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Dimming Control Scheme of Visible Light Communication Based on Joint Multilevel Time-Shifted Coding

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Abstract: Dimming control is an essential objection in the signal designing of visible light communication (VLC), which requires improving the communication performance of the system as much as possible while considering the illumination quality. Here, we studied the problem of high-efficiency transmission in an indoor VLC multi-core light-emitting diode (LED) communication model while considering dimming constraints, and propose a dimming method based on joint multilevel multi-LED time-shifted coding (ML-MTSC). The scheme utilizes the code structure of time-shifted space–time codes to encode and uses pulse amplitude modulation (PAM) to expand it to achieve the dimming control function in the proposed scenario. Simulation results show that the ML-MTSC dimming control scheme proposed in this paper has improved spectral efficiency and error performance compared with the traditional scheme.

Keywords: wireless communication; visible light communication; dimming control; multilevel modulation

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1. Introduction

Visible light communication (VLC) utilizes widely distributed light-emitting diodes (LEDs) as transmitters and photodiodes (PDs) as receivers. Due to the feature of meeting the requirements of illumination and communication, VLC will play a significant role in the indoor wireless communication field. The explosive growth in demand for mobile data traffic in people's daily life and work, the gradually intensified contradiction between wireless spectrum resources, and the extensive use of LED equipment all lay a foundation for the rise and development of VLC. It is complementary to traditional wireless communication and brings advantages of energy-saving, security, convenient layout, and high-speed communication [1,2]. To facilitate practical application, the VLC system presented in the current study generally adopted intensity modulation at the transmitter and direct detection at the receiver, which is called intensity modulation/direct detection (IM/DD) [3].

In the current research, inspired by radio frequency (RF) communication technology, multi-carrier modulation technology—OFDM (orthogonal frequency division multiplexing)—was used in visible light communication to improve the transmission rate [4]. Some scholars have gradually increased the transmission rate [5–8] by using the technology of wavelength division multiplexing combined with OFDM modulation, and realized the real-time transmission rate of 15.73 Gbit/s using multi-color multi-core LED devices. It is worth noting that the high peak-to-average power ratio (PAPR) due to this type of modulation makes it easy to exceed the linear working area of LEDs. In addition, it is observed that the reuse of multiple LED cores is a feasible method to solve the limitations of single LED device transmission characteristics and to improve the data rate of the systems. In order to reduce the influence of channel correlation in MIMO channel model in visible light communication, a new constellation design method [9] and modulation scheme design [10,11] can be adopted to enhance the transmission reliability, and the diversity gain of the system can be improved by increasing the number of receivers and designing the receiver layout [12,13]. However, the distance and the angle between the receiver and the transceiver have a great influence on the channel gain, the spatial distribution of the receiver and the transceiver are highly required, and the mobility of the transceiver is poor, which affects practical applications.

In actual life, many indoor scenes are equipped with multiple LED lights, and most of the LED lights produced on the market are composed of multiple cores; these practices naturally constitute the communication model for the input of multiple indoor lights (multiple cores per lamp), as shown in Figure 1. Visible light communication systems not only regard communication function as the only goal, but also takes illumination functions into account. Then, in the design of the system, it is necessary to consider the peak and mean constraints of VLC signals to meet the users' illumination requirements [14,15].

(**a**) multiple indoor lights (**b**) multiple cores per lamp

Figure 1. Interior multi-lamp, multi-core per lamp.

In [16], the model of multi-core LED is considered, and a transmission scheme of multi-LED multi-core VLC time-shift space–time superposition is proposed. This scheme realizes the parallel transmission of multi-core LEDs and improves the data rate of the system through the relative movement of the signal sending time of each LED and the natural linear superposition in the spatial dimension. However, the scheme does not consider the dimming requirements of the system during the design process and does not meet the actual needs. A dimming control scheme has been presented [17], which makes use of the amplitude and space resources of multi-core LEDs, and uses a unique codeword structure to achieve reliable and efficient communication and support arbitrary dimming targets. In order to improve the spectral efficiency, we can consider a multilevel scheme inspired by the multilevel multiple pulse position modulation (ML-MPPM) [18,19] scheme and multilevel weight threshold check (ML-WTCC) [20] scheme. However, these scenarios are focused on a transmitter with a single multi-core LED scenario. In [21], a novel dimming control scheme which uses an additive unique decomposable constellation is proposed for single-core LEDs with different transmitter positions. However, there is no good scheme for dimming in indoor VLC systems where the transmitters are multi-LEDs with multiple cores in different positions.

