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Dimmable Spatial Intensity Modulation for Visible-light Communication: Capacity Analysis and Practical Design

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Multiple LED arrays can be utilized in visible-light communication (VLC) to improve communication efficiency, while maintaining smart illumination functionality through dimming control. This paper proposes a modulation scheme called "Spatial Intensity Modulation" (SIM), where the effective number of turned-on LEDs is employed for data modulation and dimming control in VLC systems. Unlike the conventional pulse-amplitude modulation (PAM), symbol intensity levels are not determined by the amplitude levels of a VLC signal from each LED, but by counting the number of turned-on LEDs, illuminating with a single amplitude level. Because the intensity of a SIM symbol and the target dimming level are determined solely in the spatial domain, the problems of conventional PAM-based VLC and related MIMO VLC schemes, such as unstable dimming control, non uniform illumination functionality, and burdens of channel prediction, can be solved. By varying the number and formation of turned-on LEDs around the target dimming level in time, the proposed SIM scheme guarantees homogeneous illumination over a target area. An analysis of the dimming capacity, which is the achievable communication rate under the target dimming level in VLC, is provided by deriving the turn-on probability to maximize the entropy of the SIM-based VLC system. In addition, a practical design of dimmable SIM scheme applying the multilevel inverse source coding (MISC) method is proposed. The simulation results under a range of parameters provide baseline data to verify the performance of the proposed dimmable SIM scheme and applications in real systems.

Keywords : Visible light communications (VLC), Multiple-input multiple-output (MIMO), Multi-level inverse source coding, Dimming capacity
OCIS codes : (060.4510) Optical communication, (060.4080) Modulation

I. INTRODUCTION

In recent years, visible-light communication (VLC) technology, as a complement to radio-frequency (rf), has attracted considerable interest for future wireless communication systems [1-6]. By reusing the existing LED infrastructure built for illumination, VLC provides LED lighting as well as communication capability. Because illumination is the primary function of LED luminaries, stable dimming control is an important issue for implementing VLC. Varying the dimming level can provide power savings and energy efficiency for LED lighting systems. Furthermore, emotional lighting, which alters the dimming level according to factors related to the environment, such as mood, music, food, and temperature, have become an important illumination scheme for many applications [7-9].

To improve communication throughput by distributing signal power over multiple channels, multiple-input-multiple-output (MIMO) techniques such as spatial modulation (SM), spatial multiplexing (SMP), space shift keying (SSK), generalized SM (GSM), and generalized SSK (GSSK) have been applied to VLC systems [10-15]. In SM, the data is encoded spatially along both the luminaire index and the pulse-amplitude modulation (PAM) intensity level. In SMP, independent data streams are encoded by PAM and emitted simultaneously from all transmitters. SSK activates only

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one LED among all LEDs in a given channel. GSSK modulation method differs from classical SSK in that more than one LED can be active, to determine the spatial position corresponding to a unique data symbol [10-12]. SM and SMP are special cases of GSM, which invokes higher transmission efficiency than the GSSK method [13-15]. Unfortunately, these schemes were developed mainly for communication functionality, not for stable dimming.

Conventional PAM used for SM, SMP and GSM schemes also suffers from unstable control of LED intensity. Because accurate amplitude control and stable illumination through LED driving circuits are affected by frequency, temperature, and other system parameters, the practical implementation of PAM for both data communication and illumination functionality is very challenging. Furthermore, PAM is susceptible to noise because noise affects amplitude, which is where information is stored in a PAM signal; hence, accurate information about intensity attenuation along multiple channels is required for data decoding. In the SSK and GSSK methods, activating one or only a few LEDs does not provide dimming control, and also results in nonuniform illumination of the target area. As the primary function of LED luminaries is high-quality illumination, a VLC system with multiple LEDs should provide a homogeneous illumination distribution. To the best of the authors' knowledge, a scheme for conventional PAM-based VLC and related MIMO VLC systems, to (1) solve the problems of amplitude-based modulation and nonuniform illumination, and (2) provide stable dimming control, has not been addressed in the literature.

