Index Modulation Based Hybrid Dimming Scheme for Visible Light Communication

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***Abstract*—Recently, the index modulation technique is introduced into the visible light communication (VLC) system to convey information bits in a more energy-efficient and spectral-efficient way. However, in practice, the index modulation aided VLC system should be carefully designed to be compatible with dimming control. In this paper, a novel hybrid dimming scheme is proposed for the index modulation aided VLC system, which combines the frequency-domain and time-domain dimming strategies to maximize the channel capacity and maintain the desired illumination level. Simulation results validate the superior performance of the proposed hybrid dimming scheme.**

***Index Terms*—index modulation, hybrid dimming control, visible light communication, asymmetrically clipped optical OFDM.**

I. Introduction

In recent years, the worldwide explosion in information services and communication demands has put forward higher requirements for wireless communication systems [1]. Visible light communication (VLC), which utilized the unregulated visible light spectrum to provide communication services, has been recognized as one of the competitive complements to the conventional radio frequency communications and hence has drawn increasing attention [2]–[4].

In VLC, orthogonal frequency-division multiplexing (OFDM) is widely adopted because of its inherent resilience to the inter-symbol interference (ISI) and light flickers [5]. So far, there have been many OFDM based modulation methods to generate the required real valued and unipolar signals [6], such as the direct current biased optical OFDM (DCO-OFDM) [7], the asymmetrically clipped optical OFDM (ACO-OFDM) [8], and the hybrid optical OFDM based modulation methods [9] [10].

Index modulation is an emerging modulation technique, which creates completely new dimensions for data transmission, and hence has attracted tremendous interests over the past few years [11]. Specifically, in index modulation, the information bits are mapped not only on the conventional constellation domain, but also on the index domain of the OFDM subcarriers [12]. Recently, the index modulation technique has been introduced into the VLC systems to convey information bits in a more energy-efficient and spectral-efficient way [13] [14].

The intensity modulation and direct detection (IM/DD) scheme is generally considered in the VLC systems [15]. Besides communication, the VLC system is expected to provide high-speed communication under different required illumination level. So far, several dimming control schemes have been proposed for conventional optical OFDM [16], such as modulation based methods [17], coding based methods [18] and adaptive methods [19]. In our previous work [20], a hybrid dimming scheme is proposed for spatial modulation based VLC system. However, to the best of our knowledge, there lacks dimming control scheme intended for the index modulation aided VLC system, which is one of the key problems in the implement of practical index modulation aided VLC.

In this paper, we propose a novel hybrid dimming scheme for the index modulation aided VLC system. In the proposed scheme, the frequency-domain and time-domain dimming strategies are merged to accommodate dimmable communication. We analyze the channel capacity of the index modulation aided VLC system and obtain the closed-form expression of the channel capacity through mutual information analysis. The frequency-domain dimming is realized based on the maximization of the channel capacity and then the time-domain dimming is achieved to further adjust the illumination level. Numerical simulations are carried out and the results demonstrate the superior performance of the proposed scheme.

The rest of this paper is organized as follows. In Section II, the system model of the index modulation based VLC with ACO-OFDM as an example is introduced. In Section III, the channel capacity is analyzed and the index modulation based frequency-time-domain hybrid dimming scheme is proposed. Then the numerical simulations are carried out and the results are provided in Section IV. Finally, the paper concludes in Section V.

