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Optimal Power Allocation Scheme Based on Multi-Factor Control in Indoor NOMA-VLC Systems

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ABSTRACT In order to overcome the limitation of narrow modulation bandwidth on the performance in the visible light communication (VLC) systems, non-orthogonal multiple access (NOMA) is applied to the downlink VLC networks in this paper to improve the sum rate performance effectively. We first propose an optimal power allocation strategy which is based on the multi-factor control (MFOPA), aiming to maximize the total system capacity subject to ensuring all users' quality of service (Qos) and fairness, as well as illumination requirements. The analytical results indicate that the proposed MFOPA could provide higher system sum rate and better user fairness as well as guarantee the Qos and eye safety of each user at the same time when compared with the static power allocation (SPA) and gain ratio power allocation (GRPA) schemes, especially in high demand for signal-to-interference-plus-noise ratio (SINR). What is more, considering the residual interference may exist during the successive interference cancellation (SIC) at the receiver, namely imperfect SIC, the interference cancellation factor is also taken into account in MFOPA strategy. The numerical results are shown to demonstrate the robustness and effectiveness of the MFOPA in NOMA-VLC when the residual interference remains.

INDEX TERMS Visible light communication (VLC), non-orthogonal multiple access (NOMA), power allocation, multiple factors, imperfect successive interference cancellation (SIC).

I. INTRODUCTION

In recent years, visible light communication (VLC) has attracted more attention due to its advantages such as high rate and security, energy efficiency and license-free spectrum, which has been regarded as a potential compensatory technology of existing wireless communication technologies [1]. However, one of the main drawback in VLC is that the narrow modulation bandwidth of the light sources limits its rate performance. For this reason, many technologies such as adaptive modulation [2], multiple-input-multiple-output (MIMO) [3], [4], equalization technologies [5] and multiple access schemes [6], [7] have been proposed and studied to improve the data rates in VLC systems. In addition, orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) have also been investigated and applied to VLC systems due to their superiority of resisting inter symbol interference (ISI), which can further improve the spectral efficiency [8]–[10]. However, these two techniques cannot be directly used in VLC since the signals must be real and non-negative, which is limited by the illumination requirement and intensity modulation. Therefore, DC-biasing and clipping schemes have been presented to adjust to OFDM and OFDMA, however, resulting in the decrease of the spectrum efficiency [11], [12].

Recently, non-orthogonal multiple access (NOMA) has been proposed as one of the most potential candidate technologies for 5G systems [13]. All users can enjoy the entire time and frequency resources which is beneficial to improving the sum rate performance in NOMA-VLC. At the transmitter side, users superimpose their signals which are multiplexed in the power domain, and decode their messages by using successive interference cancellation (SIC) at the receiver. However, the residual interference may exist during SIC, since the decoding user needs to demodulate and eliminate the interference caused by users who are allocated more

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power in NOMA-VLC systems before acquiring their own effective information [14], in which interference cancellation error may occur. What's more, NOMA has been proved to be very suitable for the downlink VLC systems [15]. Accordingly, we establish an indoor downlink NOMA-VLC network equipped with one light-emitting diode (LED) and multiple users.

Studies on the application of NOMA in VLC have been proposed and demonstrated in previous works [14]–[19]. In [14], a power allocation strategy called gain ratio power allocation (GRPA) was proposed based on users' channel conditions in NOMA-VLC systems, which enhances the system performance compared with static power allocation (SPA).It was also found that the sum rate can be further promoted by adjusting transmitting semi-angle of LEDs and the field of view(FOV) of photodiodes (PDs). The authors of [16] verified the superiority of NOMA in VLC over OFDMA based on the practical indoor VLC channel models. The sum rate of NOMA-VLC with one LED and multiple users was investigated and evaluated in [17]. In addition, another power allocation scheme which maximizes the system capacity subject to user fairness and illumination intensity was proposed in [18], and a power control algorithm with low complexity was also presented and evaluated. It was shown in [19] that the application of NOMA combined with OFDMA in VLC systems was verified to achieve higher capacity through experiments. However, it is not comprehensive enough that aforementioned investigations about system performance enhancements only involve a single or partial factors that influence system performance. As a matter of fact, although the sum rate can be improved through previous works, there is the lack of tradeoff among sum rate performance and user's quality of service (Qos), fairness as well as the optical intensity simultaneously. Secondly, most of the research works focus on the scenario of only two users, and ignore the case of imperfect SIC, where the non-negligible residual interference exists due to the user mobility and feedback delay at the receiver, leading to unsatisfactory detection performance and decrease of achievable sum rate.

