

Spatial Modulation Based Color-Intensity Shift Keying in VLC System

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Abstract—In this paper, a modulation scheme referred as spatial modulation based color-intensity shift keying (SM CISK) is proposed for visible light communication (VLC) systems. The proposed scheme amalgamates conventional color shift keying (CSK), pulse amplitude modulation (PAM), and SM together to efficiently exploit the degrees of freedom in the color, the intensity, and the spatial domains. It maintains a constant average transmit power to fulfill the non-flickering requirement for the normal illumination. The bit error rate (BER) of the proposed scheme is studied based on the maximal likelihood (ML) detection. Simulation results verify that the proposed scheme outperforms the joint color-and-spatial modulation (SM CSK) and CISK modulation scheme.

Keywords—Visible light communication; Color shift keying; Pulse amplitude modulation; Spatial modulation; Bit error rate

I. INTRODUCTION

Recently, visible light communication (VLC) has become more and more popular for the researchers and scholars, which offers abundant unregulated bandwidth, high speed transmission, and excellent secure connectivity because of the significant characteristics of light transmission [1][2]. Generally, VLC systems apply intensity modulation (IM) with direct detection (DD) to realize the simple and low cost optical carrier modulation. A major attraction in VLC is its potential to simultaneously provide both lighting as well as high-speed short-range communication with inexpensive high-luminance light-emitting diodes (LEDs).

Multiple-input multiple-output (MIMO) is a very efficient and popular technology in traditional RF communications [3]. MIMO has also been employed in optical wireless communication (OWC) to achieve the improvement in the system performance and transmission rate [4]. However, due to the high correlation property of the optical wireless channels, traditional MIMO techniques are not suitable for VLC system. Spatial modulation (SM) scheme, as a simplification of MIMO technology, was proposed by R. Mesleh [5], which entirely avoids the inter-channel interference (ICI) and inherits the high spectral efficiency. The optical spatial modulation (OSM) scheme which employed the SM in the OWC system was studied in [6]. Performance analysis of the space shift keying (SSK) and generalized space shift keying (GSSK) in VLC system have been done in [7] and [8], respectively. Bit error

rate (BER) performance analysis of the traditional SM in VLC (SM-VLC) system was presented in [9] and the generalized spatial modulation (GSM) VLC system with higher spectral efficiency and multiplexing gain was introduced in [10]. These research pointed out that SM and GSM cannot perform well in highly correlated optical channels. The color shift keying (CSK) modulation scheme that modulates the signal by the combination of the three color bands (red, green and blue, RGB) of LED (TLED) was standardized in IEEE 802.15.7 for high-speed VLC systems [11]. The evaluation of the system performance of CSK scheme was studied over additive white Gaussian noise (AWGN) and the dispersive visible light channels in [12][13]. The standard has provided nine valid sets of the three potential sources to be used in a CSK system, known as colour band combinations (CBCs) [14]. An enhanced CSK scheme was further presented in [15], where the quad-LED (QLED) with four colors was utilized to get higher modulation order and improve the system performance. Nonetheless, due to the design constraints in the specially shaped CIE 1931 color space shown in Fig. 1 [16], the minimum Euclidean distance (MED) of a CSK constellation is typically much smaller than that of a conventional quadrature amplitude modulation (QAM) constellation with the same size, which results in a deteriorated link robustness in CSK systems. In addition, CSK was combined with SM in [17] which is capable of reaping the benefits from both spatial and color domains, thus offering an improved system performance in comparison with the conventional CSK or optical SM schemes. A modulation technique referred to as color-and-intensity shift keying (CISK) was proposed for VLC systems [18]. It relaxes the constant power constraint for CSK, but maintains a constant average transmit power to fulfill the non-flickering requirement of the normal illumination.