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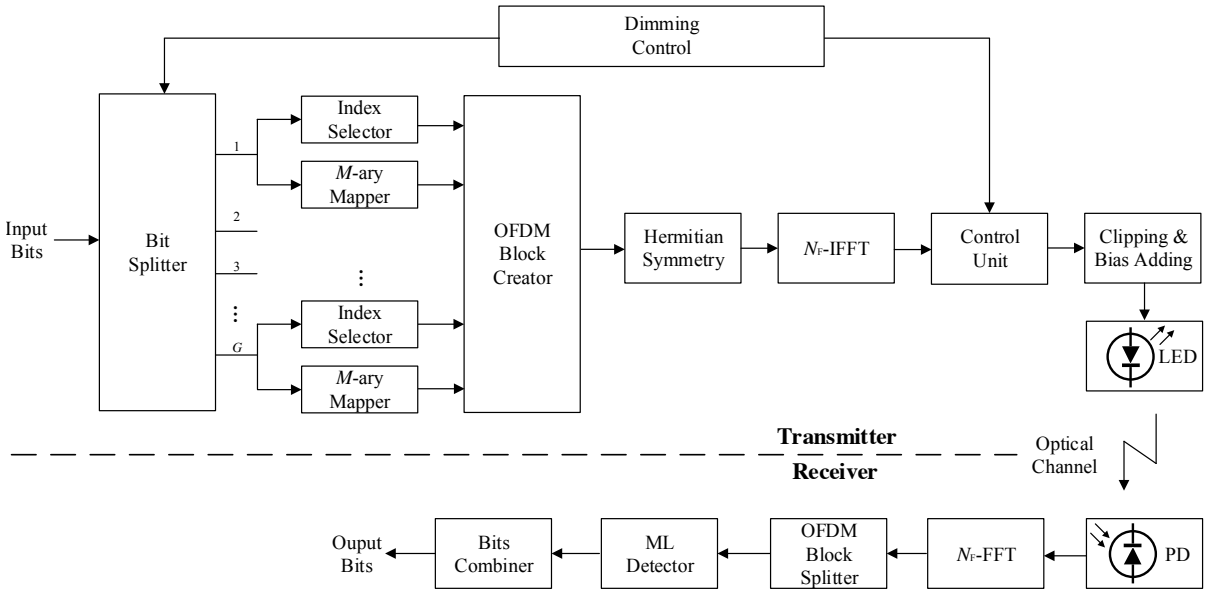


Fig. 1. The system model of the index modulation based hybrid dimming scheme for VLC.

II. System Model

We consider an index modulation aided VLC system with ACO-OFDM, the system model is illustrated in Fig. 1. The bandwidth of the system is denoted as W, which is divided into $N_{\rm F}$ subcarriers. Without loss of generality, the ACO-OFDM is adopted as an example, and therefore only $N = N_{\rm F}/4$ subcarriers are available for index selection and independent data transmission.

Using index modulation, the available subcarriers are split into G groups and each group consists of $L = N/G$ subcarriers. In each group, K out of L subcarriers are activated to transmit information. Thus the input bits are first divided into G groups. Then in each group, $\log_2 \binom{L}{K}$ bits are used to select the activated subcarriers and the remaining bits are utilized to decide the M-ary phase shift keying (PSK) or quadrature amplitude modulation (QAM) modulated symbols at the activated subcarriers. For group g with $g = 1, 2, ..., G$, the set of selected subcarrier indices is given as

$$\Omega_g = \{\omega_1^g, \omega_2^g, ..., \omega_K^g\}, \tag{1}$$

where $\omega_k^g \in \{1, 2, ..., N\}$ with $g = 1, 2, ..., G$ and $k = 1, 2, ..., K$. According to the principle of index modulation, $\Omega_{g_1} \cap \Omega_{g_2} = \varnothing$, $\Omega_1 \cup ... \cup \Omega_G = \{1, 2, ..., N\}$ with $g_1, g_2 \in \{1, 2, ..., G\}$ and $g_1 \neq g_2$.

After index selection, the OFDM block is created according to the selected subcarrier indices and mapped constellation symbols in all groups. Therefore the frequency-domain OFDM symbol $\mathbf{S}$ is given as

$$\mathbf{S} = [0, S_1, 0, S_3, ..., S_{N_{\rm F}/2-1}, 0, S^*_{N_{\rm F}/2-1}, ..., 0, S^*_1], \tag{2}$$

where S_k denotes the symbol transmitted at the k-th subcarrier. Then a $N_{\rm F}$-point inverse fast Fourier transform (IFFT) is applied to obtain the time-domain samples,

$$s_n = \frac{1}{\sqrt{N_{\rm F}}} \sum_{k=1}^{N_{\rm F}} S_k e^{\frac{j2\pi nk}{N_{\rm F}}}. \tag{3}$$