To overcome the above shortcomings of conventional VLC schemes, this paper addresses a VLC modulation scheme named "Spatial Intensity Modulation" (SIM), which is a new concept providing a dimmable VLC solution, where the desired data modulation and stable dimming control can be achieved by activating the effective number of turned-on LEDs. Unlike the existing MIMO VLC schemes, the symbol-intensity level is not determined by the amplitude levels of a VLC signal from each LED, but by counting the number of fully-brightened LEDs, where each individual LED illuminates with an identical amplitude level. Because data encoding of the SIM scheme is served solely in the spatial domain, it can support the functionalities of dimming control and data decoding without careful configuration of signal-amplitude control and optical-channel prediction. Furthermore, the proposed scheme varies both the number and formation of spatially distributed "ON" and "OFF" LEDs around a target dimming level in time to satisfy a homogeneous illumination distribution over the target area. To investigate the achievable communication rate considering the dimming level, the dimming capacity of the proposed SIM scheme is presented by deriving turn-on probabilities while maximizing the entropy. In addition, we propose multilevel inverse source coding (MISC) applied to a dimmable SIM scheme, for practical realization. The simulation results under a range of parameters, such as the number of LEDs, target dimming, and signal-to-noise ratio (SNR), provide baseline data to confirm the performance of the proposed SIM scheme and its practical implementation for dimmable VLC.

The remainder of this paper is organized as follows. The theoretical design of the SIM scheme is presented in Section II. Section III addresses the practical implementation of the SIM scheme using MISC. Section IV reports evaluations of theoretical and practical dimming capacity. Section V presents the conclusions.

II. THEORETICAL DESIGN OF SPATIAL INTENSITY MODULATION

This paper considers a MIMO VLC system consisting of spatially distributed multiple LEDs. To generate a SIM symbol, data streams are converted to a blinking sequence that is depicted in the spatial domain. Each SIM symbol is represented by the effective number of fully brightened LEDs, where the formation of turned-on LEDs can be varied in time. For dimming functionality of LED luminaries, the time average of the intensity levels of SIM symbols is set to the target dimming level.

Figure 1 gives an example of the LED array's blinking sequence based on the proposed SIM scheme, where N_t is the total number of available LEDs and n is the effective number of turned-on LEDs. Note that n is time-varying and determined by the corresponding turn-on probability. To support a homogeneous illumination distribution, the turned-on LEDs should be distributed equally across all LEDs, as shown in Fig. 1. The possible intensity levels of the total N_t of the LED array are given by the following:

$$I_n = I_m \frac{n}{N_t}. \quad n = 1, 2, \ldots, N_t. \tag{1}$$

Here I_m denotes the maximum intensity of the LED array. For example, when $N_t = 4$, the possible intensity levels become $[I_m/4, I_m/2, 3I_m/4, I_m]$. To distinguish between operating and nonoperating time of a SIM-based VLC system, the case of full darkness, *i.e.* $n = 0$ (or $I_n = 0$), is not considered. Unlike the PAM-based modulation adopted in a conventional MIMO VLC, SIM symbol intensities are determined solely in the spatial domain, by counting the effective number of "ON" LEDs.

To satisfy the target dimming level during data transmission, the probabilities for selecting the effective number of turned-on LEDs, *i.e.* the turn-on probabilities, should be determined. In general, bits of digital information represent equally likely possibilities, *i.e.* '0' and '1' have approximately equal probabilities. When dimming control is not considered, the probabilities of all SIM symbols that can occur in a single trial are the same, and this yields only an average intensity level, of approximately $0.5I_m$. Therefore,

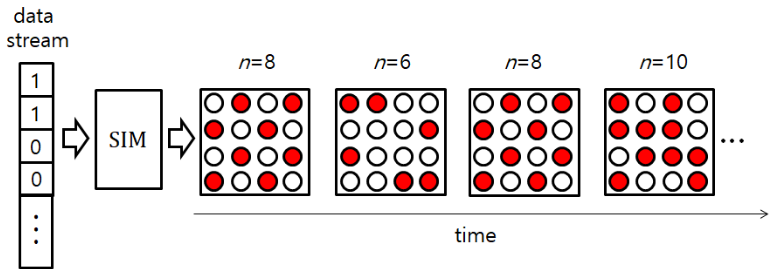


FIG. 1. Example of the total $N_t = 16$ LED array's blinking sequence, based on the spatial intensity modulation (SIM) scheme with a 50% target dimming level $((8+6+8+10)/4/16\times 100 = 50\%)$.

a scheme to provide dimming-control functionality while transmitting SIM symbols is required for practical implementation of VLC systems.

Let $p(n)$ be the turn-on probability for illumination with n turned-on LEDs. The entropy of discrete probabilities $\{p(1),\ldots,p(N_t)\}$ over n values can be represented as $H\{p(1),\ldots,p(N_t)\} = -\sum_{n=1}^{N_t} p(n)\log_2 p(n)$. Note that the normalization constraint is associated with the summation of each LED's turn-on probability. In addition, the dimming constraint is handled by varying the number of turned-on LEDs according to the corresponding probabilities in time.