In this paper, we propose a dimming control scheme based on joint multilevel-LED time-shifted coding (ML-TSC) to address the problem of high-efficiency transmission in a VLC multi-LED multi-core communication model while considering dimming constraints in indoor environments. We utilized the amplitude diversity of the multi-core LED, and superimposed the optical signals of a plurality of different LEDs and their time-delayed signals according to a specific codeword structure. In addition, we used the PAM method to perform multilevel expansion of the time-shifted spatial superposition code to realize the ML-TSC dimming method. In this paper, time division multiplexing access (TDMA) technology and ML-MPPM technology are presented as the compared scheme, which is recorded as the TDMA&ML-MPPM scheme. TDMA technology guarantees joint multi-transmitter communication, whereas ML-MPPM technology is responsible for multilevel dimming control of the VLC system. Results of the simulation show that the proposed scheme has better error performance and spectral efficiency than the TDMA&ML-MPPM scheme.

The paper is organized as follows. In Section 2, the system model of the joint multilevel multi-LED time-shifted coding dimming control scheme is introduced. Section 3 describes the code structure and implementation algorithm of the ML-MTSC scheme in detail. In Section 4, the communication reliability and effectiveness of the proposed scheme are analyzed and verified by simulation. Compared with the TDMA&ML-MPPM scheme, the proposed scheme has better communication performance. Section 5 concludes the text.

2. System Model

In this paper, we consider the scenario consisting of N LEDs as the transmitters and a PD as the receiver. Each of the LED contains $(l_{\max} - 1)$ cores. From the contents of [22], the channel gain can be represented by:

$$h_i = \begin{cases} \frac{S(m+1)}{2\pi {D_i}^2} \cos^m(\phi_i) T_S(\psi_i) g(\psi_i) \cos\psi, & 0 \le \psi_i \le \Psi_C \\ 0, & \psi_i > \Psi_C \end{cases}, \tag{1}$$

where $f(\psi_i) = T_S(\psi_i) g(\psi_i) \cos\psi$, A represents the PD's physical area, D_i is the distance from the ith LED to the PD, and m is the Lambertian index. ψ_i and ϕ_i represent the angle of incidence and angle of irradiance of the ith LED, respectively. Moreover, $T_S(\psi_i)$ and $g(\psi_i)$ are the filter gain and the concentrator gain of the ith LED, respectively. Ψ_C is the field-of-view (FOV) of the PD. Generally, in an indoor VLC scene, the distance between an LED and a PD is 1–3 (m). However, the distance between different LED cores in the same LED is a few centimeters [12]. As a result, in combination with the channel gain shown in Equation (1), we can suppose that the channel gains from different LED cores in the same LED to the PD are the same. Then, the channel gains of the proposed scenario can be summarized as:

$$\mathbf{h} = [h_1, h_2, \ldots, h_N]. \tag{2}$$

Assuming that in the scenario presented in this paper, based on the contents in [18], we can obtain that in an indoor VLC system, the intensity of reflected light is much less than that of direct light; thus, it can be negligible. Therefore, we can just consider the line of sight (LOS) link in this paper. The scenario provided in this paper is assumed to be a static link with a known channel gain, and the channel noise can be modeled as additive white Gaussian noise (AWGN). Thus, the received signal is:

$$\mathbf{y} = \mu \mathbf{h} \mathcal{S}(\mathbf{x}, M, N) + \mathbf{n}, \tag{3}$$

where $\mathcal{S}(\mathbf{x}, M, N)$ is a $N \times (M + N - 1)$ equivalent transmitted signal matrix, $\mathbf{x}$ is the original transmitted signal, $\mathbf{y}$ is the received signal, μ denotes the photoelectric conversion factor, which can be normalized as $\mu = 1$ for the sake of calculation, and $\mathbf{h}$ represents the channel gain vector. $\mathbf{n}$ is the AWGN with the mean of 0 and the variance of σ^2.

For indoor VLC systems with dimming control function, two constraints must be observed for human eye safety and LED nonlinearity: peak constraint and average constraint, respectively. Without loss of generality, the peak power can be normalized as $P = 1$. Consequently, as for each LED, the peak constraint and average constraint can be described as:

$$\begin{array}{l} 0 \leqslant x_i \leqslant l_{\max} - 1 \\ \overline{P} = E(\mathbf{x}) = \gamma P \end{array}, \tag{4}$$

where x_i is the optical power from the ith LED, $\overline{P}$ represents the average optical power, $E(\cdot)$ denotes the expectation operator, and γ is the dimming level which satisfies $\gamma \in (0, 1)$. From Equation (4), it can be seen that the dimming level is essentially the ratio of the average power to the peak power. Therefore, for the sake of achieving an arbitrary dimming target, the constraint should also be added on the average power, $\overline{P}$. Moreover, the essence of the dimmable indoor VLC system is to let the average power $\overline{P}$ be adjusted by digital communication technics such as modulation and coding so as to realize dimming control.

