Generalized Spatial Modulation Based Hybrid Dimming Scheme for Visible Light Communication

Tengjiao Wang[1], Fang Yang[1,2], Ling Cheng[3], Jian Song[1,2]
[1]Department of Electronic Engineering & Research Institute of Information Technology, Tsinghua University,
Beijing National Research Center for Information Science and Technology (BNRist), Beijing 100084, P. R. China
[2]Key Laboratory of Digital TV System of Guangdong Province and Shenzhen City,
Research Institute of Tsinghua University in Shenzhen, Shenzhen 518057, P. R. China
[3]School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, South Africa
E-mail: wangtj16@mails.tsinghua.edu.cn, fangyang@tsinghua.edu.cn, Ling.Cheng@wits.ac.za, jsong@tsinghua.edu.cn

***Abstract*—Visible light communication (VLC) is regarded as one of the promising candidate to complement the conventional radio frequency communication as it can potentially perform communication and illumination simultaneously. Recently, VLC is combined with generalized spatial modulation (GenSM) technology to improve spectral and energy efficiencies. In order to provide high speed communication and flexible dimming control simultaneously, in this paper, a spectral-efficient GenSM based hybrid dimming scheme, which combines the spatial-domain and time-domain dimming strategies, is proposed for VLC. The channel capacity of the proposed scheme is analyzed and a closed-form expression of the upper bound of the channel capacity is derived. According to the required illumination level, the spatial-domain and time-domain strategies are realized based on the maximization of the channel capacity. Simulation results substantiate the superior performance of the proposed dimming scheme over state-of-art dimming schemes.**

***Index Terms*—hybrid dimming control, generalized spatial modulation, channel capacity optimization, multiple-input multiple-output.**

I. Introduction

Recently, visible light communication (VLC) has drawn increasing attention from both academia and industry, since it can provide high-speed communication using the wide license-free visible light spectrum [1] [2]. In VLC, orthogonal frequency division multiplexing (OFDM) is one of widely used modulation technologies due to its inherent resistance to inter symbol interference [3] [4]. With the development of the light-emitting diodes (LEDs), VLC has been considered as one of the promising complements for the traditional radio frequency communications [5].

Generalized spatial modulation (GenSM) is an emerging modulation technology, which takes full advantage of the spatial domain to transmit more information [6]. Recently, GenSM is extended to the VLC system and the combination improves both the spectral efficiency and the energy efficiency of the VLC system [7]. With GenSM, some of the transmit LEDs are activated at the same time to transmit information and the combinations of the indices of the activated LEDs are utilized to transmit spatial-domain information as well [8]. So far, many academic researches have been done to evaluate the performance of the combination of GenSM and VLC, including the error performance [9] and the implementation complexity [10].

In VLC, the intensity modulation (IM) and the direct detection (DD) are widely used, where the information is modulated on the optical power of the LEDs [11]. Thus the VLC systems are required to provide precise dimming control while communicating. So far, many efforts have been devoted to the dimming methods for VLC, including modulation based methods [12], coding based methods [13] and adaptive methods [14] [15]. In [16], the authors introduce a spatial-domain dimming technique, which controls the illumination of the system through the number of activated LEDs. In [17], a hybrid dimming scheme is further introduced, which combines the spatial-domain dimming technique and the direct current biased optical OFDM (DCO-OFDM) technique to realize dimming control without direct current bias adjustment. However, since DCO-OFDM is adopted, the dynamic range is not fully exploited with high and low illumination requirements, which decreases the spectral efficiency.

This paper focuses on the spectral-efficient hybrid dimming scheme in VLC. A novel GenSM and asymmetrically clipped optical OFDM (ACO-OFDM) based hybrid dimming scheme is proposed, which combines the time-domain and spatial-domain dimming methods to realize flexible dimming control. The channel capacity is analyzed and a closed-form expression of the upper bound of the channel capacity is derived in the high signal to noise ratio (SNR) region. The channel capacity is further maximized in the proposed dimming scheme to achieve high spatial efficiency. Numerical simulations are carried out to substantiate the superior performance of the proposed dimming scheme over state-of-

Corresponding author: Fang Yang.