Inspired from the above literatures, we employ the SM CISK scheme in VLC system in this paper. For the proposed SM CISK VLC system, the bit-stream is mapped to the index of the transmit TLED, the modulation order of CSK, and the modulation order of pulse amplitude modulation (PAM), which achieves better spectral efficiency with simple operation. Therefore, the proposed scheme can improve the transmission rate and the system performance simultaneously. The maximum likelihood (ML) based signal processing of the proposed SM CISK in VLC system has been investigated.

Simulation results show that the proposed scheme can improve the system spectral efficiency significantly compared with the SM CSK and CISK schemes. In addition, the effect of the distance between the TLEDs on the system performance has also been discussed.

The rest of this paper is organized as follows. Section II provides the proposed SM CSK VLC system model. The proposed system signal processing and its ML detection have been presented in Section III. Section IV presents the simulation results. Finally, the conclusions are summarized in Section V.

II. SYSTEM MODEL

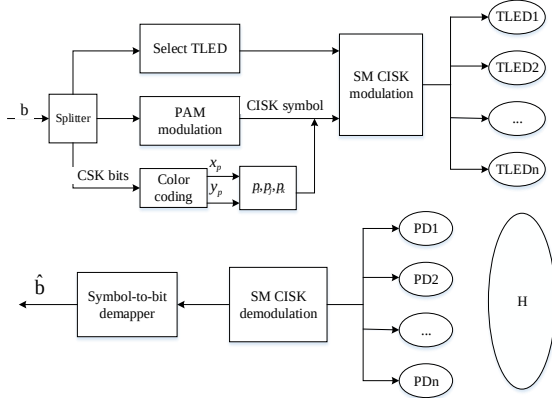


Figure 1. The proposed SM CSK system model

Fig. 1 depicts the system model presented in this paper. In this model, there exist N_t TLEDs in the transmitter and N_r photo detectors (PDs) in the receiver. The energy of the line of sight (LOS) signal is much higher than the energy of the diffusive components in VLC channel. Therefore, the LOS link is considered for modeling the VLC channel in this paper. The received signal vector through LOS link in the receiver can be expressed as

$$\mathbf{y} = r\mathbf{H}\mathbf{x} + \mathbf{w} \quad (1)$$

where $\mathbf{y}$ is a $N_r \times 3$ received signal vector and $\mathbf{x}$ is a $N_t \times 3$ transmitted signal vector. Each element of $\mathbf{x}$ is a positive value and denotes the optical intensity transmitted from the corresponding TLED. $\mathbf{w}$ is a $N_r \times 3$ noise vector and its each element can be modeled as independent identically distributed (i.i.d.) real AWGN with zero mean and variance σ^2 . r is the responsivity of the PD detector. $\mathbf{H}$ is a $N_r \times N_t$ channel matrix which represents the optical channel

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & h_{23} & \cdots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ h_{N_r,1} & h_{N_r,2} & h_{N_r,3} & \cdots & h_{N_r,N_t} \end{bmatrix} \quad (2)$$

where h_{ij} is the optical channel coefficient between the j th TLED and the i th PD, $i = 1, 2, \dots, N_r$ and $j = 1, 2, \dots, N_t$. h_{ij} is written as

$$h_{ij} = \begin{cases} \frac{(m+1)A}{2\pi d_{ij}^2} \cos^m(\phi_{ij}) T_s(\phi_{ij}) g(\phi_{ij}) \cos(\phi_{ij}), & 0 \leq \phi_{ij} \leq \Psi_c \\ 0, & \phi_{ij} > \Psi_c \end{cases} \quad (3)$$

where A is the area of each PD. Furthermore, the Lambertian factor m , which determines the directionality order, is given as

$$m = \frac{-\ln 2}{\ln(\cos \Phi_{1/2})} \quad (4)$$

where $\Phi_{1/2}$ denotes the transmitter semi-angle, d_{ij} is the distance between the i th PD and the j th TLED. Furthermore, ϕ_{ij} is the emission angle from the j th TLED to the i th PD. Additionally, ϕ_{ij} represents the angle of the incidence of the light at the i th PD from the j th TLED, Ψ_c is the PD's field of view (FOV). $T_s(\phi_{ij})$ is the transmission band-pass filter. The optical gain of the concentrator $g(\phi_{ij})$ with internal refractive index n can be written as