The system block diagram of the proposed joint multilevel multi-LED time-shifted coding (ML-MTSC) scheme is shown below.

As provided in Figure 2, after being inputted, the signals first enter the encoder for encoding according to the requirements of the dimmer controller. The encoder utilizes the encoding algorithm proposed in Section 3.2 to complete the operation. The $N \times (N + M - 1)$ equivalent transmitted signal matrix $\boldsymbol{S}$ can be obtained after encoding, and the value of each element is $0 \sim (l_{\max} - 1)$. Pulse amplitude modulation (PAM) can be used to modulate the encoder's output signal matrix to multi-core LEDs in different positions; then, the optical signals are transmitted through the optical channel with AWGN noise. At the receiver, the PD receives the superposed signals of the LEDs, samples the received signals, and sends them to the decoder. The decoder decodes the signals by utilizing the decoding algorithm provided in Section 3.2. Finally, the original transmitted signals can be obtained.

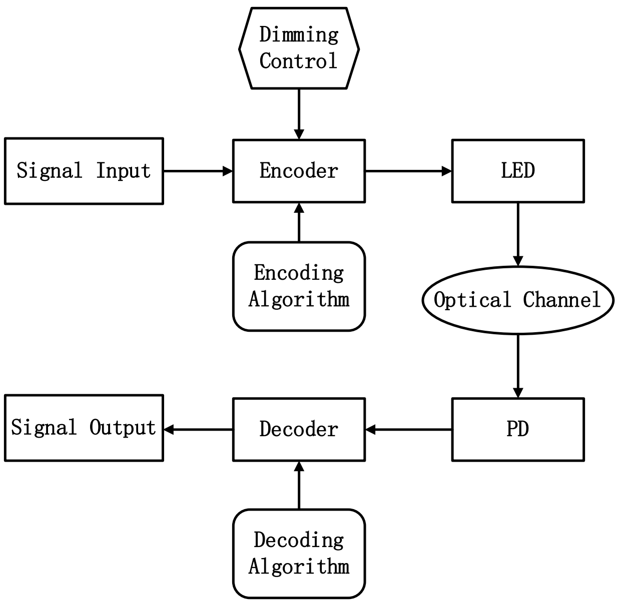

Figure 2. System block diagram of the ML-MTSC scheme.

3. Dimming Control Scheme Based on ML-MTSC

The codeword structure, coding algorithm, and decoding algorithm of the ML-MTSC scheme for the multiple LED scenario will be introduced in this section.

3.1. Codeword Structure

By using the codeword structure in [12], the multi-LED phase-shifted space–time coding scheme proposed in [13] can be extended to multilevel, which is convenient for dimming control in multi-core LEDs in different positions.

In Figure 3, a_i represents the optical power transmitted by the ith LED, which is an integer with the range of $[0, l_{\max} - 1]$, and T_s denotes the symbol period, in other words, the duration of a symbol. Each LED transmits the signal in turn with the interval of $\frac{1}{M}T_s$, where M is the number of the time slots in a symbol period. When the Nth LED transmits the signal, the first LED begins to send the next signal. The code block can be obtained after the N LED transmits the signals. As shown in Figure 3 and above, the period of a code block is:

$$T = \frac{(M + N - 1)}{M} T_S. \tag{5}$$

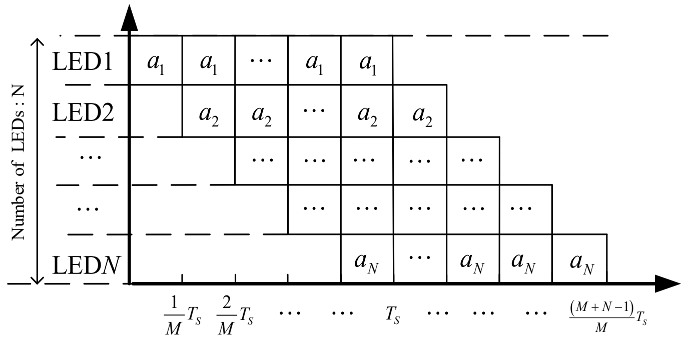

Figure 3. The codeword structure of the ML-MTSC scheme.