Herein, the entropy-maximizing probability distribution of turned-on LEDs according to the dimming level requirement is derived. The distribution is obtained by maximizing the entropy of the SIM scheme, which is given by the following:

$$\begin{aligned}&maximize\ -\sum_{n=1}^{N_t} p(n)\log_2 p(n),\\ &subject\ to\ \sum_{n=1}^{N_t} p(n)=1,\ \ \sum_{n=1}^{N_t}\frac{I_m n}{N_t}p(n)=\zeta_D I_m,\end{aligned} \tag{2}$$

where ζ_D is the target dimming ratio $(0\le \zeta_D \le 1)$, and the target dimming level becomes $\zeta_D\cdot 100$ [%]. To solve this constrained optimization problem, the method of Lagrange multipliers is used. Taking the second derivatives provides a diagonal Hessian matrix with values of $-1/p(n)$; hence, the objective function (2) is concave. This suggests that the probabilities obtained from Eq. (2) produce a global solution. The augmented objective function $L(x)$, a function of the turn-on probabilities and Lagrange multipliers, is defined as follows:

$$\begin{aligned}L(p(1),p(2),\ldots,p(N_t),\beta,\gamma) = &-\sum_{n=1}^{N_t} p(n)\log_2 p(n)\\ &-\beta\left(\sum_{n=1}^{N_t} p(n)-1\right)\\ &-\gamma\left(\sum_{n=1}^{N_t}\frac{I_m n}{N_t}p(n)-\zeta_D I_m\right),\end{aligned} \tag{3}$$

where β and γ are scalar Lagrange multipliers.

Taking the functional derivative of Eq. (3) with respect to the variables, the followings can be obtained:

$$\left.\frac{\partial L}{\partial p(n)}\right|_{p^*(n),\beta^*,\gamma^*} = -\log_2 p^*(n) - \frac{1}{\ln 2} - \beta^* - \gamma^*\frac{I_m n}{N_t} = 0, \tag{4}$$

$$\left.\frac{\partial L}{\partial \beta}\right|_{p^*(n),\beta^*,\gamma^*} = \sum_{n=1}^{N_t} p^*(n) - 1 = 0, \tag{5}$$

$$\left.\frac{\partial L}{\partial \gamma}\right|_{p^*(n),\beta^*,\gamma^*} = \sum_{n=1}^{N_t}\frac{I_m n}{N_t}p^*(n) - I_m\zeta_D = 0, \tag{6}$$

where $p^*(n)$ is the optimal turn-on probability, and (γ^*,β^*) are the optimal values for the Lagrange multipliers. By rearranging Eq. (4) with regard to $p^*(n)$, it can be expressed as

$$p^*(n) = 2^{-\frac{1}{\ln 2}-\beta^*-\gamma^*\frac{I_m n}{N_t}}. \tag{7}$$

Note that Eq. (7) can be simplified as

$$p^*(n) = 2^{-a}r^n, \tag{8}$$

where

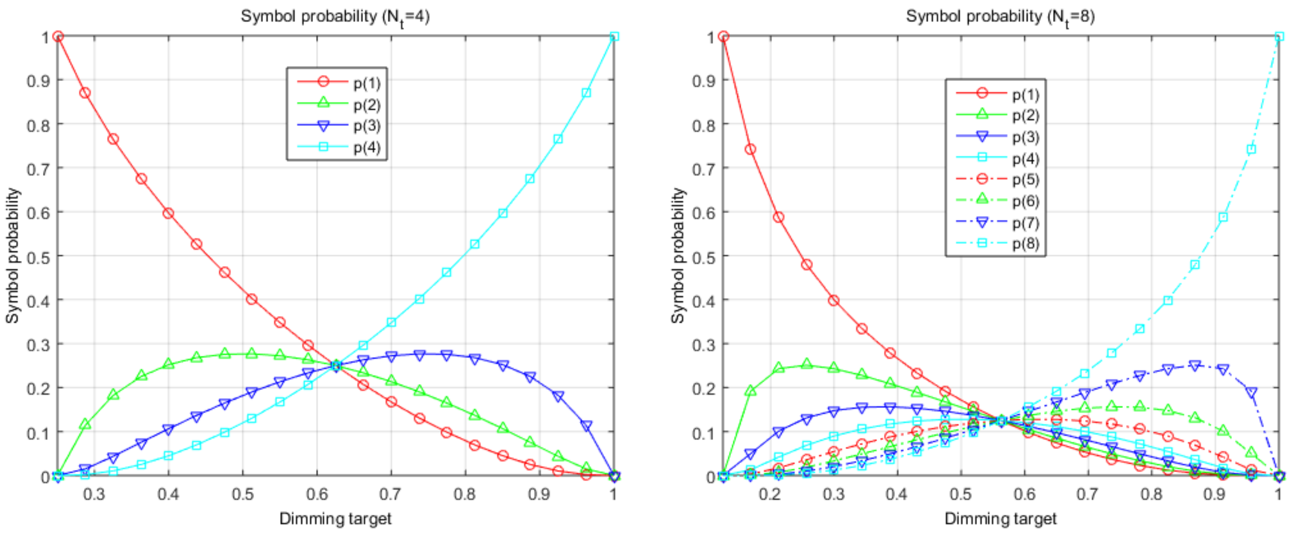
$$a = \frac{1}{\ln 2}+\beta^*, \qquad r = 2^{-\frac{\gamma^* I_m}{N_t}}. \tag{9}$$

