 059, May 2015.

[10] J. R. D. Retamal *et al.,* "4-Gbit/s visible light communication link based on 16-QAM OFDM transmission over remote phosphor-film converted white light by using blue laser diode," *Opt. Exp.*, vol. 23, no. 26, pp. 33 656–33 666, Dec. 2015.

[11] Q. Wang, Z. Wang, and L. Dai, "Multiuser MIMO-OFDM for visible light communications," *IEEE Photon. J.*, vol. 7, no. 6, Dec. 2015, Art. no. 7904911.

[12] Y. Yang, Z. Zeng, S. Feng, and C. Guo, "A simple OFDM scheme for VLC systems based on μ-law mapping," *IEEE Photon. Technol. Lett.*, vol. 28, no. 6, pp. 641–644, Mar. 2016.

[13] J. Armstrong and A. J. Lowery, "Power efficient optical OFDM," *Electron. Lett.*, vol. 42, no. 6, pp. 370–372, Mar. 2006.

[14] J. Armstrong, "OFDM for optical communications," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 189–204, Feb. 2009.

[15] G. Ntogari, T. Kamalakis, J. Walewski, and T. Sphicopoulos, "Combining illumination dimming based on pulsewidth modulation with visible-light communications based on discrete multitone," *J. Opt. Commun. Netw.*, vol. 3, no. 1, pp. 56–65, Jan. 2011.

[16] Z. Wang, W. D. Zhong, C. Yu, J. Chen, C. P. S. Francois, and W. Chen, "Performance of dimming control scheme in visible light communication system," *Opt. Exp.*, vol. 20, no. 17, pp. 18 861–18 868, Aug. 2012.

[17] X. You, J. Chen, H. Zheng, and C. Yu, "Efficient data transmission using MPPM dimming control in indoor visible light communication," *IEEE Photon. J.*, vol. 7, no. 4, Aug. 2015, Art. no. 7902512.

[18] H. Elgala and T. D. C. Little, "Reverse polarity optical-OFDM (RPO-OFDM): Dimming compatible OFDM for gigabit VLC links," *Opt. Exp.*, vol. 21, no. 20, pp. 24 288–24 299, Oct. 2013.

[19] Q. Wang, Z. Wang, and L. Dai, "Asymmetrical hybrid optical OFDM for visible light communications with dimming control," *IEEE Photon. Technol. Lett.*, vol. 27, no. 9, pp. 974–977, May 2015.

[20] R. Zhang and L. Hanzo, "Multi-layer modulation for intensity-modulated direct-detection optical OFDM," *J. Opt. Commun. Netw.*, vol. 5, no. 12, pp. 1402–1412, Dec. 2013.

[21] D. Tsonev and H. Haas, "Avoiding spectral efficiency loss in unipolar OFDM for optical wireless communication," in *Proc. IEEE ICC*, Sydney, NSW, Australia, Jun. 10–14, 2014, pp. 3336–3341.

[22] D. Tsonev, S. Videv, and H. Haas, "Unlocking spectral efficiency in intensity modulation and direct detection systems," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1758–1770, Sep. 2015.

[23] H. Elgala and T. D. C. Little, "SEE-OFDM: Spectral and energy efficient OFDM for optical IM/DD systems," in *Proc. IEEE 25th Annu. Int. Symp. PIMRC*, Washington, DC, USA, Sep. 2–5, 2014, pp. 851–855.

[24] E. Lam, S. Wilson, H. Elgala, and T. D. C. Little, "Spectrally and energy efficient OFDM (SEE-OFDM) for intensity modulated optical wireless systems," Cornell Univ., Ithaca, NY, USA, Oct. 2015. [Online]. Available: http://arxiv.org/abs/1510.08172

[25] Q. Wang, C. Qian, X. Guo, Z. Wang, D. G. Cunningham, and I. H. White, "Layered ACO-OFDM for intensity-modulated direct-detection optical wireless transmission," *Opt. Exp.*, vol. 23, no. 9, pp. 12382–12393, May 2015.

[26] M. S. Islim, D. Tsonev, and H. Haas, "On the superposition modulation for OFDM-based optical wireless communication," in *Proc. IEEE GlobalSIP*, Orlando, FL, USA, Dec. 14–16, 2015, pp. 1022–1026.

[27] A. J. Lowery, "Enhanced asymmetrically clipped optical OFDM for high spectral efficiency and sensitivity," presented at the Opt. Fiber Commun. Conf., Anaheim, CA, USA, Mar. 20–22, 2016, Paper Th2A.30.

[28] A. J. Lowery, "Comparisons of spectrally-enhanced asymmetrically-clipped optical OFDM systems," *Opt. Exp.*, vol. 24, no. 4, pp. 3950–3966, Feb. 2016.

[29] H. Elgala, R. Mesleh, and H. Haas, “An LED model for intensity-modulated optical communication systems,” *IEEE Photon. Technol. Lett.*, vol. 22, no. 11, pp. 835–837, Jun. 2010.
[30] R. Mesleh, H. Elgala, and H. Haas, “LED nonlinearity mitigation techniques in optical wireless OFDM communication systems,” *IEEE/OSA J. Opt. Commun. Netw.*, vol. 4, no. 11, pp. 865–875, Nov. 2012.
[31] L. N. Peng, S. Haese, and M. Helard, “Frequency domain LED compensation for nonlinearity mitigation in DMT systems,” *IEEE Photon. Technol. Lett.*, vol. 25, no. 20, pp. 2022–2025, Oct. 2013.
[32] X. Li, J. Vucic, V. Jungnickel, and J. Armstrong, “On the capacity of intensity-modulated direct-detection systems and the information rate of ACO-OFDM for indoor optical wireless applications,” *IEEE Trans. Commun.*, vol. 60, no. 3, pp. 799–809, Mar. 2012.
[33] J. Li, X.-D. Zhang, Q. Gao, Y. Luo, and D. Gu, “Exact BEP analysis for coherent M-ary PAM and QAM over AWGN and Rayleigh fading channels,” in *Proc. IEEE VTC–Spring*, Singapore, May 11–14, 2008, pp. 390–394.
[34] A. M. Khalid, G. Cossu, R. Corsini, P. Choudhury, and E. Ciaramella, “1-Gb/s transmission over a phosphorescent white LED by using rate-adaptive discrete multitone modulation,” *IEEE Photon. J.*, vol. 4, no. 5, pp. 1465–1473, Oct. 2012.