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Power Allocation Optimization Design for the Quadrichromatic LED Based VLC Systems with Illumination Control

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Abstract: For requiring high communication rate and high-quality illumination, multi-color light-emitting diodes (LEDs) have been utilized in visible light communication (VLC) systems and attracted substantial research interests. It should be noted that multiple colors are not independent from each other since they are jointly limited by the chromaticity constraint. Thus, taking full consideration of the multi-color crosstalk problem and actual communication and illumination constraints, this paper formulates a power-efficient illumination control optimization design to reduce power consumption for the quadrichromatic LED (QLED) based VLC systems where signal to interference plus noise ratio (SINR) and quadrangle chromaticity tolerance region constraints should be satisfied. Simulation results illustrate that our proposed optimal power allocation strategy can significantly increase power efficiency for the VLC system compared with the uniform power allocation method. Moreover, the proposed scheme can provide optimal performance under different given correlated color temperature (CCT) values.

Keywords: visible light communication (VLC); quadrichromatic light-emitting diode (QLED); multi-color crosstalk; power-efficient optimization; illumination control

1. Introduction

As an emerging short-range wireless communication technology, visible light communication (VLC) can be regarded as a potential solution for providing data transmission and the inherent lighting simultaneously, which attracts tremendous attention worldwide [1–3]. Meanwhile, serving as the transmitter of the VLC system, light-emitting diode (LED) lighting is rapidly replacing the conventional incandescent and fluorescent lighting due to the notable advantages of fast switching capability, high energy efficiency and long lifetime [4,5]. Generally, there are two kinds of LEDs, one is the phosphor-converted LED (pc-LED) and the other is the multi-color LED. The pc-LEDs are low cost and easily accessible, and they occupy a large part of the market. Unfortunately, their intrinsic modulation bandwidth is limited to MHz. As for the multi-color LEDs, the white light illumination can be achieved by mixing the multiple monochromatic lights together. Although they are more expensive and complex, their higher modulation bandwidth and natural multi-channel properties show quite large potential of high-rate data transmission. Via wavelength-division multiplexing (WDM) technique, the multi-color LED based VLC system naturally forms a color-domain multiple input and multiple output (CMIMO) channels for multiple parallel data transmission, which can provide potential high transmission rate and high-quality illumination [6,7]. It should be noted that quadrichromatic LED (QLED) with red/amber/green/blue (RAGB) colors has been recommended as an alternative to the red/green/blue LED (RGB-LED) to improve the color quality where proper color temperature can be provided for indoor lighting [8].

In essence, both illumination and communication requirements should be satisfied when we design the multi-color LED based VLC system, and the corresponding research has stimulated substantial interest in recent work. To improve communication performance, the work in Ref. [9] demonstrated an aggregate data rate of 4.5 Gbps WDM-VLC system using RGB LED and the work in Ref. [10] updated the data rate to an off-line 8 Gbps via high-order carrierless amplitude phase (CAP) modulation and hybrid post equalizer. Moreover, Ref. [11] proposed an optimization problem to maximize the multi-user sum-rate for the RGB-LED based VLC system under chromaticity and bit error rate (BER) constraints. To maximize the minimum Euclidean distance (MED) for communication performance optimization, Ref. [12] investigated the constellation design of color shift keying (CSK) to obtain better BER performance. Considering the energy consumption problem, Ref. [13] proposed an energy-efficient optimization design for the multi-color based VLC system. However, the overlapping spectra of the multi-color LED may cause an inevitable channel crosstalk problem for the VLC system, and the practical illumination requirements should be satisfied under the specific circumstances. Moreover, to improve the adaptivity for the practical illumination scenarios, Commission Internationale de l'Eclairage (CIE) [14] proposed quadrangle chromaticity tolerance region for LED products to replace a fixed chromaticity point in CIE1931 chromaticity diagram, which is neglected in previous works. Accordingly, with the characteristic of adjustable chromaticity tolerance region, multi-color LEDs can provide the proper correlated color temperature (CCT) for high-quality illumination.

Motivated by the above-mentioned analysis, we propose a power-efficient illumination control optimization design for the multi-color LED based VLC systems to reduce energy consumption. More specifically, an optimal power allocation strategy is demonstrated to maximize power efficiency for the QLED based VLC systems with the consideration of the multi-color crosstalk problem and actual communication and illumination requirements where signal to interference plus noise ratio (SINR) and quadrangle chromaticity tolerance region constraints should be satisfied. Fortunately, the formulated optimization design is a convex problem and the toolbox CVX in MATLAB can be utilized for effectively solving the convex programs [15]. Simulation results show that better error performance can be obtained when the channel crosstalk problem is considered. Moreover, the proposed power allocation strategy can significantly reduce power consumption compared with uniform power allocation method with fixed chromaticity point, and the optimal power allocation strategy is discussed under different given CCT values for high-quality illumination. To sum up, our major contributions lie in the optimization design of the power allocation strategy for the QLED LED based VLC system under the practical communication and illumination constraints.