Inserting Eq. (8) into (5), the equation can be simplified as follows:

$$2^a = \frac{r(1-r^{N_t})}{1-r}. \tag{10}$$

Then, Eq. (6) can be expressed as

$$\zeta_D = \frac{2^{-a}}{N_t}\left(\frac{r(1-r^{N_t-1})}{(1-r)^2} - \frac{(N_t-1)r^{N_t}}{(1-r)} + N_t r^{N_t}\right). \tag{11}$$



(a) (b)

FIG. 2. Optimal turn-on probabilities maximizing the entropy, when (a) $N_t = 4$ and (b) $N_t = 8$.

From Eqs. (9) and (11), the optimal Lagrange coefficients (β^*, γ^*) are determined. Using these coefficients, the optimal turn-on probability set $\{p^*(1), p^*(2), \ldots, p^*(N_t)\}$ maximizing the entropy with the given dimming constraint, can be obtained.

Figure 2 shows the optimal turn-on probabilities that maximize the entropy according to the dimming ratio, when the total number of LEDs is set to 4 and 8. To satisfy the target dimming ratio, the entropy-maximizing turn-on probability for each SIM signal level is different. For example, when $N_t = 4$, $\zeta_D = 0.775$, the turn-on probabilities maximizing entropy are set to $p(1) = 0.098$, $p(2) = 0.165$, $p(3) = 0.276$, $p(4) = 0.461$. This means that each SIM symbol should occur at the designated probabilities, according to the target dimming ratio. It can be seen that the curves are symmetrical with regard to the dimming ratio corresponding to the medium intensity ($\zeta_D = 0.625$ for $N_t = 4$, $\zeta_D = 0.563$ for $N_t = 8$). This enables the transmission of a SIM symbol maximize entropy, and thus, satisfying turn-on probabilities according to target dimming level.

Note that the proposed scheme randomly varies both the number and formation of spatially distributed "ON" and "OFF" LEDs around a target dimming level, in time. This is because a homogeneous illumination distribution over the target area cannot be achieved when signals are transmitted only with specific LED numbers and patterns. At the receiver, the signal can be decoded by measuring the received light intensity when a single photodioide (PD) is used, and by counting the number of turned-on LEDs when an array-type PD or image sensor is used.

III. PRACTICAL SIM DESIGN USING MULTILEVEL INVERSE SOURCE CODING

In the previous section we observed that the turn-on probabilities $p(n)$ present different values according to the target dimming ratio. The dimming constraint is handled by varying in time the number of turned-on LEDs according to the corresponding probabilities. This paper extends the concept of inverse source coding [16] to so-called "multilevel inverse source coding" (MISC), to meet the target dimming level of the SIM scheme from binary input data (0's and 1's). It preserves a way to attain the maximum entropy while satisfying the dimming target. In addition, it changes the symbol probabilities of '0' and '1' from 50% to appropriate values.In constructing codewords for MISC, Huffman codes (widely used for source coding) were considered. An example of a multilevel Huffman table using four different symbols is shown in Table 1, and the corresponding tree representation in Fig. 3. It can be observed that the SIM symbols are represented in binary data based on multilevel Huffman encoding. Similar to a general Huffman tree structure, the value of each node in Fig. 3 is the sum of its child values. In this example, the average intensity level of the SIM symbols can be

TABLE 1. Example of multilevel Huffman coding ($N_t = 4$, $\zeta_D = 0.775$)

Intensity	Turn-on probability	Codeword/Length
$I_m/4$	0.098	111 / 3
$I_m/2$	0.165	110 / 3
$3I_m/4$	0.276	10 / 2
I_m	0.461	0 / 1

obtained by $I_m \times 0.461 + 3I_m / 4 \times 0.276 + I_m / 2 \times 0.165 + I_m / 4 \times 0.098 = 0.775 \times I_m$.