$$g(\phi_{ij}) = \begin{cases} \frac{n^2}{\sin^2 \Psi_c}, & 0 \leq \phi_{ij} \leq \Psi_c \\ 0, & \phi_{ij} \geq \Psi_c \end{cases} \quad (5)$$

and $\Psi_c \leq \pi/2$ is the PD's field of view (FOV).

It is seen from Fig.1 that the input bit stream b is firstly divided into three parts for CSK modulation, TLED index modulation, and PAM modulation, respectively. The CSK-modulated symbols will be transformed to RGB light intensity which will further control the light emission of the selected TLED with SM. We activate only one TLED of N_t transmitters for a transmission. At the PD receivers, the received signal can be processed by the symbol-to-bit demapper, where the joint ML detection algorithm is employed to recover the original bits. M -CSK bits are used to map the constellation symbol, where M is the modulation order of the CSK modulation, K -PAM modulation is used to carry information bits, where K is the modulation order of the PAM modulation. Therefore, the overall system bit rate can be represented as

$$\eta = \log_2 N_t + \log_2 M + \log_2 K. \quad (6)$$

In addition, according to [16], the CSK bits are mapped to a signal point of the two-dimension (2D) CSK constellation, in the form of chromaticity values (x_p, y_p) , as indicated by the color coding module of Fig.1. Each CSK symbol (x_p, y_p) can be further converted into the light intensity values p_i, p_j and p_k as [17] and we have

$$\begin{cases} x_p = p_i x_i + p_j x_j + p_k x_k \\ y_p = p_i y_i + p_j y_j + p_k y_k \\ p_i + p_j + p_k = 1 \end{cases} \quad (7)$$

where (x_i, y_i) , (x_j, y_j) , and (x_k, y_k) refer to the chromaticity values at the central wavelengths of the three different light sources used in the system. Each of (x_i, y_i) , (x_j, y_j) or (x_k, y_k) may represent one CSK symbol, while each of the remaining CSK symbols corresponds to a pair of x and y chromaticities. Hence, through (7), each non-zero chromaticity coordinate (x, y) will be converted into an intensity group of $p = (p_i, p_j, p_k)$.

For the conventional SM scheme, the spatial information transmitted by the index of the transmit TLED will vanish. Therefore, we cannot recover the transmitted information bits in the receiver, which may lead to the performance loss. Hence, the SM scheme need to be modified to avoid the ‘silence’ problem among all the TLEDs, which means that the transmit signal vector $\mathbf{x}$ must have non-zero elements at any given time instance. Consequently, the intensity of the K -ary PAM modulation can be expressed as

$$I_k = \frac{2I}{K+1}k, k=1,2,\dots,K \quad (8)$$

where I is the mean emitted optical power. Then, by multiplying the intensity p with I_k , we can get a CISK symbol $x_n = p \cdot I_k$. In addition, to fulfill the non-flickering constraint of normal illumination, the average transmit CISK signal power $\bar{I} = \frac{1}{K} \sum_k I_k$ should be kept as a constant over one communication. Therefore, the transmitted signal is $\mathbf{x} = [0, \dots, x_n, \dots, 0]$.