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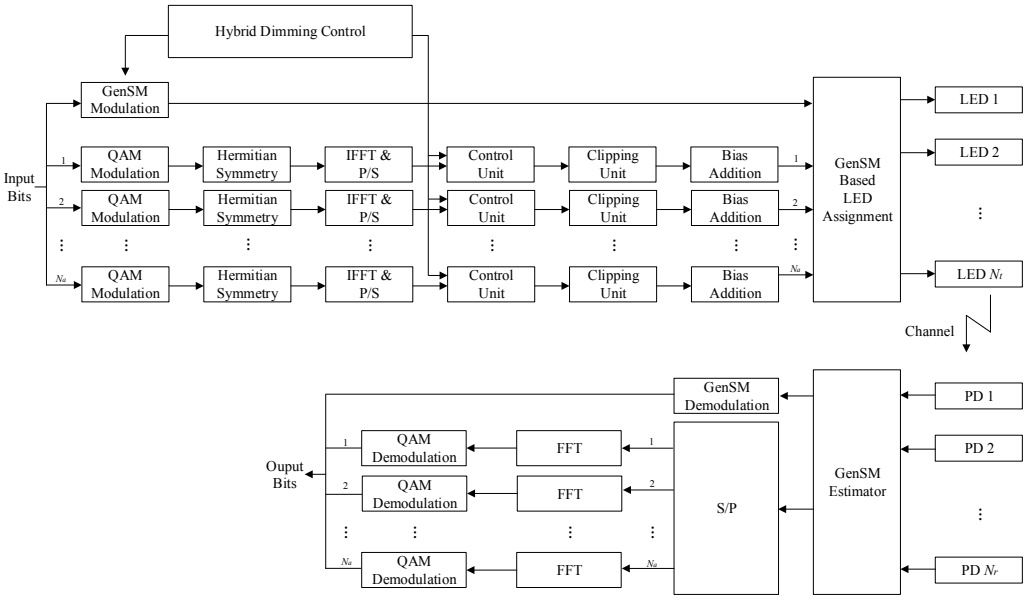


Fig. 1. The system model of the GenSM based hybrid dimming scheme.

art dimming schemes.

The remainder of this paper is organized as follows. The system model of the GenSM based VLC and the ACO-OFDM is briefly introduced in Section II. Then the channel capacity of the system is analyzed through the mutual information in Section III. In Section IV, the novel hybrid dimming scheme for VLC is proposed based on the maximization of the channel capacity. Simulation results are demonstrated in Section V and the paper concludes in Section VI.

II. System Model

A. GenSM Based Visible Light Communication

The system model of the considered GenSM based VLC system with OFDM is depicted in Fig. 1. The transmitter is equipped with N_t LEDs and the receiver is equipped with N_r photo detectors (PDs). Since GenSM is adopted, N_a LEDs are activated simultaneously in the VLC transmitter [6].

The input bits are split into two parts at the transmitter. One part is utilized to decide the indices of the activated LEDs according to the principle of GenSM. The other part is utilized to decide the transmitted symbols on the activated LEDs. It is further split into N_a streams and each stream is modulated by the M-ary quadrature amplitude modulation (M-QAM). The k-th frequency-domain symbol in the i-th data stream is denoted as $S_{i,k}$. It is then processed through the Hermitian symmetry block and the inverse fast Fourier transformation (IFFT) block to ensure that the time-domain symbol after IFFT is real, which is given as

$$s_{i,n} = \frac{1}{\sqrt{N}} \sum_{k=1}^{N} S_{i,k} e^{\frac{j2\pi nk}{N}}, \tag{1}$$

where $s_{i,n}$ denotes the n-th time-domain symbol in the i-th stream and N denotes the number of subcarriers. Then the time-domain symbols are clipped and added by the direct current bias to ensure that the transmitted symbols are within the dynamic range of the LEDs. Finally, the transmission function of the system is given as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}, \tag{2}$$