Table 2 shows an example of MISC when $N_t = 4$. Because '0' and '1' are equally probable, the turn-on probability for each codeword is represented by $(0.5)^x$, where the length of the codeword is x. The length of each codeword in Table 2 is inversely proportional to the probability of the corresponding intensity level. In this case, the average dimming ratio can be calculated as $I_m \times 0.5 + 3I_m / 4 \times 0.25 + I_m / 2 \times 0.125 + I_m / 4 \times 0.125 = 0.781 \times I_m$. Using the table, evenly composed binary data are transformed to data with 78.1% as '1's, and thus the target dimming ratio can be achieved.

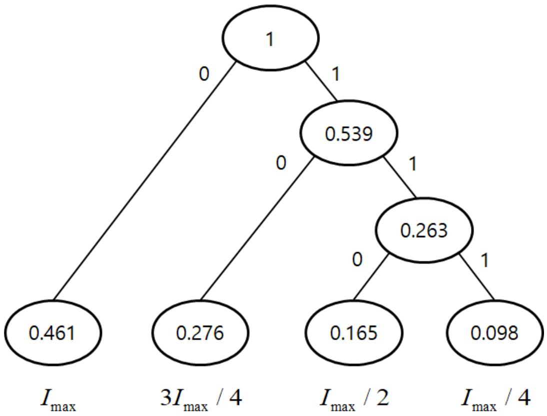


FIG. 3. Binary tree of multilevel Huffman encoding ($N_t = 4$, $\zeta_D = 0.775$).

TABLE 2. Example of multilevel inverse source coding ($N_t = 4$, $\zeta_D = 0.781$)

Codeword/Length	Turn-on probability	Intensity
111/3	0.125	$I_m / 4$
110/3	0.125	$I_m / 2$
10/2	0.25	$3I_m / 4$
0/1	0.5	I_m

Figure 4 shows turn-on probabilities using MISC according to the dimming ratio, when the total number of LEDs is set to 4 and 8. Because the probability value is scaled to a power of 0.5 according to the length of the codeword, turn-on probabilities in certain ranges of dimming ratio present identical values. As N_t increases, the shapes of the curves in Fig. 4 become close to those in Fig. 2; this means that the entropy of the MISC-based approach can be maximized by increasing the total number of available LEDs.

To retrieve the original information at the receiving side, the mapping table containing two attributes, codeword and corresponding intensity, as shown in Table 2 is used. After the symbol intensity has been received, the candidate codeword from the mapping table can be selected. Unlike the conventional PAM scheme, a symbol's intensity level is determined not by the amplitude levels of VLC signals, but by counting the effective number of turned-on LEDs in the SIM scheme. Therefore, the proposed SIM scheme obviates the need for the channel prediction that is essential for the PAM-based VLC scheme.

Figure 5 presents the achievable dimming level of a SIM scheme based on the optimal turn-on probabilities and the practical MISC-based approach. It can be seen that there is a small performance gap between the curves based on optimal and practical turn-on probabilities. However, as N_t increases, the performance gap becomes insignificant. Because small differences in dimming level cannot be perceived by the human eye, the use of MISC for a SIM