From the above, we can determine that $\mathbf{x} = (x_1, x_2, \cdots, x_N)$ is the symbol sequence that N LEDs need to transmit, where $x_i \in \{0, 1, \cdots (l_{\max} - 1)\}$, and it can be obtained by mapping a binary sequence with a length of $\log_2 l_{\max}$. In this study, we assumed that the original binary data are equiprobable and uncorrelated, i.e., the probabilities of '0′ and '1′ in the original binary data are identical and the positions of them are not correlated. Therefore, the element x_i in the symbol sequence $\mathbf{x}$ is the equal probability distribution in the set to which it belongs. When N (the number of the LEDs) is fixed and the dimming level requirement of the system is $\gamma \in (0, 0.5]$, the codeword structure in Figure 3 can be used and $a_i = x_i$. It can realize the dimming control function by adjusting the time slot number M. When the dimming level requirement of the VLC system is $\gamma \in (0.5, 1)$, it is necessary to send the symbol $(l_{\max} - 1)$ when the LEDs are free and $a_i = l_{\max} - 1 - x_i$. It can be thought as encoding the block under the condition of $\gamma \in (0, 0.5]$, then inverting the whole block. In this paper, inverting x_i is defined as $(l_{\max} - 1 - x_i)$. For instance, the second LED in Figure 3 is spare in the first time slot. When the required dimming level is $\gamma \in (0.5, 1)$ and $t \in \left(0, \frac{1}{M}T_s\right)$, LED2 will send the symbol '$(l_{\max} - 1)$'. Additionally, when $t \in \left(\frac{1}{M}T_s, \frac{N+1}{M}T_s\right)$, LED2 will send the symbol '$(l_{\max} - 1 - x_i)$'.

The full power output is $N \times (M + N - 1)$, when $0 < \gamma \leq 0.5$, the output power is $N \times M/2$; then, we can derive the dimming ratio as follows:

$$\gamma = \frac{\frac{N \times M}{2}}{N \times (M + N - 1)} = \frac{M}{2(M + N - 1)} \tag{6}$$

From the above description, the equation for calculating the dimming level of the proposed ML-MTSC scheme can be expressed as:

$$\gamma = \begin{cases} \frac{M}{2(M+N-1)}, & 0 < \gamma \leq 0.5 \\ 1 - \frac{M}{2(M+N-1)}, & 0.5 < \gamma < 1 \end{cases}. \tag{7}$$

3.2. Implementation of the Algorithm

First, we will introduce the encoding algorithm, the dimming control scheme based on the joint multilevel time-shifted coding is realized by multi-core LEDs in different positions. In general indoor VLC systems, the number of LEDs utilized for communication N is fixed, and the dimming level γ is a definite value according to the users' requirements. After the number of slots M is calculated by Equation (7), the equivalent transmitting signal matrix $\boldsymbol{S}$ can be obtained according to the codeword structure in Figure 3. The detailed process of the encoding algorithm is shown in Algorithm 1. Through the algorithm, N groups of binary data sequences can be jointly encoded to obtain a transmitting signal matrix $\boldsymbol{S}(\boldsymbol{x}, M, N)$. However, the channel gains between each LED and the PD are different because the N LEDs are in different positions. As shown in Equation (2), the channel gains can be represented by a channel gain vector of length N. The vector is multiplied by the transmitting signal matrix $\boldsymbol{S}$ to obtain an equivalent transmitted signal vector $\boldsymbol{r}$ with length $(M+N-1)$, which can be recorded as:

$$\boldsymbol{r} = \mu \boldsymbol{h}\boldsymbol{S}(\boldsymbol{x}, M, N), \tag{8}$$

The equivalent transmitted signal can also be thought of as the received signal vector without noise. In other words, it is the signal vector that can be obtained by the receiver after the optical signals are transmitted by LEDs at different positions and superimposed in the noiseless free-space optical channel.

Algorithm 1: Encoding Algorithm of the ML-MTSC Scheme

Input Dimming level γ, Number of LEDs N, Number of cores per LED $(l_{\max}-1)$, Binary data of each LED needs to send.
Step 1. Divide the transmitted information of each LED into several $\lfloor \log_2 l_{\max} \rfloor$ length binary sequence $\mathbf{b}$
Step 2. The binary sequence $\mathbf{b}_i$ of the ith LED is mapped to the decimal symbol x_i
Step 3. The number of slots M is calculated according to Equation (7)
Step 4. Encode according to the codeword structure in Figure 3.

```
If 0 < γ ≤ 0.5
For i = 1 : N
    For j = 1 : N + M − 1
        If i ≤ j ≤ i + M − 1
            S_ij = a_i = x_i
        Else j < i or j > i + M − 1
            S_ij = 0
Else 0.5 < γ < 1
For i = 1 : N
    For j = 1 : N + M − 1
        If i ≤ j ≤ i + M − 1
            S_ij = a_i = 1 − x_i
        Else j < i or j > i + M − 1
            S_ij = 1
```