where $\mathbf{x} \in \mathbb{R}^{N_t \times 1}$ denotes the transmitted signal at the transmitter. $\mathbf{y} \in \mathbb{R}^{N_r \times 1}$ denotes the received signal at the receiver. $\mathbf{H} \in \mathbb{R}^{N_r \times N_t}$ denotes the VLC channel matrix. $\mathbf{w} \in \mathbb{R}^{N_r \times 1} \sim \mathcal{N}(\mathbf{0}, \sigma_{\mathrm{n}}^2 \mathbf{I}_{N_r})$ represents the additive white Gaussian noise (AWGN) with variance σ_{n}^2. According to the principle of GenSM, only N_a elements in $\mathbf{x}$ are non-zero, which is given as

$$\mathbf{x} = [0, ..., x_{p_1}, ..., x_{p_{N_a}}, ..., 0]^{\mathrm{T}}, \tag{3}$$

where $x_{p_i}, i \in [1, N_a]$ denotes the time-domain symbol in the p_i-th stream.

B. Asymmetrically Clipped Optical OFDM

ACO-OFDM is one of the most widely used OFDM scheme in VLC [18], which is adopted in this paper to realize the hybrid dimming. It is worth noting that other kinds of ACO-OFDM based methods such as layered ACO-OFDM [19] and hybrid ACO-OFDM [20] can be easily applied to the proposed hybrid scheme as well.

In the ACO-OFDM system with N subcarriers, the QAM symbols are only transmitted on the odd subcarriers to satisfy the Hermitian symmetry. Thus the frequency-domain symbol in the i-th stream is expressed as

$$\mathbf{S}_i = [0, S_{i,1}, 0, S_{i,3}, ..., S_{i,N/2-1}, 0, S_{i,N/2-1}^*, ..., 0, S_{i,1}^*]. \tag{4}$$

The corresponding time-domain symbols after IFFT satisfy the anti-symmetry property, which is

$$s_{i,n} = -s_{i,n+N/2}, \quad 0 < n < \frac{N}{2}. \tag{5}$$

Thus we can clip either the positive part or the negative part of the time-domain symbols without any information loss. The positive and negative clipped ACO-OFDM symbols are denoted as $s_{i,n}^{\mathrm{PACO}}$ and $s_{i,n}^{\mathrm{NACO}}$, which are given as

$$s_{i,n}^{\mathrm{PACO}} = \begin{cases} s_{i,n}, & s_{i,n} \geq 0 \\ 0, & s_{i,n} < 0, \end{cases} \tag{6}$$

and

$$s_{i,n}^{\mathrm{NACO}} = \begin{cases} 0, & s_{i,n} > 0 \\ s_{i,n}, & s_{i,n} \leq 0. \end{cases} \tag{7}$$

It is proved that the clipping distortion only affects the even subcarriers, which will not influence the demodulation at the receiver [21], thus the received frequency-domain symbols is given as

$$S_{i,n}^{\mathrm{PACO}} = S_{i,n}^{\mathrm{NACO}} = \frac{S_{i,n}}{2}, \text{when } n \text{ is odd}. \tag{8}$$

Then the ACO-OFDM symbols are rescaled and direct current bias are added. The positive ACO-OFDM symbols are added by the minimum current of the LED dynamic range I_{L} and the negative ACO-OFDM symbols are added by the maximum current of the LED dynamic range I_{H}, respectively. Thus the n-th transmitted symbol in the i-th stream is given as

$$x_{i,n}^{\mathrm{PACO}} = \begin{cases} \beta_i s_{i,n} + I_{\mathrm{L}}, & s_{i,n} \geq 0 \\ I_{\mathrm{L}}, & s_{i,n} < 0, \end{cases} \tag{9}$$

and

$$x_{i,n}^{\mathrm{NACO}} = \begin{cases} I_{\mathrm{H}}, & s_{i,n} > 0 \\ \beta_i s_{i,n} + I_{\mathrm{H}}, & s_{i,n} \leq 0, \end{cases} \tag{10}$$

where β_i is the scaling factor in the i-th stream. The proportion of the PACO-OFDM symbols and the NACO-OFDM symbols can be adjusted to control the illumination level of the system, which will be explained in detail in Section IV.