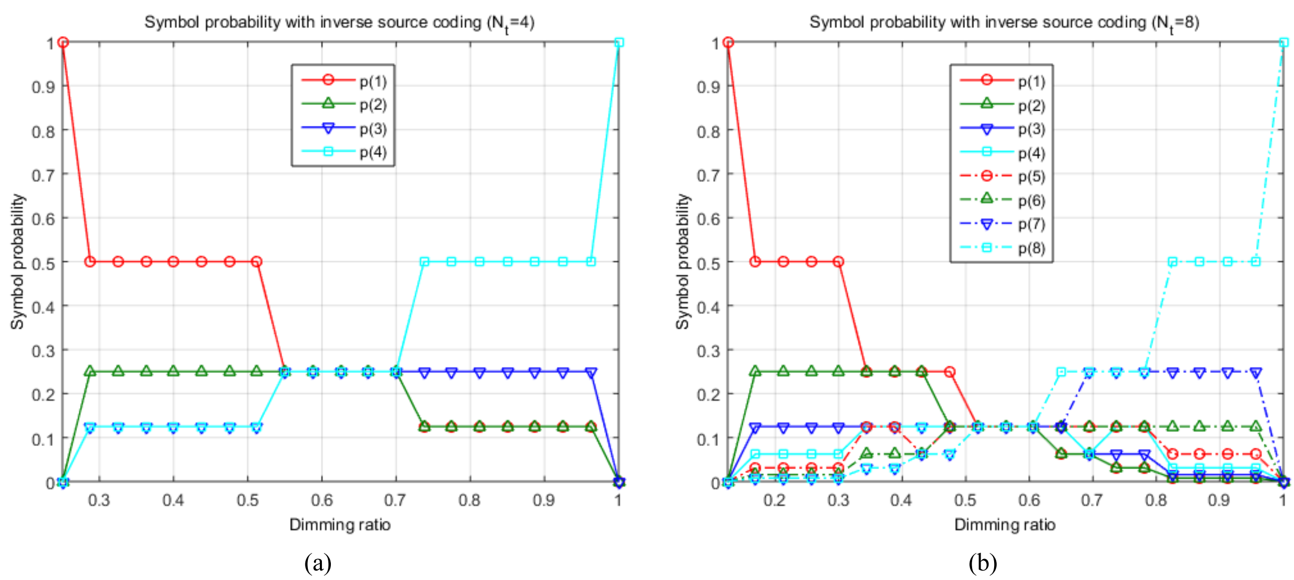
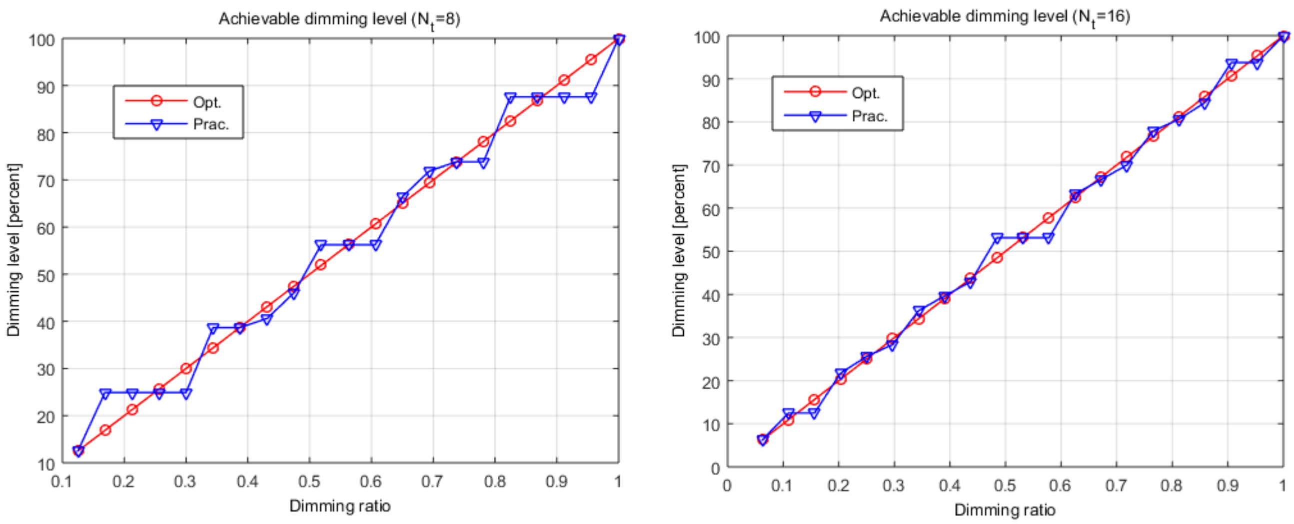


FIG. 4. Practical turn-on probabilities maximizing the entropy using multilevel inverse source coding, when (a) $N_t = 4$ and (b) $N_t = 8$.



(a) (b)

FIG. 5. Achievable dimming level of the SIM scheme, when (a) $N_t = 4$ and (b) $N_t = 8$.

scheme is practical for real systems.