Due to the Hermitian symmetry property of the frequency-domain ACO-OFDM symbols, the time-domain samples satisfy the anti-symmetry property, which is given as

$$s_n = -s_{n+N_{\rm F}/2}, \quad 0 < n < \frac{N_{\rm F}}{2}. \tag{4}$$

Thus either the positive part or the negative part of the time-domain samples can be clipped without any information loss. The positive and negative clipped time-domain samples are further given as

$$s_n^{\rm PACO} = \begin{cases} s_n, & s_n \geq 0, \\ 0, & s_n < 0, \end{cases} \tag{5}$$

and

$$s_n^{\rm NACO} = \begin{cases} 0, & s_n > 0, \\ s_n, & s_n \leq 0, \end{cases} \tag{6}$$

where $s_n^{\rm PACO}$ and $s_n^{\rm NACO}$ denote the positive and negative ACO-OFDM samples, respectively. In order to get the unipolar samples within the dynamic range of the LEDs, the samples need to be rescaled and added by the direct current bias. The transmitted time-domain positive and negative ACO-OFDM samples are further given as

$$x_n^{\rm PACO} = \begin{cases} \beta s_n + I_{\rm L}, & s_n \geq 0, \\ I_{\rm L}, & s_n < 0, \end{cases} \tag{7}$$

and

$$x_n^{\mathrm{NACO}} = \begin{cases} I_{\mathrm{H}}, & s_n > 0, \\ \beta s_n + I_{\mathrm{H}}, & s_n \leq 0, \end{cases} \tag{8}$$

where β is the scaling factor. I_{L} and I_{H} denote the allowed minimum and maximum currents of the dynamic range of the LEDs, respectively.

Then the time-domain samples are transmitted over the optical channel. At the receiver, the fast Fourier transform (FFT) is applied to derive the frequency-domain signals. Thus the frequency-domain transmission function is given as

$$Y_k = X_k H_k + W_k, \ k = 1, 2, ..., N_{\mathrm{F}}, \tag{9}$$

where X_k and Y_k denote the frequency-domain transmitted and received signals at the k-th subcarrier, respectively. H_k is the optical channel coefficient and $W_k \sim \mathcal{N}(0, \sigma^2)$ is the additive white Gaussian noise (AWGN) with variance σ^2. We follow [21] to define the signal to noise ratio (SNR) of the system, which is expressed as

$$\gamma = \frac{P}{N_{\mathrm{F}} \sigma^2}, \tag{10}$$

where P is the total transmit electric power of the whole system.

III. Proposed Hybrid Dimming Scheme

In this section, the index modulation based hybrid dimming scheme is proposed based on the maximization of the channel capacity.

A. Channel Capacity Analysis

In each group of the index modulation aided VLC system, the mutual information can be decomposed due to the chain rule of mutual information,

$$I(\mathbf{x}_{\mathrm{s}}, \mathbf{x}_{\mathrm{c}}; \mathbf{y}) = I(\mathbf{x}_{\mathrm{s}}; \mathbf{y} | \mathbf{x}_{\mathrm{c}}) + I(\mathbf{x}_{\mathrm{c}}; \mathbf{y}), \tag{11}$$

where $\mathbf{x}_{\mathrm{c}}$ and $\mathbf{x}_{\mathrm{s}}$ denote the index-domain symbols and the constellation-domain symbols in each group, respectively. Thus the total mutual information can be expressed as the sum of the index-domain information $I(\mathbf{x}_{\mathrm{c}}; \mathbf{y})$ and the constellation-domain information $I(\mathbf{x}_{\mathrm{s}}; \mathbf{y} | \mathbf{x}_{\mathrm{c}})$.

According to the properties of the mutual information, the constellation-domain part can be given as

$$I(\mathbf{x}_{\mathrm{s}}; \mathbf{y} | \mathbf{x}_{\mathrm{c}}) = \sum_{j=1}^{\binom{L}{K}} \Pr(\mathbf{x}_{\mathrm{c}} = \Psi_j) I(\mathbf{x}_{\mathrm{s}}; \mathbf{y} | \mathbf{x}_{\mathrm{c}} = \Psi_j), \tag{12}$$

where Ψ_j denotes the j-th index-domain symbol with $j \in \{1, 2, ..., \binom{L}{K}\}$, and $I(\mathbf{x}_{\mathrm{s}}; \mathbf{y} | \mathbf{x}_{\mathrm{c}} = \Psi_j)$ denotes the mutual information when the index-domain symbol is selected to be Ψ_j, which can be expressed as

$$I(\mathbf{x}_{\mathrm{s}}; \mathbf{y} | \mathbf{x}_{\mathrm{c}} = \Psi_j) = \sum_{i \in \Psi_j} \log_2(1 + \frac{\gamma |H_i|^2 L}{K}). \tag{13}$$