III. Theoretical Channel Capacity Analysis

As shown in [22], the channel capacity of the GenSM based system can be analyzed by the mutual information between the transmitted symbols and the received symbols. Due to the chain rule of mutual information, the total mutual information can be decomposed into two parts,

$$I(\mathbf{x}, x^{\mathrm{index}}; \mathbf{y}) = I(\mathbf{x}; \mathbf{y}|x^{\mathrm{index}}) + I(x^{\mathrm{index}}; \mathbf{y}), \tag{11}$$

where x^{index} denotes the indices of the activated LEDs. $I(\mathbf{x}; \mathbf{y}|x^{\mathrm{index}})$ and $I(x^{\mathrm{index}}; \mathbf{y})$ denote the mutual information carried by the QAM symbols and the spatial-domain symbols, respectively.

Suppose the diagonalization precoding is adopted in the VLC system, the mutual information $I(\mathbf{x}; \mathbf{y}|x^{\mathrm{index}})$ can be expressed as the sum of N_a independent equivalent channels, which is

$$I(\mathbf{x}; \mathbf{y}|x^{\mathrm{index}}) = \frac{1}{N_c} \sum_{m=1}^{N_c} \sum_{u \in \Omega_m} \log_2\left(1 + \frac{P_{u,m}\sigma_{u,m}^2}{\sigma_{\mathrm{n}}^2}\right), \tag{12}$$

where $N_c = \binom{N_t}{N_a}$ denotes the number of different spatial-domain symbols. Ω_m denotes the set of indices of the activated LEDs in the m-th spatial-domain symbol. $P_{u,m}$ denotes the transmit power allocated to the u-th LED in Ω_m. $\sigma_{u,m}$ denotes the singular value of the channel matrix $\mathbf{H}$. σ_{n}^2 denotes the variance of the noise.

According to [22], the spatial-domain mutual information $I(x^{\mathrm{index}}; \mathbf{y})$ has no closed-form expression. In VLC, the SNR is generally considered to be high. Thus the high SNR approximation is utilized to derive the upper bound of spatial-domain mutual information [23], which is

$$I(x^{\mathrm{index}}; \mathbf{y}) = \log_2 N_c = \log_2\left(\frac{N_t!}{N_a!(N_t - N_a)!}\right). \tag{13}$$

Due to the Hermitian symmetry requirement of ACO-OFDM, only a quarter of the subcarriers are utilized to transmit independent symbols. Thus the upper bound of the channel capacity is finally derived as

$$\begin{aligned} C = \frac{W}{4N_c} \sum_{m=1}^{N_c} \sum_{u \in \Omega_m} \log_2\left(1 + \frac{P_{u,m}\sigma_{u,m}^2}{\sigma_{\mathrm{n}}^2}\right) + \\ \frac{W}{4} \log_2 \frac{N_t!}{N_a!(N_t - N_a)!}. \end{aligned} \tag{14}$$

where W denotes the whole bandwidth of the system.

IV. Proposed Hybrid Dimming Scheme

The proposed hybrid dimming scheme combines the spatial-domain dimming methods and the time-domain dimming methods to realize precise dimming control, which is composed of two steps.

A. GenSM Based Spatial-Domain Dimming

In the first step, the spatial-domain dimming is realized based on the maximization of the channel capacity. Since the second term of the channel capacity in (14) is independent with the power allocation, the power allocation problem can be formulated as

$$\begin{aligned} \max_{P_{u,m}} \ & \frac{W}{4N_c} \sum_{m=1}^{N_c} \sum_{u \in \Omega_m} \log_2\left(1 + \frac{P_{u,m}\sigma_{u,m}^2}{\sigma_{\mathrm{n}}^2}\right) \\ \text{s.t.} \ & \sum_{u \in \Omega_m} P_{u,m} = P, \quad m = 1, 2, ..., N_c, \end{aligned} \tag{15}$$

where P represents the total transmit power at the transmitter. We utilize the Lagrange multiplier method to solve the power allocation problem, where the Lagrange function is given as

$$\begin{aligned}\mathcal{L}(P_{1,m},...,P_{N_a,m},\lambda_1,...,\lambda_{N_c}) = \\ \frac{W}{4N_c}\sum_{m=1}^{N_c}\sum_{u\in\Omega_m}\log_2(1+\frac{P_{u,m}\sigma_{u,m}^2}{\sigma_{\rm n}^2})+ \\ \sum_{m=1}^{N_c}\lambda_m(\sum_{u\in\Omega_m}P_{u,m}-P).\end{aligned} \tag{16}$$