Motivated by previous observations, the contribution of this paper are summarized as two aspects. Firstly, we establish an indoor downlink NOMA-VLC framework for one LED and N users. And then, to the best of our knowledge, this is the first work to develop an optimal power allocation strategy on the basis of considering multiple factors that control the system performance simultaneously, which is called MFOPA. Our goal is to maximize the total system capacity subject to ensuring all users' Qos demand and fairness as well as eye security. Moreover, considering the residual interference within the process of SIC at the receiver, the interference cancellation factor ε is also taken into account in the proposed MFOPA strategy. Numerical results show that MFOPA can significantly enhance the system sum rate performance for various ε on condition that all users' Qos demand, fairness and illumination requirements can be satisfied at the same time in comparison to SPA where the power assigned to each user is only depended on the power allocation factor α and GRPA where only channel gain values are considered based on SPA, especially in the case of high demand for signal-to-interference-plus-noise ratio (SINR). Consequently, the validity and robustness of the proposed MFOPA strategy can get demonstrated and verified.

II. SYSTEM MODEL

We consider a scenario with one LED transmitter and N users in an indoor NOMA-VLC network, as shown in Fig. 1, in which LED is assumed to be located at the center of the room ceiling. By implementing NOMA to VLC systems, users distributed in the room are superimposed in the power-domain by allocating different transmission power levels according to their channel gains, and perform SIC decoding to obtain the information they need after receiving the optical signals through their own PDs. Hence, the time and frequency resources can be entirely shared by all users leading to the promoted spectral efficiency.

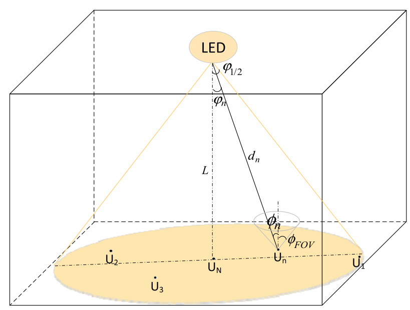

FIGURE 1. Indoor NOMA-VLC DL network with 1 LED and N users.

A. VLC CHANNELS

Based on the characteristics of VLC channels, the received signals by users generally consist of two components,LOS link and NLOS link [20]. However, only the LOS path gain is considered in this paper because the energy of the diffuse component is much less than that of LOS link according to [3], [21], [22]. Therefore, the channel gain between the LED and the user n can be calculated by

$$h_n = \begin{cases} \frac{(m+1)A_n}{2\pi d_n^2}\cos^m(\varphi_n)T_s(\phi_n)g(\phi_n)\cos(\phi_n), \\ \qquad 0 \le \phi_n \le \phi_{FOV} \\ 0, \qquad \phi_n > \phi_{FOV} \end{cases} \quad (1)$$

In (1), A_n, ϕ_n and ϕ_{FOV} denote the PD area, incidence and FOV of user n, respectively. d_n is the distance from LED to user n, φ_n is the irradiance of the transmitter, $T_s(\phi_n)$ represents the gain of the optical filter, and $g(\phi_n)$ is the gain of the optical concentrator calculated by

$$g(\phi_n) = \begin{cases} \frac{n^2}{\sin\phi_{FOV}^2}, & 0 \le \phi_n \le \phi_{FOV} \\ 0, & \phi_n > \phi_{FOV} \end{cases} \quad (2)$$

where n is the refractive index. In addition, m denotes the order of Lambertian emission given by

$$m = -\frac{1}{\log_2 \left[\cos\left(\varphi_{1/2}\right)\right]} \tag{3}$$

where $\varphi_{1/2}$ is the semi-angle of the LED transmitter at half power.

B. SYSTEM MODEL

In this paper, an indoor downlink network of NOMA-VLC equipped with one LED and N users is considered, and 8-ary Pulse Position Modulation (PPM) is utilized to modulate the signals [23]. Fig. 2 illustrates the schematic of the NOMA-VLC system with three users. According to the principle of NOMA, users are assigned different power values depending on their channel gain h_n at the transmitter side, denoted as p_n. Assuming $h_1 \leq h_2 \leq \cdots \leq h_n \leq \cdots \leq h_N$, we have $p_1 \geq p_2 \geq \cdots \geq p_n \geq \cdots \geq p_N$. Moreover, let $\{s_n\}$ represent N messages sent by LED transmitter simultaneously, also S denotes total transmitting signal using superposition coding which is given by

$$S = \sum_{n=1}^{N} \sqrt{p_n} s_n + I_{DC} \tag{4}$$

where p_n is the power value allocated to the nth user in NOMA-VLC, and I_{DC} is the DC-offset which can be denoted as a constant C for the sake of description. Therefore, we have

$$S = \sum_{n=1}^{N} \sqrt{p_n} s_n + C \tag{5}$$

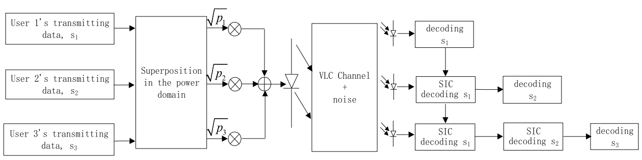

FIGURE 2. The schematic of NOMA-VLC system with three users.