Output Transmitted data matrix $\mathcal{S}(\mathbf{x}, M, N)$
End

The decoding algorithm is the inverse process of the encoding algorithm. As shown in Equation (3), the received signal $\boldsymbol{y}$ at the receiver from the PD is a $1 \times (M+N-1)$ column vector. From the discussion in this section, the equivalent transmitting signal $\boldsymbol{r}$ is also a column vector of $1 \times (M+N-1)$, and the maximum likelihood (ML) detection algorithm is utilized to detect the received signal. The detection algorithm compares the probability density function $p(\boldsymbol{y}|\boldsymbol{r})$ of the received signal $\boldsymbol{y}$ under the condition of equivalent transmitted signal $\boldsymbol{r}$, and utilizes the minimum distance from the received signal $\boldsymbol{y}$ to the equivalent transmitted signal $\boldsymbol{r}$ as the criterion to find the closest estimated signal. The ML detection algorithm is equivalent to the minimum Euclidean distance (MED) detection algorithm due to the input signal being equiprobable and the system noise being modeled as AWGN. The detector can be described as:

$$\hat{\boldsymbol{r}} = \operatorname{argmin} \|\boldsymbol{y} - \boldsymbol{r}\|_2^2, \tag{9}$$

where $\hat{\boldsymbol{r}}$ represents the estimation of the equivalent transmitted signal, and $\|\cdot\|_2^2$ denotes the square of the two-norms operator which is used to calculate the Euclidean distance between the received signal $\boldsymbol{y}$ and the equivalent transmitted signal $\boldsymbol{r}$. From Equation (8), it is shown that the equivalent transmitted signal can be obtained by the transmitted signal matrix and the channel gain vector. The transmitting signal matrix can be uniquely determined by the transmitted signal sequence $\boldsymbol{x}$ after the dimming level γ and the number of N LEDs are determined. Therefore, when the equivalent transmitted signal $\hat{\boldsymbol{r}}$ is estimated by the

ML detection algorithm at the receiver, the estimated value $\hat{\mathbf{x}}$ of the transmitted signal sequence can be uniquely determined by referring to the table. The estimated value $\hat{x}$ of the transmitted signal sequence is a $1 \times N$ column vector, and the element $\hat{x}_i$ represents the estimated value of the transmitted signal from the ith LED in the current period. Then, we mapped $\hat{x}_i$ to a binary sequence $\hat{\mathbf{b}}_i$ with length $\lfloor \log_2 l_{\max} \rfloor$, the binary data that the ith LED needs to send in the current cycle can be recovered. Algorithm 2 presents the decoding algorithm:

Algorithm 2: Decoding Algorithm of the ML-MTSC Scheme

Input Number of LEDs N, Dimming level γ, Number of cores in a LED $(l_{\max} - 1)$, Received signal $\mathbf{y} = (y_1, y_2, \cdots, y_{N+M-1})$
Step 1. The number of slots M is calculated according to Equation (7)
Step 2. Utilize ML detection algorithm to detect
$\hat{\mathbf{r}} = \text{argmin}\|\mathbf{y} - \mathbf{r}\|_2^2$.
The estimated transmitted signal sequence $\hat{\mathbf{x}}$ can be uniquely determined by looking up the table according to $\hat{\mathbf{r}}$
Step 3. Map the decimal estimated value $\hat{x}_i$ transmitted by the ith LED in the previous step to a binary sequence $\hat{\mathbf{b}}_i$ with length $\lfloor \log_2 l_{\max} \rfloor$.
Output The estimated value of the binary data that each LED needs to send
End

4. Performance Analysis and Simulation Results

This section presents the spectral efficiency and the error performance of the proposed ML-MTSC dimming control scheme, analyzed by simulations.

Before providing the performance analysis and simulation results above, the contrast scheme applied in this paper is introduced first. The ML-MTSC dimming control scheme presented in this paper is aimed at indoor VLC systems with dimming control functions, where the transmitters are multi-core LEDs in different positions and the receiver is a single PD. This scenario can be equivalent to sending different messages to the same user from different base stations in different positions. For this scenario, time division multiple access (TDMA) technology is usually utilized. The essence of TDMA technology is to assign different time slots to different transmitters and send information to the same receiver at different times. The receiver can distinguish the information of different transmitters by time and the requirement of joint multi-transmitter communication can be realized. Considering that each LED is a multi-core LED and the dimming control function is required in indoor VLC systems, the multilevel dimming control scheme should be applied to adjust the brightness. At present, the most classical and popular multilevel dimming control scheme is ML-MPPM. Through the combination of multilevel dimming control schemes and TDMA technology, a communication scheme with both communication and dimming control functions can be realized in the indoor VLC scenario where the transmitters are multi-core LEDs in different positions and the receiver is a single PD.