Thus the optimal power allocation can be derived as

$$P_{u,m} = (\mu - \frac{\sigma_{\rm n}^2}{\sigma_{u,m}^2})^+, \tag{17}$$

$$\mu = \frac{P+\sum_{i=1}^{M_m}\frac{\sigma_{\rm n}^2}{\sigma_{u,m}^2}}{M_m}, \tag{18}$$

where $(x)^+ = \{x(x>0); 0(x\leq 0)\}$ represents the positive part function. M_m denotes the number of non-zero $P_{u,m}$ in the m-th spatial-domain symbol. Then the derived optimal power allocation is taken back to (14) to obtain the channel capacity.

Then N_a is further optimized based on the channel capacity maximization. The first term of (14) can be simplified on condition that the channel capacity is independent with the specific spatial-domain symbols, which can be expressed as

$$\begin{aligned}\frac{W}{4N_c}\sum_{m=1}^{N_c}\sum_{u\in\Omega_m}\log_2(1+\frac{P_{u,m}\sigma_{u,m}^2}{\sigma_{\rm n}^2}) \approx \\ \frac{W}{4}\sum_{u=1}^{N_a}\log_2(1+\frac{P_u\sigma_u^2}{\sigma_{\rm n}^2}).\end{aligned} \tag{19}$$

Then we utilize the Stirling's approximation to express the second term of (14), which is given as

$$\begin{aligned}\frac{W}{4}\log_2\frac{N_t!}{N_a!(N_t-N_a)!}\approx\frac{W}{4}[(N_t+\frac{1}{2})\log_2(N_t)-\frac{\log_2(2\pi)}{2} \\ -(N_t-N_a+\frac{1}{2})\log_2(N_t-N_a)-(N_a+\frac{1}{2})\log_2(N_a)].\end{aligned} \tag{20}$$

Thus the upper bound of the channel capacity can be approximated as

$$\begin{aligned}C\approx\frac{W}{4}[\sum_{u=1}^{N_a}\log_2(1+\frac{P_u\sigma_u^2}{\sigma_{\rm n}^2})+(N_t+\frac{1}{2})\log_2(N_t)-\frac{\log_2(2\pi)}{2} \\ -(N_t-N_a+\frac{1}{2})\log_2(N_t-N_a)-(N_a+\frac{1}{2})\log_2(N_a)].\end{aligned} \tag{21}$$

Then the expression (21) can be maximized through many numerical iterative methods to derive the optimal N_a, including the steepest descent algorithm, the conjugate gradient method and so on.

B. ACO-OFDM Based Time-Domain Dimming

In VLC, the illumination level can be defined as

$$\eta = \frac{\sum_{i=1}^{N_a}\mathbb{E}[I_i]}{(I_H-I_L)N_t}\times 100\%, \tag{22}$$

where I_i denotes the current of the i-th LED and $\mathbb{E}[\cdot]$ represents the expectation operator. Thus if a specific illumination requirement η is given, the sum of the expectations of the currents is limited as

$$\sum_{i=1}^{N_a}\mathbb{E}[I_i] = \eta(I_H-I_L)N_t. \tag{23}$$

It is proven that the positive and negative ACO-OFDM symbols follow the clipped Gaussian distribution according to the central limit theorem [21]. Thus the expectations of the two kinds of symbols are given as

$$\mathbb{E}[I_i^{\rm PACO}] = I_L + \sigma_i^{\rm s}/\sqrt{2\pi}, \tag{24}$$

and

$$\mathbb{E}[I_i^{\rm NACO}] = I_H - \sigma_i^{\rm s}/\sqrt{2\pi}, \tag{25}$$

where $I_i^{\rm PACO}$ and $I_i^{\rm NACO}$ denote the current of the positive ACO-OFDM and the negative ACO-OFDM symbols in the i-th LED, respectively. $\sigma_i^{\rm s2}$ denotes the root mean square of the unclipped symbols in the i-th LED. Thus the expectation of I_i is further given as