Suppose the activated subcarriers are selected with equal probability $\Pr(\mathbf{x}_{\mathrm{c}} = \Psi_j) = 1/\binom{L}{K}$, thus the mutual information can be further derived as

$$\begin{aligned} I(\mathbf{x}_{\mathrm{s}}; \mathbf{y} | \mathbf{x}_{\mathrm{c}}) &= \sum_{j=1}^{\binom{L}{K}} \frac{1}{\binom{L}{K}} \sum_{i \in \Psi_j} \log_2(1 + \frac{\gamma |H_i|^2 L}{K}) \\ &= \frac{1}{\binom{L}{K}} \sum_{j=1}^{\binom{L}{K}} \sum_{i \in \Psi_j} \log_2(1 + \frac{\gamma |H_i|^2 L}{K}) \\ &= \frac{K}{L} \sum_{i=1}^{L} \log_2(1 + \frac{\gamma |H_i|^2 L}{K}). \end{aligned} \tag{14}$$

On the other hand, the index-domain mutual information can be given as

$$\begin{aligned} I(\mathbf{x}_{\mathrm{c}}; \mathbf{y}) = \frac{1}{\binom{L}{K}} \sum_{j=1}^{\binom{L}{K}} \int_{\mathbf{y}} f(\mathbf{y} | \mathbf{x}_c = \Psi_j) \\ \times \log_2(\frac{f(\mathbf{y} | \mathbf{x}_c = \Psi_j)}{f(\mathbf{y})}) \mathrm{d}\mathbf{y}, \end{aligned} \tag{15}$$

where $f(\mathbf{y})$ is the probability distribution function of $\mathbf{y}$, and $f(\mathbf{y} | \mathbf{x}_c = \Psi_j)$ is the conditional probability distribution function when $\mathbf{x}_c = \Psi_j$. According to [21], the index-domain mutual information has no closed-form expression. Thus the upper bound of the index-domain mutual information can be utilized as an approximation, which is given by

$$I(\mathbf{x}_{\mathrm{c}}; \mathbf{y}) \approx \log_2 \binom{L}{K}. \tag{16}$$

Thus the channel capacity C of the index modulation aided VLC system is expressed as

$$\begin{aligned} C &= \frac{W}{N_{\mathrm{F}}} G I(\mathbf{x}_{\mathrm{s}}, \mathbf{x}_{\mathrm{c}}; \mathbf{y}) \\ &= \frac{W}{4L} (I(\mathbf{x}_{\mathrm{s}}; \mathbf{y} | \mathbf{x}_{\mathrm{c}}) + I(\mathbf{x}_{\mathrm{c}}; \mathbf{y})). \end{aligned} \tag{17}$$

We substitute (14) and (16) into (17), and the channel capacity is finally derived as

$$C \approx \frac{W}{4L} \log_2 \binom{L}{K} + \frac{WK}{4L^2} \sum_{i=1}^{L} \log_2(1 + \frac{\gamma |H_i|^2 L}{K}). \tag{18}$$

B. Index Modulation Based Frequency-Domain Optimization

The proposed hybrid dimming scheme consists of two steps. In the first step, the frequency-domain dimming is applied based on the maximization of the channel capacity.