In addition, let D represent the peak optical intensity for practical implementation. Based on (4) and (5), considering the signals must be real and non-negative as well as illumination requirements in VLC, we can obtain

$$\sum_{n=1}^{N} \sqrt{p_n} \leq C \tag{6}$$

$$\sum_{n=1}^{N} \sqrt{p_n} + C \leq D \tag{7}$$

At the receiver side, all users in the illumination area receive the signals from the LED transmitter using PDs equipped by themselves, denoted as y_n. After the constant DC-offset is removed, y_n is given by

$$y_n = h_n \sum_{k=1}^{N} \sqrt{p_k} s_k + n_n \tag{8}$$

In (8), n_n represents the additive white Gaussian noise (AWGN) with zero mean and total variance σ^2, which can be regarded as the sum of shot noise and thermal noise. If user n performs perfect SIC at the receiver side, which means the interference caused by users that are allocated more power levels than user n is entirely cancelled, the achievable rate of user n can be obtained as follows:

$$r_n' = B \cdot \log_2 \left(1 + \frac{h_n^2 p_n}{h_n^2 \sum\limits_{k=n+1}^{N} p_k + \sigma^2} \right) \tag{9}$$

where B is the bandwidth of the VLC system, and p_n represents the power value for user n.

However, taking the users' random mobility and feedback delay into account in NOMA-VLC, it is non-negligible that the residual interference may remain during SIC at the receiver, which leads to the decrease in user detection performance. We denote ε as the percentage of the residual interference within the process of SIC [24]. According to the rate expression described in (9), the accurate achievable rate of user n can be formulated as

$$r_n = B \cdot \log_2 \left(1 + \frac{h_n^2 p_n}{h_n^2 \sum\limits_{k=n+1}^{N} p_k + \varepsilon \cdot h_n^2 \sum\limits_{k=1}^{n-1} p_k + \sigma^2} \right) \tag{10}$$

In (10), let $\bar{r}_n$ represent the second term of (10), then we have

$$r_n = B \cdot \bar{r}_n \tag{11}$$

In this paper, the Qos requirement of each user is also considered for practical implementation of NOMA-VLC in addition to the factors including the optical signal, eye safety and interference cancellation factor. By this means, achievable rate of each user in NOMA-VLC must be no less than the required SINR so as to ensure normal communication. Considering this restricted condition, we have

$$r_n \geq T_n \tag{12}$$

where T_n is the targeted SINR to guarantee the required Qos of user n in NOMA-VLC systems.

According to (6), (7), (10) and (12), the achievable sum rates and user fairness in NOMA-VLC is jointly determined by the power vector $\mathbf{p} = (p_1, p_2, \ldots, p_N)^T$ and interference cancellation factor ε. Hence, optimal power allocation plays a significant role in boosting the performance of NOMA-VLC systems. And the above expressions will serve as an important basis for later mathematical model development in the next section which focuses on the power allocation in NOMA-VLC subject to multiple factors control.

III. OPTIMAL POWER ALLOCATION STRATEGY BASED ON MULTI-FACTOR CONTROL (MFOPA)

In this section, we propose a novel optimal power allocation strategy based on multi-factor control (MFOPA) for an indoor NOMA-VLC scenario with multiple users, aiming to maximize the total system capacity under the Qos demand, fairness and eye security of each user simultaneously.

We first build the objective function maximizing the total system utility based on (10) and introduce the logarithmic utility function in which the user fairness can get guaranteed. And then (6), (7), (10) and (12) are used as the limiting conditions to ensure the Qos and optical intensity of all users in the system. Finally, the optimal power control solution of the problem formulated is obtained using the optimization theory.

A. PROBLEM FORMULATION

We can see from the prior works that logarithmic utility function has been proved to be very suitable for multi-user communication to achieve better fairness among users [24]. By considering (10), the total system utility is the sum contribution of all users in NOMA-VLC, which is given by

$$\sum_{n=1}^{N}\log_2 r_n = \sum_{n=1}^{N}\log_2 (B\cdot \bar{r}_n) \tag{13}$$

$$= \sum_{n=1}^{N}\left(\log_2 B + \log_2 \bar{r}_n\right) \tag{14}$$

$$= \sum_{n=1}^{N}\log_2 B + \sum_{n=1}^{N}\log_2 \bar{r}_n \tag{15}$$

From (13) to (15), the optimization of sum utility is equivalent to optimizing the second term in (15) due to the constant B which represents the bandwidth of the VLC system. Therefore, motivated by above discussion in this paper, the final mathematic optimization model of power allocation in NOMA-VLC is formulated as follows,