$$\mathbb{E}[I_i] = \alpha(I_L+\sigma_i^{\rm s}/\sqrt{2\pi}) + (1-\alpha)(I_H-\sigma_i^{\rm s}/\sqrt{2\pi}). \tag{26}$$

where $\alpha(0\leq\alpha\leq 1)$ denotes the proportion of the positive ACO-OFDM symbols in a frame. Taken back into (23), the proportion α is further derived as

$$\alpha = \begin{cases}1, & \eta<\eta_{\min} \\ \frac{\eta(I_H-I_L)N_t-N_aI_H+\sum_{i=1}^{N_a}\sigma_i^{\rm s}/\sqrt{2\pi}}{N_a(I_L-I_H)+\sum_{i=1}^{N_a}2\sigma_i^{\rm s}/\sqrt{2\pi}}, & \eta_{\min}\leq\eta\leq\eta_{\max} \\ 0, & \eta>\eta_{\max},\end{cases} \tag{27}$$

where $\sigma_i^{\rm s}$ is given by the optimal power allocation. The thresholds $\eta_{\min}$ and $\eta_{\max}$ are derived as

$$\eta_{\min} = \frac{N_aI_H-\sum_{i=1}^{N_a}\sigma_i^{\rm s}/\sqrt{2\pi}}{(I_H-I_L)N_t}, \tag{28}$$

and

$$\eta_{\max} = \frac{N_aI_L+\sum_{i=1}^{N_a}\sigma_i^{\rm s}/\sqrt{2\pi}}{(I_H-I_L)N_t}. \tag{29}$$

Thus the illumination of the VLC system can be controlled through the proportion of the two kinds of symbols. For intermediate illumination requirement, the positive ACO-OFDM and the negative ACO-OFDM are transmitted with proportion α. While for low dimming requirement $\eta<\eta_{\min}$ and the high dimming requirement $\eta>\eta_{\min}$, only the positive ACO-OFDM and the negative ACO-OFDM are transmitted, respectively.

The proposed hybrid dimming scheme can be further extended to other kinds of optical communication. For example, the extension to the nonlinear optical communication systems [24] will be our future work.

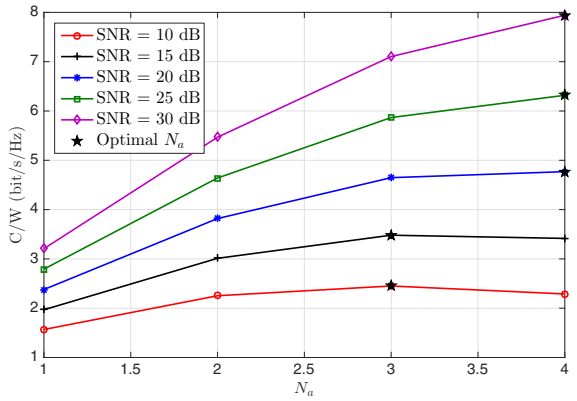


Fig. 2. Comparison of the channel capacity versus the number of activated LEDs N_a, where the number of transmit LEDs is 4.

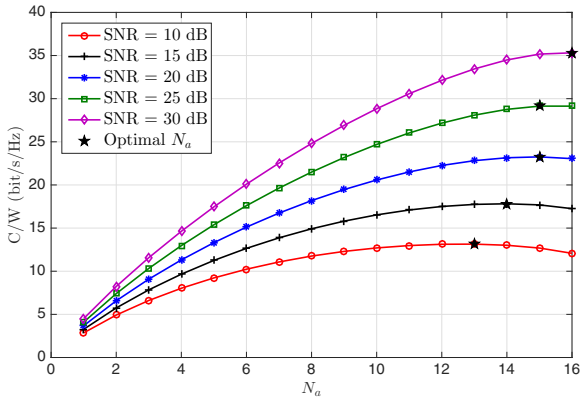


Fig. 3. Comparison of the channel capacity versus the number of activated LEDs N_a, where the number of transmit LEDs is 16.