The reminder of this paper is organized as follows: In Section 2, the system model for the multi-color LED based VLC system is established with channel crosstalk. Section 3 demonstrates the optimal power allocation strategy via collaboratively guaranteeing the practical luminance, chromaticity and SINR constraints. The corresponding simulation results and performance comparison are given in Section 4, and conclusions have been made in Section 5.

2. System Model

In the multi-color LED based VLC system with intensity modulation and direct detection (IM/DD), we consider N-color LED as transmitters and N photodiodes (PDs) as receivers. Thus, the data are divided into N parts to form CMIMO channels for multiple parallel transmission, and the system model is shown in Figure 1. At the transmitter side, the source data vector can be sorted by $\mathbf{d} = [d_1, d_2, \cdots, d_N]^T$. Utilizing pulse amplitude modulation (PAM), the M-level PAM source data are normalized in the range of $[-1, 1]$ where M is the modulation order. Thus, the transmitted signal $\mathbf{s}$ can be expressed as

$$\mathbf{s} = \boldsymbol{\gamma} \circ \mathbf{d} + \mathbf{I}_{DC}, \tag{1}$$

where amplifiers are utilized to fully exploit the dynamic range of LEDs with amplification coefficient denoted as $\gamma = [\gamma_1, \gamma_2, \cdots, \gamma_N]^T$, and $\circ$ is the Hadamard product. To ensure the non-negativity of the input signal, direct current (DC)-bias vector $\mathbf{I}_{DC} = [I_{DC}^1, I_{DC}^2, \cdots, I_{DC}^N]^T$ should be added. Since $E[\gamma \circ \mathbf{d}] = \mathbf{0}$, the average illumination level is uniquely determined by DC bias $\mathbf{I}_{DC}$ where $E[\cdot]$ is the expectation operator [16]. Meanwhile, the multi-color light should be guaranteed to be mixed into white light in the free space.

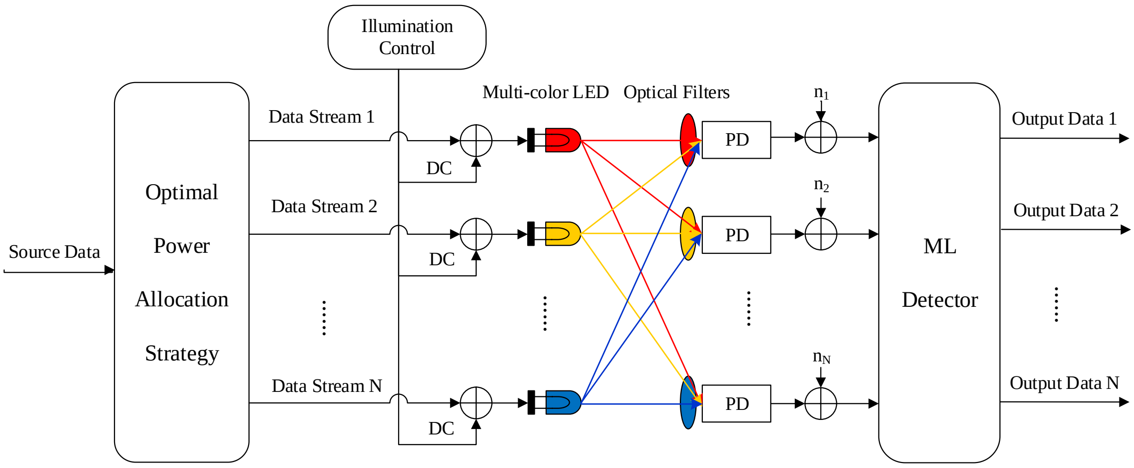

Figure 1. CMIMO model for the multi-color light-emitting diodes (LED) based visible light communication (VLC) system.

In general, multi-color LEDs can be modeled as Lambertian emitters. According to the literature [17], the effect of reflected light can be ignored compared with the direct light where the reflected light is much weaker than the direct light. Thus, line of sight (LOS) path can be considered for the indoor VLC system. Accordingly, the channel gain h_{ij} between jth color LED chip and ith receiver PD is determined by [1]

$$h_{ij} = \begin{cases} \frac{\mu(m+1)A}{2\pi d_{ij}^2} cos^m(\phi) T_s(\psi) g(\psi) cos(\psi), & 0 \leq \psi \leq \Psi_C \\ 0, & \psi > \Psi_C \end{cases} \tag{2}$$

where A is the effective detector area of the PD, d_{ij} denotes the distance between jth color LED chip and ith PD, μ is the receiver responsivity, ϕ and ψ represent the angle of irradiance and incidence respectively. m is the order of Lambertian emission which is given by the semi-angle at half-power of the LED $\Phi_{1/2}$ as $m = \frac{-ln2}{ln(cos\Phi_{1/2})}$. $T_s(\psi)$ is the gain of the optical filter, $g(\psi)$ is the gain of an optical concentrator, and Ψ_C denotes field-of-view (FOV) for the PD.