III. ML BASED SIGNAL PROCESSING OF THE PROPOSED SCHEME

In this section, the signal processing of the proposed SM CISK modulation scheme in VLC system is elaborated. The received SNR of the proposed system is proportional to the square of the average received optical signal power [10], which is defined as

$$\gamma = \frac{(r\bar{P}_r)^2}{\sigma^2} \quad (9)$$

where $\bar{P}_r$ is the average received optical power of all the different colors at one PD and it can be expressed as

$$\bar{P}_r = \frac{1}{N_r} \sum_{i=1}^{N_r} \sum_{l=1}^4 P_r^{(i,l)} \quad (10)$$

where $P_r^{(i,l)}$ is the received optical power from the l th color of all the activated LEDs to the i th PD and it is given by

$$P_r^{(i,l)} = \sum_{j=1}^{N_t} g_{lj} P_t^{(ij,l)} \quad (11)$$

where $P_t^{(ij,l)}$ denotes the optical power of the l th color transmitted from the j th LED to the i th PD. Furthermore, g_l is the filter coefficient of the l th color.

In SM system, maximum likelihood (ML) is the optimal method for signal detection and it is also employed in this paper. The ML algorithm based signal detection of the proposed SM CISK VLC system is presented as

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}} \|\mathbf{y} - r\mathbf{H}\mathbf{x}\|^2 \quad (12)$$

where $\hat{\mathbf{x}}$ represents the detected symbol vector.

IV. SIMULATION RESULTS

In this section, we present the simulation results about the SER performance of the proposed scheme in indoor VLC system. The corresponding system parameters are listed in Table 1. In the simulation, we assume that the center coordinate

of the ground is set as (0, 0, 0). The coordinate of the transmitter is (0, 0, 3m) and the radius of the PD circle is 0.3m. In order to match the real case, the receiver coordinate is set to be randomly distributed within the room. The indoor 4×4 SM CISK system is shown in Fig. 2.

TABLE 1. SIMULATION PARAMETERS

Room	Length(X)	5m
	Width(Y)	5m
	Height(Z)	3m
Transmitter	Height from the floor	3m
	LED semi-angle, $\Phi_{1/2}$	30°
	Distance between two TLEDs d_{tx}	2m
Receiver	Height from the floor	1m
	PD responsivity, r	1 A/W
	PD detection area, A	1cm ²
	Reflective index, n	1
	PD FOV, Ψ_c	80°
	Distance between two PDs d_{rx}	1m

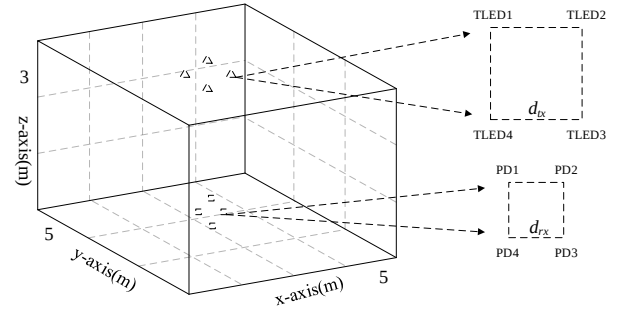


Figure 2. Visual representation of the 4 × 4 SM CISK VLC system.

Fig. 3 and Fig. 4 show the simulation BER results of the SM CISK, SM CSK and the CISK schemes in indoor VLC system with $N_r = N_t = 4$. To make a fair comparison, all the modulated schemes convey 4 bits and 8 bits for a communication process, respectively. It is observed from Fig. 3 that, for the proposed SM CISK scheme in VLC system, at the target BER of about 10^{-3} , we can get about 1.5dB and 4.0dB SNR gains compared with the SM CSK and CISK scheme in VLC system, respectively. The same phenomenon happens in Fig.4. Moreover, from these two figures, we can see that with the increase of transmission rate, the performance difference between the proposed scheme and other modulated schemes becomes larger and larger. The performance enhancement of the proposed SM CISK scheme is mainly due to the gain of spatial modulation, it can provide a reduced signal constellation size by conveying data bits in the spatial domain.

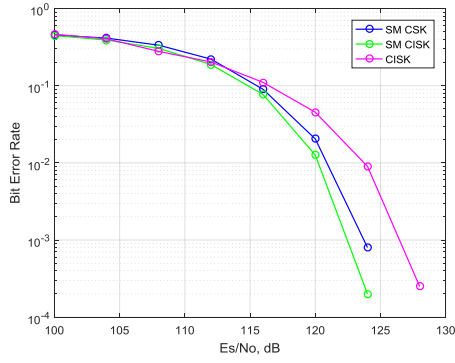


Figure 3. BER results of SM CISK VLC system with bit rate 4 bits/s.