Its working principle is as follows: Firstly, the transmission signal is sent in n time slots, i.e., the codeword length is n. $(l_{\max} - 1)$ is the number of wicks in an LED lamp, then $l_{\max}$ is the maximum power that each LED can achieve, which is usually called the modulation level. S_i is the transmission signal of the ith time slot; thus, $i \in \{0, 1, 2, \cdots, n\}$ and $S_i \in \{0, 1, 2, \cdots l_{\max}\}$. We define the code weight of multilevel codeword as:

$$\omega = \sum_{i=1}^{n} S_i, \tag{10}$$

Then, we can derive $\omega \in \{0, 1, 2, \cdots, n(l_{\max} - 1)\}$. A set of codewords with equal code weight can then be used as the codeword set at the transmitting end, and its dimming level is as follows:

$$\gamma = \frac{\omega}{n(l_{\max} - 1)} \tag{11}$$

Let $R_{n,\omega}$ represent the codeword set with code length n and code weight ω, and $|R_{n,\omega}|$ represent the size of codeword set; its spectral efficiency can be expressed as:

$$v = \frac{\lfloor \log_2 |R_{n,\omega}| \rfloor}{n}. \tag{12}$$

To further understand the principle of ML-MPPM, Table 1 gives the codeword set when $l_{\max} = 3$, $n = 4$, and $\omega = 3$, and the dimming level at this time is $\gamma = 3/8$.

Table 1. The codeword set of ML-MPPM when $l_{\max} = 3$, $n = 4$, and $\omega = 3$.

0111	1011	1101	1110
2100	2010	2001	0210
0201	0021	1200	1020
1002	0120	0102	0012

It can be seen from Table 1 that at this time, the size of the codeword set is $|R_{4,3}| = 16$, and based on Equation (12), the spectral efficiency under this condition is:

$$v = \frac{\lfloor \log_2 |R_{4,3}| \rfloor}{4} = 1. \tag{13}$$

Combining the ML-MPPM dimming control scheme with TDMA technology, we can realize a communication scheme with both communication and dimming control functions for the indoor VLC model discussed in this paper. Under the condition that the number of LEDs is the same as the number of wicks of each LED, the spectrum efficiency and error performance of the TDMA&ML-MPPM scheme and the ML-MTSC scheme proposed in this paper are analyzed and compared in this section.

4.1. Spectral Efficiency

Spectral efficiency is an important index to measure the dimming control scheme of indoor VLC systems. It indicates the data rate that can be achieved by a communication scheme with limited bandwidth. The index of the ML-MTSC dimming control scheme proposed in this paper is shown as follows:

$$\nu = \frac{R_b}{B} = \frac{R_b}{\frac{1}{T_s}} = \frac{\frac{N \lfloor \log_2 l_{\max} \rfloor}{\frac{T_s(M+N-1)}{M}}}{N \frac{1}{T_s}} = \frac{M}{M+N-1} \lfloor \log_2 l_{\max} \rfloor. \tag{14}$$

In this section, we compare the spectral efficiency of the ML-MTSC dimming control scheme with that of TDMA&ML-MPPM dimming control scheme. For a fair comparison, the number of the LEDs was two, and the number of cores per LED was three, i.e., $(l_{\max} - 1) = 3$; thus, so the modulation order of each multilevel dimming control scheme was $l_{\max} = 4$. The spectral efficiency of the two schemes was compared, as shown in Figure 4.

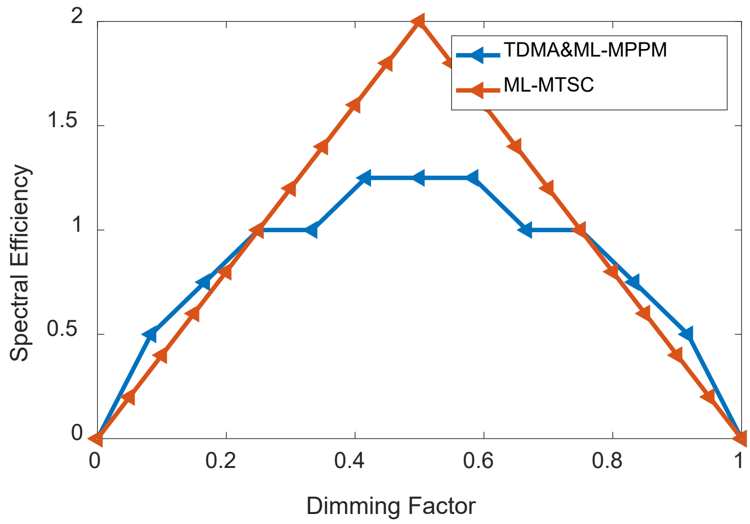

Figure 4. Spectral efficiency of the ML-MTSC scheme and the TDMA&ML-MPPM scheme.