According to Ref. [7], the crosstalk problem inherently exists in the multi-color LED based VLC system for the overlapping spectra, and the spectral power distribution (SPD) $S(\lambda)$ can be modeled as

$$\begin{cases} S(\lambda) = \dfrac{g(\lambda, \lambda_0, \Delta\lambda_{0.5}) + 2g^5(\lambda, \lambda_0, \Delta\lambda_{0.5})}{3}, \\ g(\lambda, \lambda_0, \Delta\lambda_{0.5}) = exp\{-[(\lambda - \lambda_0)/\Delta\lambda_{0.5}]^2\}, \end{cases} \tag{3}$$

where λ_0 and $\Delta\lambda_{0.5}$ denote the peak wavelength and half spectral width respectively. Accordingly, the spectral model for the QLED with RAGB colors at temperature of 300 K is shown in Figure 2. We can see that the overlapping spectra of the multi-color LED may cause color crosstalk problem and the realistic optical filters cannot separate the interference light completely. Meanwhile, we assume the color crosstalk problem only takes place between the two adjacent color bands due to their close wavelength [18]. Therefore, the color crosstalk matrix $\mathbf{T}$ is given as

$$\mathbf{T} = \begin{bmatrix} 1-\tau & \tau & 0 & \cdots & 0 \\ \tau & 1-2\tau & \tau & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & \tau & 1-2\tau & \tau \\ 0 & \cdots & 0 & \tau & 1-\tau \end{bmatrix}_{N\times N} \tag{4}$$

where τ is interference coefficient with $\tau \in [0, 0.5)$. Correspondingly, the error performance for the traditional WDM-VLC system utilizing multi-color LED can be significantly improved if the color crosstalk problem is considered.

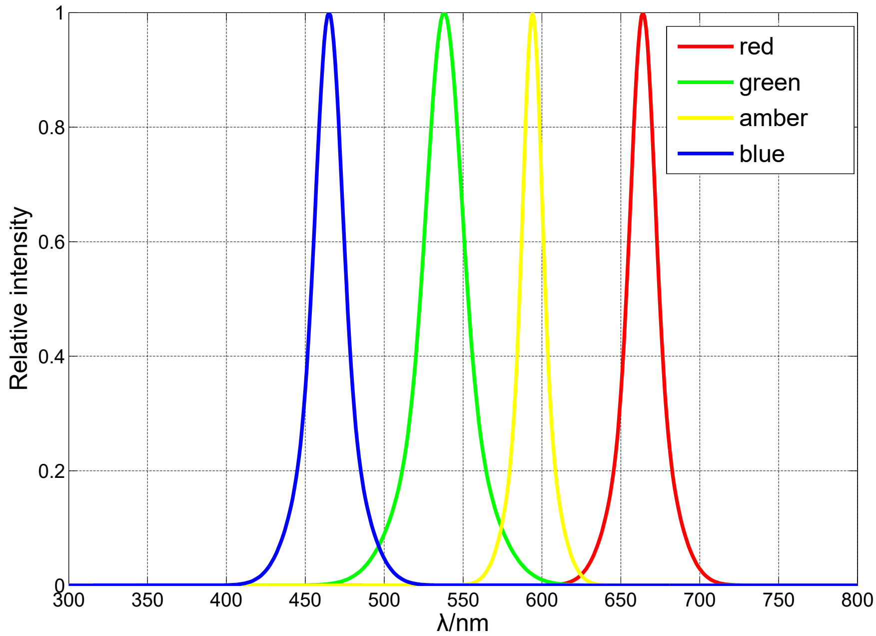

Figure 2. Spectral model for the quadrichromatic LED (QLED) with red/amber/green/blue (RAGB) colors.

At the receiver side, equipped with the specific optical filters, the receiver PDs are used to detect the received signals with defined wavelengths. Accordingly, the received signal is given as

$$\mathbf{r} = \mathbf{THs} + \mathbf{n}, \tag{5}$$

where the channel gain matrix $\mathbf{H}$ can be expressed as $\mathbf{H} = diag([h_{11}, h_{22}, \cdots, h_{NN}])$ because the interval for multi-color LED chips is negligible compared with the distance between the transceivers Ref. [19], and $diag(\cdot)$ denotes the diagonal matrix. Based on [20], $\mathbf{n}$ can be modeled as signal-independent additive white Gaussian noise (AWGN) with zero mean and noise variance σ^2.

Combining Equations (1) and (5), the received signal $\mathbf{r}$ can be rewritten by

$$\mathbf{r} = \mathbf{TH}\gamma \circ \mathbf{d} + \mathbf{THI}_{DC} + \mathbf{n}. \tag{6}$$

After removing the DC component $\mathbf{THI}_{DC}$, the received signal $\tilde{\mathbf{r}}$ is expressed as

$$\tilde{\mathbf{r}} = \mathbf{TH}\gamma \circ \mathbf{d} + \mathbf{n}. \tag{7}$$

It should be noted that the ith PD is interested in the data information from the ith color chip while the data from other color chips can be regarded as interference. Thus, the received signal from the ith receiver is given by

$$\tilde{r}_i = t_{ii} h_{ii} \gamma_i d_i + \sum_{j=1, j \neq i}^{N} t_{ij} h_{jj} \gamma_j d_j + \sigma^2, \tag{8}$$

where t_{ij} is the item from the ith row and jth column of color crosstalk matrix $\mathbf{T}$.