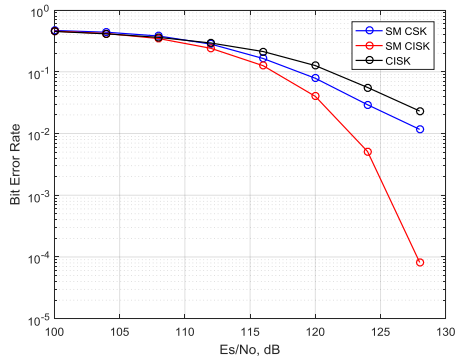


Figure 4. BER results of SM CISK VLC system with bit rate 8 bits/s.

Fig. 5 plots the BER performance of two different modulation combinations of the proposed SM CISK scheme. For fair comparison, the transmission bit rate is set to be 6.0bits/s with $N_r = N_t = 4$ and SM CISK (M, K). It is shown that the proposed scheme with $M = 8, K = 2$ outperforms the scheme with $M = 4, K = 4$, and more performance gains can be achieved with the increase of SNR. When BER is 10^{-4} , the former scheme obtains about 5.0dB gains compared with the latter scheme. Therefore, we can obtain that the signal constellation size of PAM has more influence on the system performance than the constellation size of CSK.

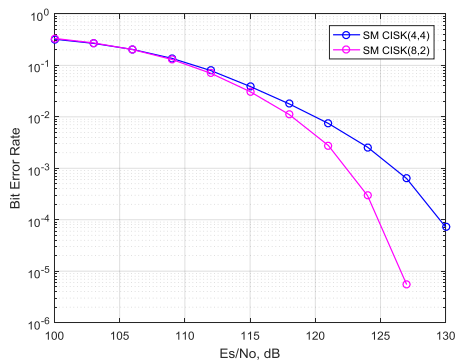


Figure 5. BER performance of the SM CISK VLC scheme over VLC channel.

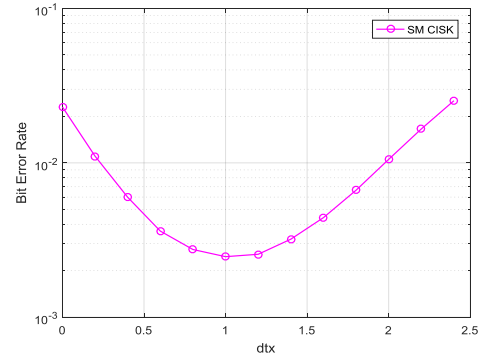


Figure 6. BER performance about d_{tx} in SM CISK VLC system.

Fig. 6 depicts the BER performance of the proposed system with 8CSK and 2PAM modulation and SNR=122dB versus d_{tx} which is the distance between TLEDs. It is found that the BER performance drops first and then goes up with the increase of d_{tx} and the optimal performance can be obtained at $d_{tx}=1.0m$. The reason is that the distance d_{tx} is related to the channel gain and also the channel correlation of the VLC channels. When d_{tx} increases, the channel gain decreases but the channel correlation becomes weak. Therefore, the optimal d_{tx} is an equilibrium point between the channel gain and the channel correlation.

V. Conclusion

In this paper, we propose a SM CISK modulation based VLC system that combines CSK, PAM, and SM techniques together. It utilizes the color domain, intensity domain, and the spatial domain to improve the system performance and the transmission bit rate simultaneously. Simulations demonstrate the benefits of the proposed modulation scheme, which outperforms the conventional SM CSK and CISK schemes without compromising the non-flickering requirement of illumination. The effect of the different distances between the TLEDs on the system BER performance has also been investigated.

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