From Figure 4, it is not difficult to see that the spectral efficiency of the ML-MTSC dimming control scheme is higher than that of the TDMA&ML-MPPM scheme at $\gamma \in (0.25, 0.75)$ when the LED number and the dimming level are the same. The spectral efficiency of a single LED is shown in Figure 4. TDMA is a time division multiplexing technique, where multiple LEDs transmit signals separately at different times to achieve joint communication. However, there is no gain in spectral efficiency. With the increase in N, the efficiency of communication will not change. The proposed ML-MTSC scheme makes full use of the spatial superposition of optical signals and the amplitude diversity of the multi-core LEDs. It can achieve multi-LED joint communication and realize the dimming control function. The efficiency can be improved with the increase in N.

4.2. Bit Error Performance

Error performance is another important index to evaluate the dimming control scheme of indoor VLC systems, which is used to measure the reliability of data transmission. The error performance is usually characterized by an error rate curve which describes the variation in the symbol error rate (SER) with the signal-to-noise ratio (SNR). From the contents in [16], the SNR under the normalized peak power constrained is defined as:

$$\text{SNR} = 10\text{lg}\frac{1}{R_C\sigma^2}, \tag{15}$$

where R_C is the bit rate. SER represents the ratio of the number of the error symbols to the number of the total transmitted symbols. It is often used to evaluate the reliability of multilevel signal design schemes. In order to investigate the error performance of the ML-MTSC scheme under different channel conditions. In Figure 5, the error rate curves of the ML-MTSC scheme and the TDMA&ML-MPPM scheme with $N = 2$, $l_{\max} = 4$, $\gamma = 1/3$ are provided under the condition on $h_1 : h_2 = 1 : 1$, $h_1 : h_2 = 1 : 2$, $h_1 : h_2 = 1 : 3$, and $h_1 : h_2 = 1 : 4$.

As can be seen in Figure 5, with the increase in channel difference, the error performance of the two schemes gradually becomes worse. This is because with the increase in channel difference, it means that one of the two LEDs is in an environment with relatively worse channel condition. The greater the difference, the worse the relative channel condition. The error performance of this channel deteriorates sharply, leading to the decrease in the system error performance. At the same time, we can see that the error performance of the ML-MTSC scheme is better than that of the TDMA&ML-MPPM scheme under all channel conditions. The greater the channel difference, the more obvious the error performance gain of the ML-MTSC scheme compared with the TDMA&ML-MPPM scheme. This is because the error performance of the system is related to the minimum Euclidean distance of the equivalent transmitted signal, and the equivalent transmitted signal encoded by the ML-MTSC scheme of N LEDs is equivalent to the tradeoff between the channel gains of the better channel and the worse channel while the channel gains of the TDMA&ML-MPPM scheme are not compromised. Therefore, the MED of equivalent transmitted signal of the TDMA&ML-MPPM scheme is less than that of the ML-MTSC scheme.

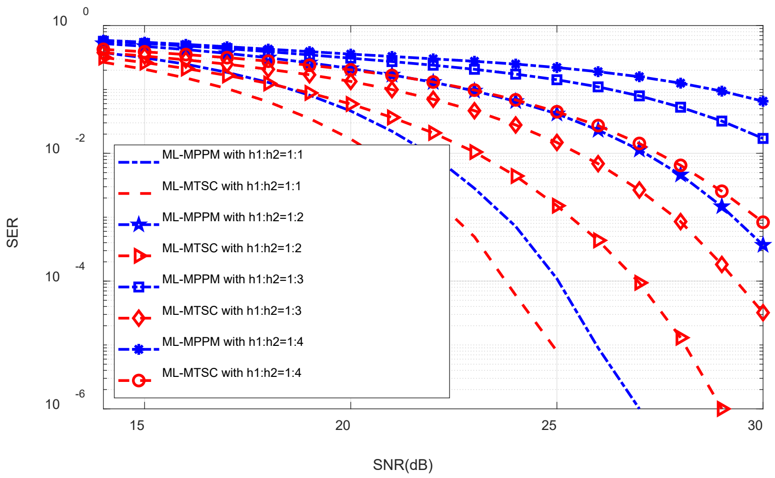

Figure 5. Error performance of the ML-MTSC scheme and the TDMA&ML-MPPM scheme.