3. The Proposed Optimal Power Allocation Strategy

Considering the practical color crosstalk problem, we have built the CMIMO model for the multi-color LED based VLC system. Moreover, as a green wireless communication technique, a power-efficient VLC system should be established with the consideration of energy saving problem. Thus, this paper aims to formulate a power-efficient illumination control optimization design to reduce energy consumption for the multi-color LED based VLC systems. Accordingly, the optimal power allocation strategy is proposed where the necessary communication and illumination constraints should be satisfied.

3.1. Illumination and Communication Constraints

(1) ***Illuminance Constraint***

In order to achieve the desired brightness levels for users, illuminance constraint should be satisfied [21]. The multi-color LED transmitter should maintain constant brightness level where the mixed white light should be unflickering, so the illuminance constraint can be expressed as

$$\mathbf{1}^T \boldsymbol{\Phi} = \sum_{i=1}^{N} \Phi_i = P_t, \tag{9}$$

where $\boldsymbol{\Phi} = [\Phi_1, \Phi_2, \cdots, \Phi_N]^T$ is the luminous flux vector, Φ_i is the luminous flux for the ith color LED chip and P_t denotes the total luminous flux for the multi-color LED.

(2) ***Quadrangle Chromaticity Constraint***

Chromaticity is the basic characteristic of the color perceived by human eyes. In CIE 1931 color space chromaticity diagram, the chromaticity of color can be represented by the coordinate point (x, y), as shown in Figure 3. Accordingly, we assume the the corresponding chromaticity coordinate is (x_i, y_i) for the ith color LED chip. Based on the Grassmann's laws, the desired chromaticity coordinate of the mixed light $\mathbf{p} = (\hat{x}, \hat{y})$ can be calculated by [22]

$$\begin{aligned} \hat{x} &= \frac{\mathbf{a}^T \boldsymbol{\Phi}}{\mathbf{b}^T \boldsymbol{\Phi}} = \frac{\sum_{i=1}^{N} \frac{x_i}{y_i} \Phi_i}{\sum_{i=1}^{N} \frac{1}{y_i} \Phi_i}, \\ \hat{y} &= \frac{\mathbf{1}^T \boldsymbol{\Phi}}{\mathbf{b}^T \boldsymbol{\Phi}} = \frac{\sum_{i=1}^{N} \Phi_i}{\sum_{i=1}^{N} \frac{1}{y_i} \Phi_i}, \end{aligned} \tag{10}$$

where $\mathbf{a} = [\frac{x_1}{y_1}, \frac{x_2}{y_2}, \cdots, \frac{x_N}{y_N}]^T$ and $\mathbf{b} = [\frac{1}{y_1}, \frac{1}{y_2}, \cdots, \frac{1}{y_N}]^T$ are the constant coefficients vectors.

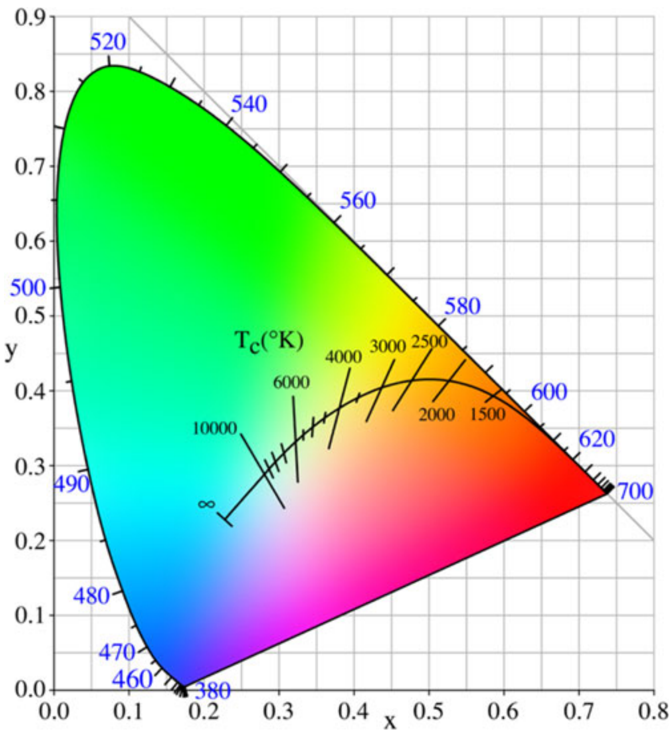

Figure 3. CIE 1931 color space chromaticity diagram.