The first part of (18) can be approximated using the Stirling's approximation, which is expressed as

$$\begin{aligned} &\frac{W}{4L} \log_2 \binom{L}{K} = \frac{W}{4L} \log_2 \frac{L!}{K!(L-K)!} \\ \approx &\frac{W}{4L} [(L + \frac{1}{2}) \log_2(L) - (L - K + \frac{1}{2}) \log_2(L - K) \\ &- (K + \frac{1}{2}) \log_2(K) - \frac{\log_2(2\pi)}{2}]. \end{aligned} \tag{19}$$

Generally, the optical channel is constituted by the direct line-of-sight component, the reflections and the noises [22]. In this paper, the simplified AWGN channel is adopted for theoretical analysis. Under the AWGN channel model, the optical channel coefficient is set to be $|H_k| = 1$ with $k = 1, 2, ..., N_{\mathrm{F}}$. Thus the second part of (18) can be further simplified as

$$\frac{WK}{4L^2}\sum_{i=1}^{L}\log_2(1+\frac{\gamma|H_i|^2L}{K}) = \frac{WK}{4L}\log_2(1+\frac{\gamma L}{K}). \quad (20)$$

Thus the channel capacity under the AWGN channel is further approximated as

$$\begin{aligned} C \approx & \frac{WK}{4L}\log_2(1+\frac{\gamma L}{K}) + \frac{W}{4L}[(L+\frac{1}{2})\log_2(L) - \frac{\log_2(2\pi)}{2} \\ & - (L-K+\frac{1}{2})\log_2(L-K) - (K+\frac{1}{2})\log_2(K)], \end{aligned} \quad (21)$$

and the derivative of C in terms of K is given as

$$\begin{aligned} C' = & \frac{W}{4L}\log_2(\frac{(K+\gamma L)(L-K)}{K^2}) - \frac{W}{4\ln 2L(K+\gamma L)} \\ & + \frac{W(2L-2K+1)}{8\ln 2L(L-K)} - \frac{W(2K+1)}{8\ln LK}. \end{aligned} \quad (22)$$

In order to maximize the channel capacity, the optimal number of activated subcarriers in each group K can be derived by solving the equation $C' = 0$. Since the closed-form solution of the optimal K is not easy to obtain, numerical iterative methods can be used to solve the equation.

C. ACO-OFDM Based Time-Domain Dimming

In the second step, the positive and negative ACO-OFDM based time-domain dimming method is applied to further adjust the illumination level. The dimming level of the index modulation aided VLC system can be described as

$$\eta = \frac{\mathbb{E}[I_{\mathrm{LED}}] - I_{\mathrm{L}}}{(I_{\mathrm{H}} - I_{\mathrm{L}})} \times 100\%, \quad (23)$$

where $\mathbb{E}[I_{\mathrm{LED}}]$ denotes the expectation of the LED current. As a result, in order to obtain the illumination level η, the expectation $\mathbb{E}[I_{\mathrm{LED}}]$ should be set to

$$\mathbb{E}[I_{\mathrm{LED}}] = \eta(I_{\mathrm{H}} - I_{\mathrm{L}}) + I_{\mathrm{L}}. \quad (24)$$

According to [23], the ACO-OFDM symbols follow the clipped Gaussian distribution, the expectation of which is derived as $\sigma_{\mathrm{s}}/\sqrt{2\pi}$, where σ_{s} denotes the root mean square of the unclipped Gaussian distributed symbols. Thus after clipping and bias adding, the expectations of the positive and negative ACO-OFDM symbols are given as

$$\mathbb{E}[I^{\mathrm{PACO}}] = I_L + \frac{\sigma_{\mathrm{s}}}{\sqrt{2\pi}}, \quad (25)$$

and

$$\mathbb{E}[I^{\mathrm{NACO}}] = I_H - \frac{\sigma_{\mathrm{s}}}{\sqrt{2\pi}}, \quad (26)$$

where $\mathbb{E}[I^{\mathrm{PACO}}]$ and $\mathbb{E}[I^{\mathrm{NACO}}]$ denote the expectation of the positive and negative ACO-OFDM symbols, respectively. Thus the proportion of the two kinds of symbols can be utilized to adjust the expectation of the LED current. If we denote the proportion of the positive ACO-OFDM symbols as α, the expectation of LED current can be expressed as

$$\mathbb{E}[I_{\mathrm{LED}}] = \alpha(I_L + \frac{\sigma_{\mathrm{s}}}{\sqrt{2\pi}}) + (1-\alpha)(I_H - \frac{\sigma_{\mathrm{s}}}{\sqrt{2\pi}}). \quad (27)$$