Figure 6 compares the entropies of the SIM scheme based on the optimal and practical turn-on probabilities, with regard to the dimming ratio. It can be observed that the curves based on optimal and practical turn-on probabilities are close, for a range of dimming ratios. This means that the SIM scheme using MISC always guarantees robust performance in terms of entropy. The entropy of the SIM scheme increases with increasing total number of spatially distributed LEDs. When $N_t = 4, 8$, and 16, the maximum number of bits required to provide luminous amplitude becomes 2, 3, and 4 respectively. Note that the dimming ratio providing maximum entropy is the dimming ratio corresponding to the medium intensity of all LEDs, which varies according to N_t. Because the turn-on probabilities of all SIM symbols are the same at that intermediate intensity level, the maximum entropy value can be observed there.

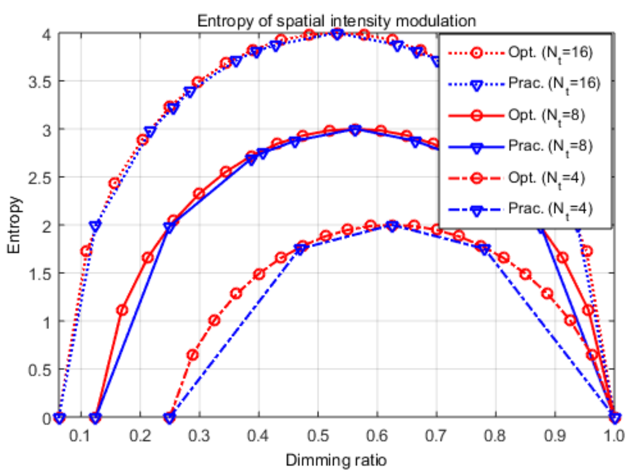


FIG. 6. Entropy versus the dimming ratio.

IV. ANALYSIS OF DIMMING CAPACITY

In this section, the dimming capacity of the SIM scheme is investigated by considering the VLC channel quality. “Dimming capacity” means the achievable communication rate, based on the modulation scheme and the target dimming constraint. To express the dimming capacity, mutual information based on the differential entropy is used. Assuming additive white Gaussian noise (AWGN), the received signal Y can be expressed as follows:

$$\mathrm{Y} = \mathrm{X} + \mathrm{Z}, \tag{12}$$

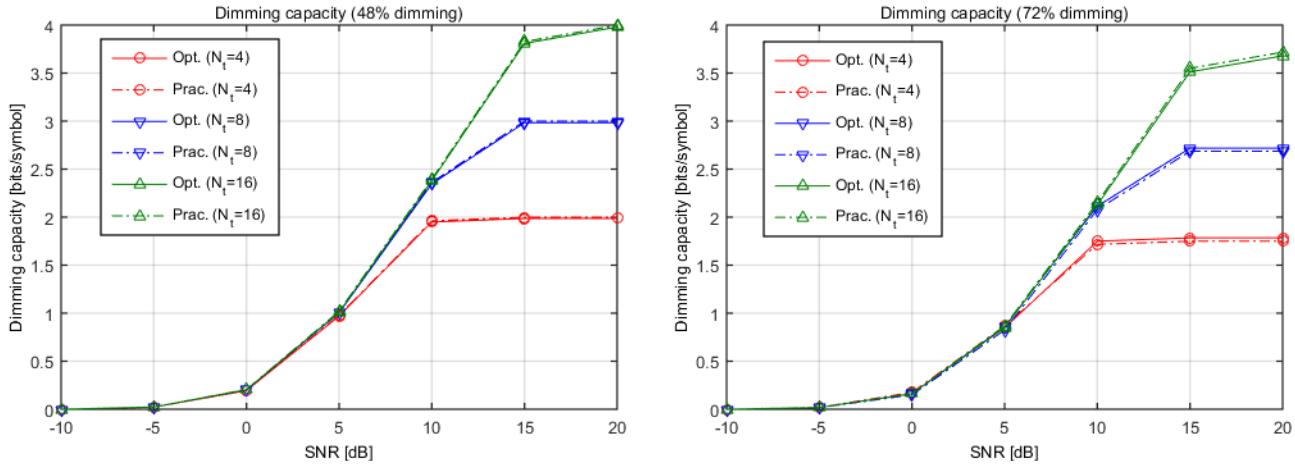
where X is the transmitted signal and $Z \sim N(0, \sigma^2)$. The mutual information between X and Y can be expressed as:

$$\begin{aligned} I(X;Y) &= H(Y) - H(Y \mid X) = H(Y) - H(Z) \\ &= -\int_{-\infty}^{\infty} P_Y(y)\log_2 P_Y(y)dyn \\ &\quad -\int_{-\infty}^{\infty} P_Z(z)\left(\log_2 \frac{1}{\sqrt{2\pi\sigma^2}} - \frac{z^2}{2\sigma^2}\log_2 e\right)dz \\ &= -\int_{-\infty}^{\infty} P_Y(y)\log_2 P_Y(y)dy - \frac{1}{2}\log_2(2\pi e\sigma^2), \end{aligned} \tag{13}$$

where

$$P_X(x) = \sum_{n=1}^{N_t} p^*(n)\delta(x - I_n), \tag{14}$$

$$P_Y(y) = \sum_{n=1}^{N_t} p^*(n)P_Z(y - I_n), \tag{15}$$



(a) (b)

FIG. 7. Dimming capacity versus SNR, when the dimming level is (a) 48% and (b) 72%.

$$P_Z(z) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-z^2}{2\sigma^2}\right). \tag{16}$$

Figure 7 presents the dimming capacity with various numbers of N_t, for target dimming levels of 48% and 72%. To observe the change in performance depending on the channel quality, the range of the signal-to-noise ratio (SNR) is set to $-10dB \sim 20dB$. Here the SNR is defined as I_m / σ, due to the visible-light communication link. The MISC-based practical approach achieve a capacity performance very close to the optimal result. With increasing SNR, the achievable communication rates of both the dimmable SIM scheme based on optimal turn-on probability and that based on the MISC approach increase. At high SNR (> 20 dB), the dimming capacity of both methods saturate. When the dimming level is set to 48% and the SNR is high, the SIM schemes with $N_t = 16$ and $N_t = 4$ can provide approximately 4 bits/symbol and 2 bits/symbol respectively. In addition, the performance gaps between the three cases ($N_t = 4,8,16$) become large with increasing SNR ($<15dB$). Because the medium intensity level of SIM symbols results in the maximum entropy (see Fig. 6), the dimming capacity at a 48% dimming level is greater than that at 72%.

Figure 8 presents the dimming capacity of the SIM scheme depending on both SNR and dimming ratio. As the SNR increases, the dimming capacity is saturated, regardless of the dimming ratio. However, the maximum dimming capacity increases with the increasing number of available spatial LEDs, N_t. When a large number of available spatial LEDs is employed, the SNR value resulting in saturation of the dimming capacity becomes large.

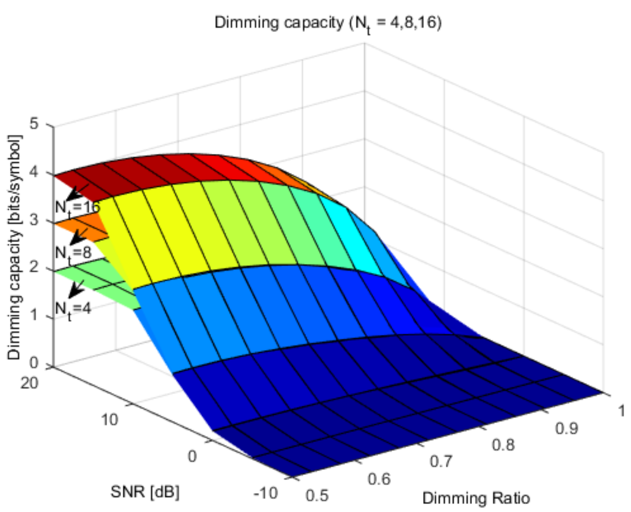


FIG. 8. Dimming capacity, depending on both SNR and dimming ratio.

V. CONCLUSION

In this paper, spatial intensity modulation (SIM), which uses the effective number of turned-on LEDs to encode data and support target dimming, was designed and investigated. Because data encoding in the SIM scheme is served solely in the spatial domain, it can avoid the need for careful configuration of signal-amplitude control, nonuniform illumination capability, and optical-channel prediction, which are strongly required in conventional PAM-based and related MIMO VLC methods. By solving the optimization problem, the turn-on probabilities that maximize the entropy of the SIM scheme were provided. For practical implementations of the SIM scheme with dimming requirements, a multilevel inverse source coding (MISC) was proposed. To analyze the achievable communication rate, the dimming capacity of the SIM scheme was derived under the target dimming constraint. The numerical results indicated that the capacity performances based on the optimal turn-on probability and on the practical MISC approach were close, over a range of SNR. In addition, it was observed that the maximum capacity of the SIM scheme depends strongly on the SNR, the total number of LED lights, and the target dimming level.

ACKNOWLEDGMENT

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