Since human eyes have limitation on color discrimination, small chromaticity change for the white light can be tolerated. According to Ref. [14], quadrangle chromaticity tolerance can be utilized as a statistical measurement to distinguish chromaticity difference between two colors in CIE 1931 chromaticity diagram, which is recommended for LED products. If the chromaticity point moves within the quadrangle range, human eyes almost could not notice the light color variation. Compared with the fixed chromaticity point, quadrangle chromaticity constraint can provide more freedom to improve the system performance. The chromaticity tolerance with quadrangle range for the target white color under different CCTs is shown in Figure 4, and the corresponding chromaticity center points are listed in Table 1 where A, B, C and D represent the four corners of the quadrangle. It should be noted that the proportion of the blue and green component becomes higher with the increase of CCT values. Accordingly, the quadrangle chromaticity constraint can be calculated as

$$\begin{cases} k_1 x - y + l_1 \leq 0, \\ k_2 x - y + l_2 \leq 0, \\ -k_3 x + y - l_3 \leq 0, \\ -k_4 x + y - l_4 \leq 0, \end{cases} \tag{11}$$

where k_i and l_i denote the coefficients determined by the quadrangle range in the chromaticity diagram. We set $\mathbf{K} = \begin{bmatrix} k_1 & k_2 & -k_3 & -k_4 \\ -1 & -1 & 1 & 1 \end{bmatrix}^T$ and $\mathbf{L} = [l_1, l_2, -l_3, -l_4]^T$ here, so the quadrangle chromaticity constraint can be rewritten as

$$\mathbf{Kp} + \mathbf{L} \leq \mathbf{0}. \tag{12}$$

Table 1. Coordinate of four corners for quadrangle chromaticity constraint under different correlated color temperatures (CCTs).

CCT	Center Point	(x, y) Tolerance Quadrangle			
		A	B	C	D
3000 K	(0.4339, 0.4033)	(0.4562, 0.4260)	(0.4303, 0.4173)	(0.4150, 0.3821)	(0.4373, 0.3893)
3500 K	(0.4078, 0.3930)	(0.4303, 0.4173)	(0.4003, 0.4035)	(0.3895, 0.3709)	(0.4150, 0.3821)
4000 K	(0.3818, 0.3797)	(0.4003, 0.4035)	(0.3737 ,0.3880)	(0.3671, 0.3583)	(0.3895, 0.3709)
4500 K	(0.3613, 0.3670)	(0.3737, 0.3882)	(0.3550, 0.3754)	(0.3514, 0.3482)	(0.3672, 0.3585)
5000 K	(0.3446, 0.3551)	(0.3550, 0.3753)	(0.3375, 0.3619)	(0.3366, 0.3373)	(0.3514, 0.3481)
5700 K	(0.3287, 0.3425)	(0.3375, 0.3619)	(0.3205, 0.3476)	(0.3221, 0.3256)	(0.3366, 0.3374

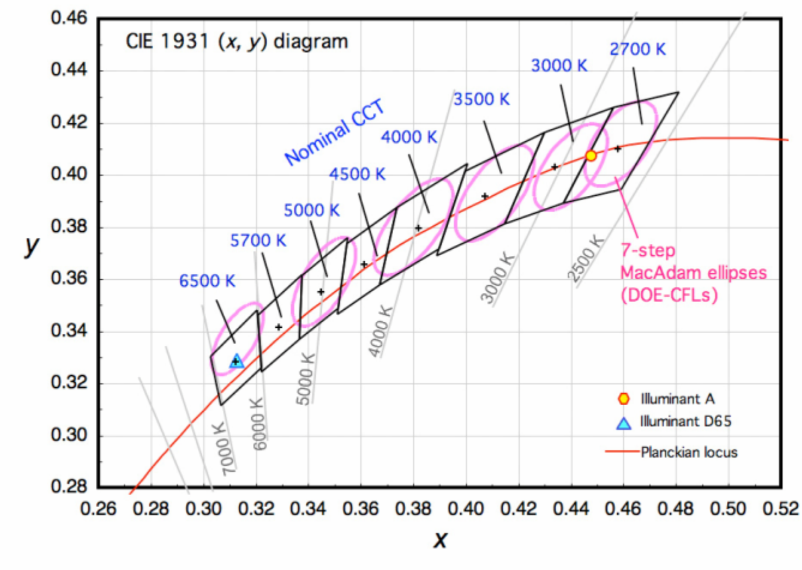

Figure 4. The chromaticity tolerance with quadrangle range for LED products in the CIE 1931 chromaticity diagram.