Combing (24) and (27), the proportion α is derived according to the given illumination level, which is

$$\alpha = \begin{cases} 1, & \eta < \ _{\min} \quad \eta \\ \frac{(\eta-1)(I_{\mathrm{H}}-I_{\mathrm{L}})+\sigma_{\mathrm{s}}/\sqrt{2\pi}}{I_{\mathrm{L}}-I_{\mathrm{H}}+2\sigma_{\mathrm{s}}/\sqrt{2\pi}}, & \eta_{\min} \le \eta \le \eta_{\max} \\ 0, & \eta > \ _{\max}, \quad \eta \end{cases} \quad (28)$$

where $\eta_{\min}$ and $\eta_{\max}$ are given as

$$\eta_{\min} = \frac{\sigma_{\mathrm{s}}}{(I_{\mathrm{H}} - I_{\mathrm{L}})\sqrt{2\pi}}, \quad (29)$$

and

$$\eta_{\max} = 1 - \frac{\sigma_{\mathrm{s}}}{(I_{\mathrm{H}} - I_{\mathrm{L}})\sqrt{2\pi}}. \quad (30)$$

As a result, under the appropriate illumination level $\eta_{\min} < \eta < \eta_{\max}$, both the positive and negative ACO-OFDM symbols are transmitted with the proportion α.

If the illumination requirement is higher than $\eta_{\max}$ or lower than $\eta_{\min}$, only the negative or the positive symbols are utilized. In conventional dimming schemes, the scaling factor is further adjusted to meet the illumination requirement. While in our proposed hybrid dimming scheme, the number of activated subcarriers K provides another dimension for dimming control. Specifically, under the specific illumination levels $\eta_1 > \eta_{\max}$ and $\eta_2 < \eta_{\min}$, the transmitted symbols are required as

$$\sigma_{\mathrm{s},1} = \sqrt{2\pi}(1-\eta_1)(I_{\mathrm{H}} - I_{\mathrm{L}}), \quad (31)$$

and

$$\sigma_{\mathrm{s},2} = \sqrt{2\pi}\eta_2(I_{\mathrm{H}} - I_{\mathrm{L}}). \quad (32)$$

Therefore, the SNR of the received signals can be further given as

$$\gamma_1 = \frac{GK\sigma_{\mathrm{s},1}^2}{\sigma^2 N_{\mathrm{F}}} = \frac{2\pi GK(1-\eta_1)^2(I_{\mathrm{H}} - I_{\mathrm{L}})^2}{\sigma^2 N_{\mathrm{F}}}, \quad (33)$$

and

$$\gamma_2 = \frac{GK\sigma_{\mathrm{s},2}^2}{\sigma^2 N_{\mathrm{F}}} = \frac{2\pi GK\eta_2^2(I_{\mathrm{H}} - I_{\mathrm{L}})^2}{\sigma^2 N_{\mathrm{F}}}. \quad (34)$$

Thus the optimal K can be derived by substituting (33) and (34) into (21) to maximize the channel capacity. As a result, the required illumination level is achieved from both the frequency- and time-domain dimming methods.

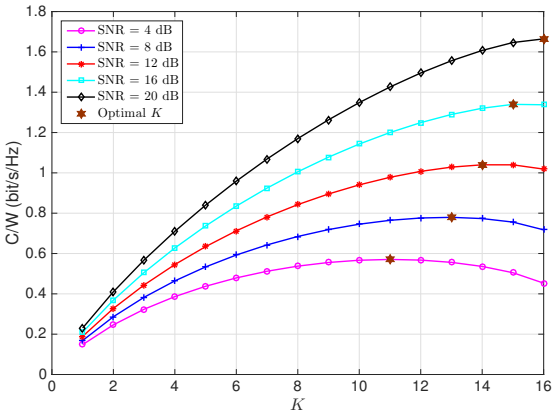


Fig. 2. Channel capacity versus the number of activated subcarriers in each group, where the number of subcarriers in each group is $L = 16$.