V. Simulation Results

In order to validate the superior performance of the proposed hybrid dimming scheme, we consider a GenSM based VLC system using positive and negative ACO-OFDMs with the parameters generally considered in the existed researches. The minimum and maximum current levels of the dynamic range for the LEDs are set to $I_L = 0$ and $I_H = 1A$, respectively. The total transmit power and bandwidth are set to unity. The number of subcarriers is set to $N = 64$.

As illustrated in Fig. 2 and Fig. 3, the channel capacities versus the number of activated LEDs are simulated with different number of LEDs at the transmitter and receiver. The optimal N_a given by the proposed expression (21) is also illustrated in the figures. In Fig. 2, the number of LEDs is $N_t = N_r = 4$ and it is $N_t = N_r = 16$ in Fig. 3. It can be seen from the figures that the channel capacities increase with the growth of the SNR of the whole system. The channel capacity in Fig. 3 is much higher than that in Fig. 2 under the same SNR and N_a, since more spatial diversity is achieved with larger N_t. In the figures, the channel capacities start to fall after the optimal point with different rate, which is because of the falling of the spatial-domain mutual information. It is also shown that the optimal N_a derived by (21) is accordant with the real value, which validate the accuracy of the proposed expression.

The simulations of the channel capacities versus the illumination levels are carried out in Fig. 4. The channel capacities of the proposed scheme, the DCO-OFDM based hybrid dimming scheme with repetition coding (RC) in [17] and the DCO-OFDM based hybrid dimming scheme with spatial multiplexing are simulated for comparison. According to Fig. 2, $N_a = 3$ LEDs are activated to transmit signals under SNR = 10 dB and SNR = 15 dB for the channel capacity maximization. As demonstrated in Fig. 4, the proposed scheme achieves higher channel capacity than the DCO-OFDM scheme with RC in [17] under all the dimming levels due to the optimal power allocation. In the DCO-OFDM scheme with multiplexing, since different signals are

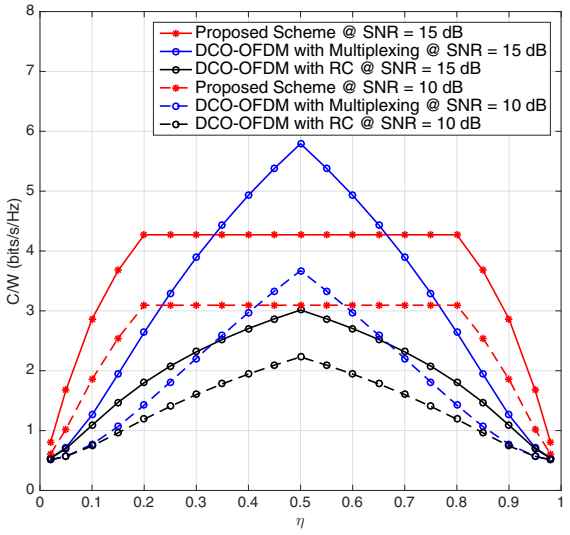


Fig. 4. Comparison of the channel capacity versus the illumination levels η, where the number of transmit LEDs is 4.

transmitted in the activated LEDs, it achieves much higher channel capacity than the DCO-OFDM scheme with RC. It can also be seen that the proposed scheme achieves high channel capacity under much wider dimming levels, since it utilizes the whole dynamic range of the LEDs in both PACO-OFDM and NACO-OFDM. Moreover, the proposed scheme enjoys much less demodulation complexity, since there is no need to adjust the DC bias and scaling factor in the proposed scheme. However, in the middle dimming levels, the DCO-OFDM scheme with multiplexing outperforms the proposed schemes because more subcarriers are utilized.

VI. Conclusion

In this paper, a novel hybrid dimming scheme, which combines the spatial-domain dimming and time-domain dimming, is proposed for visible light communication. The

channel capacity of the proposed scheme is derived and maximized to realize flexible dimming control and high spectral efficient communication at the same time. Compared with the conventional schemes, the proposed hybrid dimming scheme enjoys high spectral efficiency under much wider illumination requirements, which achieves a better balance between the illumination and the communication. The power consumption analysis and the extension to other kinds of optical communications will be our future work.

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