(3) ***Amplitude Constraint***

For the VLC system, considering the nonlinearity for the LED, the modulated PAM signal should be nonnegative. Thus, the nonnegative constraint should satisfy $\gamma_i \leq I^i_{DC} = c_i\Phi_i$ where c_i is the conversion coefficient for luminous flux to the forward current. Meanwhile, the transmitted signal exceeding the maximum value would suffer clipping distortion, so the maximum amplitude constraint should be satisfied as well and we have $\gamma_i \leq I^i_{max} - I^i_{DC} = I^i_{max} - c_i\Phi_i$ where I^i_{max} is the maximum permissible value. As a result, the amplitude constraint can be expressed as

$$0 \leq \boldsymbol{\gamma} \leq \min(\mathbf{I}_{max} - \mathbf{c} \circ \boldsymbol{\Phi}, \mathbf{c} \circ \boldsymbol{\Phi}), \tag{13}$$

where $\mathbf{c} = [c_1, c_2, \cdots, c_N]^T$ denotes the luminous flux to the forward current conversion coefficient vector, $\mathbf{I}_{max} = [I^1_{max}, I^2_{max}, \cdots, I^N_{max}]^T$ denotes the maximum permissible current level vector.

(4) ***SINR Constraint***

To obtain better communication quality, SINR is an essential requirement for improving the performance of the VLC system [23]. Based on the proposed CMIMO model for the multi-color LED based VLC system, the SINR at the ith receiver is given by

$$SINR_i = \frac{\mathbb{E}(t^2_{ii}h^2_{ii}\gamma^2_i d^2_i)}{\sum^N_{j=1,j\neq i}\mathbb{E}(t^2_{ij}h^2_{jj}\gamma^2_j d^2_j) + \sigma^2}, \tag{14}$$

where $\mathbb{E}(d_i^2) = \frac{M+1}{3(M-1)}$ [8] and we define $\beta = \frac{M+1}{3(M-1)}$ here. To satisfy the SINR constraint, the minimum SINR requirement is set as ξ. Thus, the SINR constraint can be expressed as

$$\frac{t_{ii}^2 h_{ii}^2 \gamma_i^2}{\sum_{j=1, j\neq i}^{N} t_{ij}^2 h_{jj}^2 \gamma_j^2 + \frac{1}{\beta}\sigma^2} \geq \xi, i = 1, 2, \cdots, N \tag{15}$$

For convenience, we define the following notations further:

(1) Define the matrix $\mathbf{F}$ with entries $f_{ij} = t_{ij}^2 h_{jj}^2$.

(2) Define the matrix $\mathbf{W}$ with entries $w_{ij} = \begin{cases} 0, & j = i \\ f_{ij}, & j \neq i \end{cases}$

(3) Define the matrix $\mathbf{G} = diag([\frac{1}{f_{11}}, \frac{1}{f_{22}}, \cdots, \frac{1}{f_{NN}}])$.

(4) Define $e^{\mathbf{m}} = \gamma^2$.

Accordingly, the SINR constraint can be equivalently rewritten as

$$\frac{(e^{\mathbf{m}})_i}{(\mathbf{G}(\mathbf{W}\gamma^2 + \frac{1}{\beta}\sigma^2))_i} \geq \xi, i = 1, 2, \cdots, N \tag{16}$$

where $(\cdot)_i$ is the ith element in the vector.

3.2. Problem Formulation

In this subsection, an optimal power allocation strategy is proposed to maximize the power efficiency for the multi-color LED based VLC systems. Considering the electrical power, the total power consumption is given by $\sum_{i=1}^{N}(c_i\Phi_i)^2$. Thus, combining the above-mentioned illumination and communication constraints, the main problem can be formulated as:

$$\begin{aligned} Obj.\ & \min_{\mathbf{m}, \mathbf{\Phi}} \sum_{i=1}^{N} (c_i \Phi_i)^2 \\ s.t.\ & \mathbf{1}^T \mathbf{\Phi} = \sum_{i=1}^{N} \Phi_i = P_t, \\ & \mathbf{Kp} + \mathbf{L} \leq \mathbf{0}, \\ & \mathbf{0} \leq \sqrt{e^{\mathbf{m}}} \leq \min(\mathbf{I}_{max} - \mathbf{c} \circ \mathbf{\Phi}, \mathbf{c} \circ \mathbf{\Phi}), \\ & \frac{(e^{\mathbf{m}})_i}{(\mathbf{G}(\mathbf{W}\gamma^2 + \frac{1}{\beta}\sigma^2))_i} \geq \xi, i = 1, 2, \cdots, N \\ & \mathbf{\Phi} \geq \mathbf{0}, \end{aligned} \tag{17}$$

which is a convex optimization problem with respect to the optimization variables $\mathbf{\Phi}$ and $\mathbf{m}$, where the objective function is the minimum value subject to several linear matrix inequalities. Several optimization algorithms such as interior point algorithm have been proposed to solve the problem (17). In this paper, we adopt CVX, a MATLAB optimization toolbox to obtain the optimal solutions [15].

4. Simulation Results

In this section, we have carried out the simulations for the multi-color LED based VLC system to testify the performance of our proposed power-efficient illumination control optimization design. Here, we adopt QLED with RAGB as transmitters (i.e., $N = 4$). The parameters utilized in the simulations are listed in Table 2. Meanwhile, we set two-level PAM signal for transmission with modulation order $M = 2$. Maximum likelihood (ML) detection is adopted at the receiver side in the following simulations.