Here, we discuss the influence of LED wick number on SER performance, and give the change in symbol error rate relative to SNR when $N = 2$, $h_1 : h_2 = 1 : 1$, as shown in Figure 6. With the increase in the number of LED cores, the error performance becomes worse. This is because the modulation level of multi-level symbols used in coding is determined by $l_{\max}$. With the increase in the order of codewords, the Euclidean distance between codewords becomes smaller, and the error performance in receiving and detecting will increase accordingly.

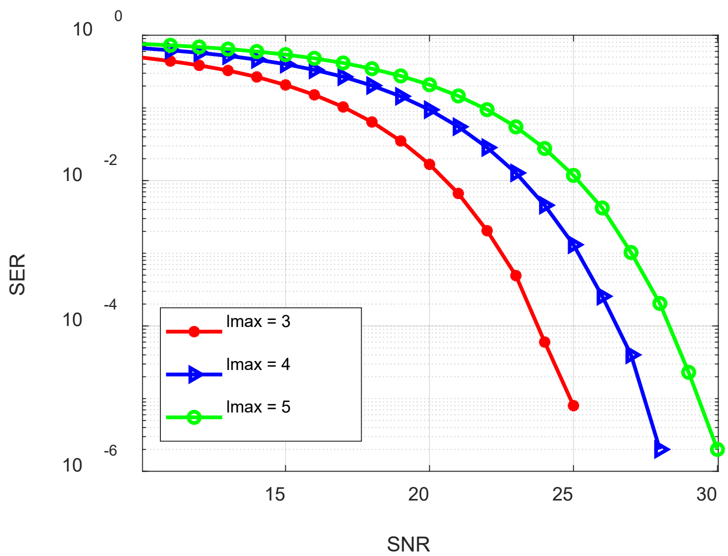

Figure 6. Error performance at different LED cores. In order to study the influence of the dimming level on the error performance of the ML-MTSC scheme proposed in this paper, we provide SER curves with different dimming levels under the condition of $N = 2$, $l_{\max} = 4$, and $h_1 : h_2 = 1 : 1$. The curves are shown in Figure 7 when the dimming level γ is $1/3$, $1/4$, and $1/5$.

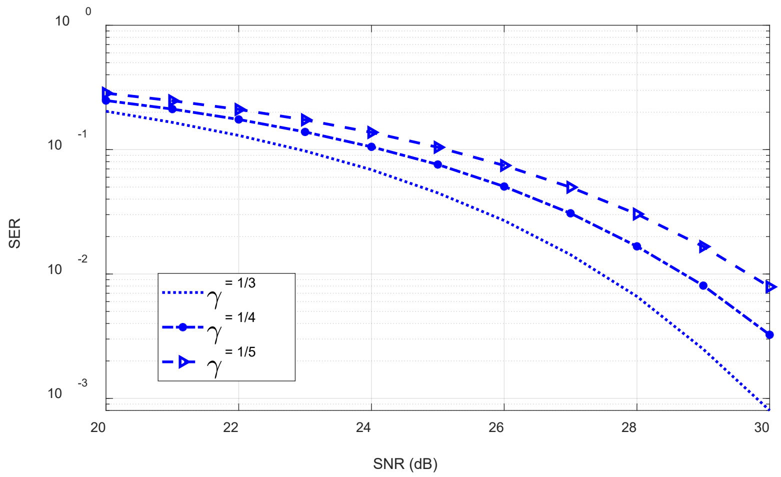

Figure 7. Error performance at different dimming levels.

It can be seen from Figure 7 that when γ is less than $1/2$, with the improvement in dimming level γ, the error performance of the system will be improved. This is because with the increase in dimming level γ, the average power used by the LED transmitter will increase; thus, the power resource utilized by the transmitters will increase. Therefore, the error performance of the system and the reliability of the communication system will be improved.

5. Conclusions

In this paper, a novel dimming control scheme based on joint multilevel time-shift codes is proposed for the scenario where the transmitters are multi-core LEDs in different positions and the receiver is a single PD. The scheme is equivalent to a multilevel extension of the multi-LED phase-shift space–time codes, which adapts to the proposed scenario. It can realize the normal digital communication function and the brightness adjustment function in the whole range. Simulation results show that the proposed dimming control scheme improves the error performance and spectral efficiency compared with the traditional TDMA & ML-MPPM scheme when considering the model mentioned above. Therefore, the ML-MTSC scheme proposed in this paper can be used as an effective scheme to realize indoor visible light communication and illumination with multi-core LEDs in different positions at the transmitter and a single PD at the receiver.

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