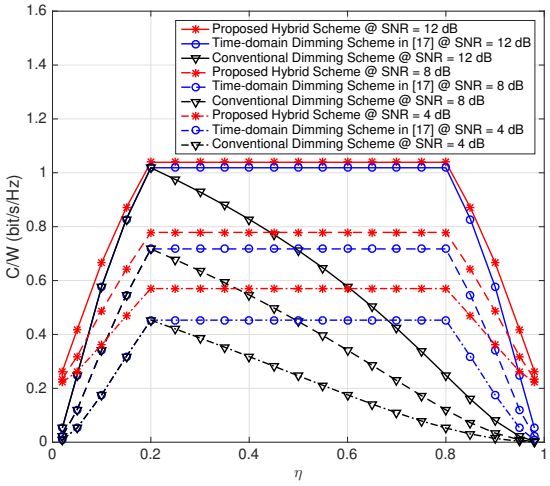


Fig. 3. Comparison of the channel capacity versus the illumination levels η, where the number of subcarriers in each group is $L = 16$.

IV. Simulation Results

In this section, the simulation results are provided to show the performance of the proposed hybrid dimming scheme. We consider an index modulation aided VLC system with $N_{\mathrm{F}} = 256$ subcarriers. Since ACO-OFDM is adopted, only $N = N_{\mathrm{F}}/4 = 64$ subcarriers can be utilized to transmit independent information. The subcarriers are divided into $G = 4$ groups and in each group only $L = 16$ subcarriers can be selected to transmit independent information. The AWGN channel is adopted in the simulations with $|H_k| = 1$ for $k = 1, 2, ..., N_{\mathrm{F}}$.

In Fig. 2, the channel capacities with different numbers of activated subcarriers K and SNRs γ are investigated. It can be seen from the figure that with the same number of activated subcarriers, the channel capacity rises with the increase of the SNR, which is because of the improvement of the constellation-domain capacity with higher SNR. It can also be seen that the optimal number of activated subcarriers is different with different SNRs. For example, the optimal number is $K = 14$ with SNR $= 12$ dB and $K = 15$ with SNR $= 16$ dB. It is worth noting that the optimal number of activated subcarriers becomes larger with higher SNR. It is because under the lower SNR situation, the contribution of the constellation-domain capacity to the total channel capacity is limited, therefore, smaller number of activated subcarriers can provide more index-domain capacity to maximize the total channel capacity. While under the higher SNR situation, the constellation-domain capacity improves and dominates the total channel capacity. Thus more subcarriers are activated to realize the maximization of the total channel capacity.

In Fig. 3, the channel capacities with different illumination requirements are investigated. The conventional ACO-OFDM dimming scheme using scaling factor adjustment and the time-domain dimming scheme proposed in [23] are simulated as comparisons. The dynamic range of the LED is $I_{\mathrm{L}} = 0$ and $I_{\mathrm{H}} = 2\mathrm{A}$. The signal power is limited as $\sigma_{\mathrm{s}} \leq 1\mathrm{A}$. It can be seen from the figure that the proposed hybrid dimming scheme enjoys much higher channel capacity than the conventional dimming scheme especially under the appropriate and high illumination requirements, which is because the illumination level can be controlled by the proportion of the positive and negative ACO-OFDM symbols in the proposed scheme while maintaining the channel capacity under appropriate illumination requirements. With time-domain strategies, the dimming scheme proposed in [23] can also maintain the channel capacity under the appropriate illumination requirements. However, the proposed hybrid dimming scheme still enjoys higher channel capacity, especially under the low and high illumination requirements, which is mainly because of the frequency-domain optimization step in the hybrid scheme. The adjustment of the number of the activated subcarriers provides another dimension for the channel capacity maximization. The performance gap becomes larger at low SNR region. For example, under the illumination requirement $\eta = 50\%$, the proposed scheme has 1.64 dB gain over the conventional dimming scheme and 0.08 dB gain over the time-domain dimming scheme with SNR $= 12$ dB. When SNR $= 4$ dB, the gains become 3.64 dB and 0.99 dB, respectively.

V. Conclusion

In this paper, a two-step hybrid dimming scheme has been proposed for the index modulation aided VLC system. The jointly frequency-time-domain dimming strategies have been utilized to maximize the channel capacity and realize the accurate dimming control. Simulation results have verified the superior performance of the proposed scheme over the state-of-art dimming schemes. The theoretical analysis and the numerical simulations in this paper can provide theoretical

basis and practical guidance for the implement of the index modulation technique in practical VLC systems.

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