Firstly, we show the performance comparison between our proposed optimal power allocation strategy and uniform power allocation method for the CMIMO system model. The chromaticity coordinate for the uniform allocation scheme is $(\frac{1}{3}, \frac{1}{3})$, which is contained in the quadrangle chromaticity range with CCT= 5700 K and the corresponding parameters have been listed in Table 1. Figure 5 shows the transmission power for different colors versus the total luminous flux ranging from 10 lm to 180 lm with interference coefficient $\tau = 0.05$. The simulation results indicate that the proposed optimal power allocation strategy obtains significant performance gains compared with the uniform power allocation method, reducing about 12.4% power consumption where the power efficiency improvement is independent of the luminous flux. Meanwhile, we can see that the transmission power of red, amber and green color chips keep medium levels, while the transmission power of the blue color chip keeps a low level. As for the transmission power efficiency for each color chip, compared with the uniform power allocation method, the red, amber and blue color chips can also achieve significant transmission power improvement, while the rate of transmission power for the green color chip increased. Since quadrangle chromaticity tolerance range has been modified to replace a fixed chromaticity coordinate in CIE 1931 chromaticity diagram, we can obtain more degrees of freedom to improve the system performance, which is consistent with the simulation results.

Table 2. Simulation parameters utilized in the QLED VLC system.

Parameters	Values
Type of white LED	RAGB LED
Number of LED chips N	4
Angle of irradiance ϕ	30°
Angle of incidence ψ	40°
Half Power angle of LED $\Phi_{1/2}$	60°
FOV Ψ_C	60°
Receiver responsivity μ	0.4 A/W
Distance between LED and PD d_{ij}	2 m
Effective detector area of PD	1 cm^2
Optical filter gain	1
Optical concentrator gain	1.5
Maximum forward current for each chip I_{max}	0.7 A
SINR requirement ξ	5 dB
Noise variance σ^2	10^{-14} W
Peak wavelength of each color	R 664 nm A 594 nm G 538 nm B 465 nm
Chromaticity point of each color	R (0.69406, 0.30257) A (0.59785, 0.39951) G (0.22965, 0.70992) B (0.12301, 0.09249)
Luminance flux-Forward current conversion coefficient of each color	R 0.021 A/lm A 0.014 A/lm G 0.005 A/lm B 0.015 A/lm

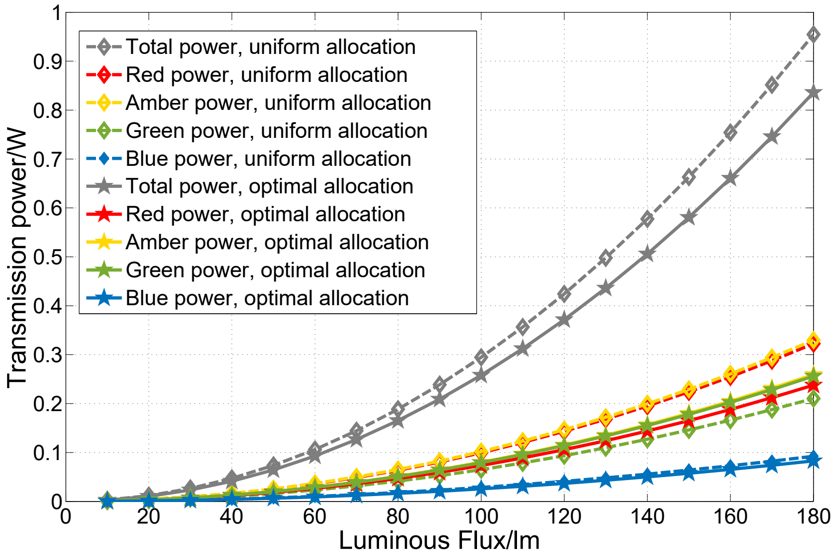

Figure 5. Transmission power comparison between the proposed optimal power allocation strategy and the uniform power allocation method with interference coefficient $\tau = 0.05$ under CCT = 5700 K.

Next, the performance for the proposed optimal power allocation strategy under different CCT values is compared, where six CCT values are investigated with quadrangle chromaticity range based on Ref. [14]. As shown in Figure 6, the curves of total transmission power have the consistent variation tendency for different CCT values. With the increase of CCT values, higher power efficiency can be achieved. As illustrated in Section 3.1, the proportion of the blue and green component becomes higher at larger CCT values. Due to the higher forward current-luminance flux efficiency for blue and green component, the total transmission power can be reduced. Thus, the optimal power allocation under the required CCT values can be obtained for high-quality illumination.

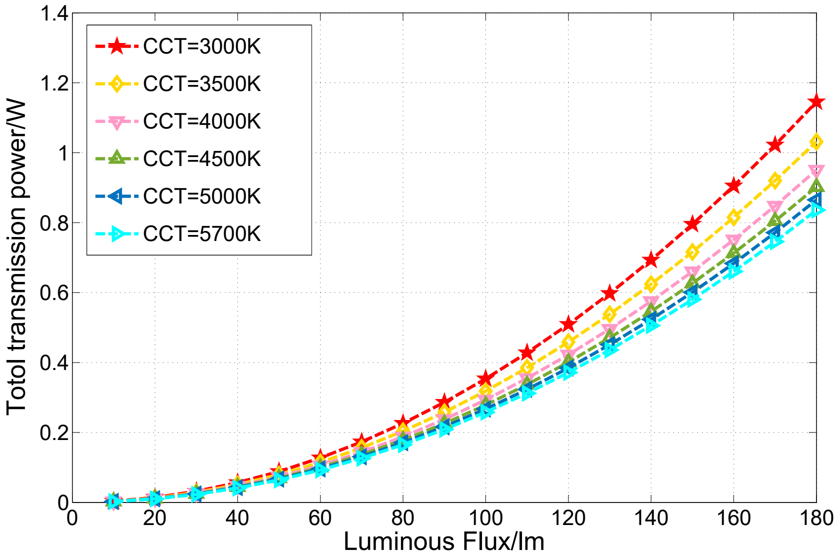

Figure 6. Total transmission power comparison for the proposed optimal power allocation strategy under different CCT values with interference coefficient $\tau = 0.05$.

Furthermore, we compare the error performance for the CMIMO model and the traditional WDM model without the consideration of crosstalk problem. Figure 7 illustrates the error performance versus luminous flux under different interference coefficients $\tau = 0.05, 0.01$ under CCT = 5700 K. Compared with the traditional WDM model, the CMIMO model always shows better BER performance since we consider the crosstalk problem for the practical multi-color LED based VLC system. Meanwhile, we can see that the BER curves show a down and up tendency with the increase of luminous flux. Unlike radio frequency (RF) system, higher electrical power may cause clipping distortion problem due to the narrow dynamic range of an LED for the VLC system. Thus, proper DC bias value is required to avoid the clipping distortion problem.

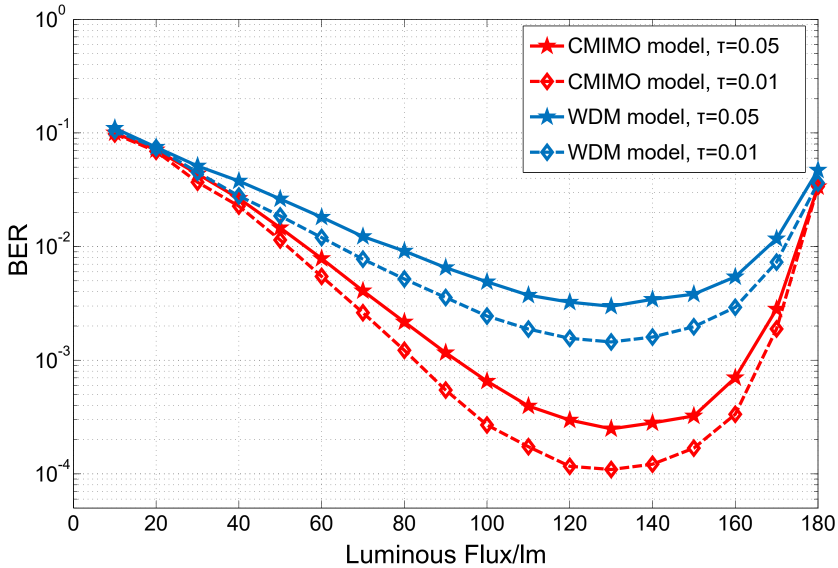

Figure 7. Error performance for the CMIMO model and the conventional WDM model under different interference coefficient under CCT = 5700 K.

In conclusion, the proposed optimal power allocation strategy can improve the overall performance for the multi-color LED based VLC system further. Compared with the uniform power allocation method, our proposed scheme behaves more power-efficiently while satisfying the necessary illumination and communication requirements. Moreover, considering the practical crosstalk problem, the CMIMO model can maintain better error performance.

5. Conclusions

In this paper, we have investigated a power-efficient illumination control optimization design for the CMIMO VLC system with multi-color LED. To increase the practicality of the system, crosstalk interference and quadrangle chromaticity constraint are taken into consideration. Since the VLC system is the combination of illumination and communication, an optimal power allocation strategy is proposed to maximize power efficiency via collaboratively satisfying the illuminance, chromaticity, amplitude and SINR constraints. Simulation results have testified that the proposed optimal power allocation strategy can significantly reduce the total transmission power compared with the uniform power allocation method. Moreover, higher power efficiency can be achieved under larger CCT value due to the increase of the blue and green light component in the mixed light. Furthermore, it is also concluded that better error performance can be obtained for the CMIMO model considering crosstalk interference and proper DC bias value is required to avoid the clipping distortion problem.

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