$$\max_{\mathbf{p}} \sum_{n=1}^{N}\log_2\left[\log_2\left(1+\frac{h_n^2 p_n}{h_n^2\sum_{k=n+1}^{N}p_k+\varepsilon\cdot h_n^2\sum_{k=1}^{n-1}p_k+\sigma^2}\right)\right] \tag{16a}$$

$$s.t. \sum_{n=1}^{N} p_n \le P \tag{16b}$$

$$\sum_{n=1}^{N}\sqrt{p_n} \le C \tag{16c}$$

$$\sum_{n=1}^{N}\sqrt{p_n} + C \le D \tag{16d}$$

$$r_n \ge T_n \tag{16e}$$

$$\mathbf{p} \ge \mathbf{0} \tag{16f}$$

where $\mathbf{p} = (p_1, p_2, \ldots, p_N)^T$ is the power vector consisting of N components, and P is the maximal transmitted power. What's more, we define $\sum_{k=n+1}^{N} p_k = 0$, for $n = N$ and $\sum_{k=1}^{n-1} p_k = 0$, for $n = 1$. Apparently, the programme (16) is non-convex because of the convexity of the whole problem except for the objective function (16a) as well as constraint condition (16c), (16d) and (16e).

B. PROBLEM - SOLVING PROCEDURE

Due to the non-convexity of the original formulated model, it is first transformed into the convex programme by introducing auxiliary variables through the optimization theory [26]. Hence the new equivalent convex problem of (16) can be expressed as follows,

$$\max_{\mathbf{f},\mathbf{c},\mathbf{l},\mathbf{u},\mathbf{z},\mathbf{w},\lambda} \sum_{n=1}^{N}\log_2\left[\log_2\left(1+e^{f_n}\right)\right] \tag{17a}$$

$$s.t.\ e^{l_n} + \sum_{k=n+1}^{N} e^{u_{nk}} + \varepsilon\cdot\sum_{i=1}^{n-1} e^{z_{ni}} \le 1 \tag{17b}$$

$$l_n = f_n - c_n + g_n, \quad n = 1, \ldots, N \tag{17b$_1$}$$

$$u_{nk} = f_n - c_n + c_k, \quad n = 1, \ldots, N-1, \quad k = n+1, \ldots, N \tag{17b$_2$}$$

$$z_{ni} = f_n - c_n + c_i, \quad n = 2, \ldots, N, \quad i = 1, \ldots, n-1 \tag{17b$_3$}$$

$$\sum_{n=1}^{N} e^{c_n} \le P \tag{17c}$$

$$\sum_{n=1}^{N} e^{\frac{c_n}{2}} \le C \tag{17d}$$

$$\sum_{n=1}^{N} e^{\frac{c_n}{2}} + C \le D \tag{17e}$$

$$-e^{c_n} + \sum_{k=n+1}^{N} e^{w_{nk}} + \varepsilon\cdot\sum_{i=1}^{n-1} e^{\lambda_{ni}} \le -e^{t_n} \tag{17f}$$

$$w_{nk} = v_n + c_k, \quad n = 1, \ldots, N-1, \quad k = n+1, \ldots, N \tag{17f$_1$}$$

$$\lambda_{ni} = v_n + c_i, \quad n = 2, \ldots, N, \ i = 1, \ldots, n-1 \tag{17f$_2$}$$

$$t_n = g_n + v_n, \quad n = 1, \ldots, N \tag{17f$_3$}$$

$$e^{c_n} \ge 0, \quad n = 1, \ldots, N \tag{17g}$$

where $\mathbf{f} = (f_1, f_2, \ldots, f_N)^T$, $\mathbf{c} = (c_1, c_2, \ldots, c_N)^T$, $\mathbf{l} = (l_1, l_2, \ldots, l_N)^T$, $\mathbf{u} = \left(u_{12}, u_{13}, \ldots, u_{1N}, u_{23}, \ldots, u_{(N-1)N}\right)^T$, $\mathbf{z} = \left(z_{21}, z_{31}, z_{32}, \ldots, z_{N1}, \ldots, z_{N(N-1)}\right)^T$, $\mathbf{w} = \left(w_{12}, w_{13}, \ldots, w_{1N}, w_{23}, \ldots, w_{(N-1)N}\right)^T$, $\lambda = (\lambda_{21}, \lambda_{31}, \lambda_{32}, \ldots, \lambda_{N1}, \ldots, \lambda_{N(N-1)})^T$, $v_n = \ln T_n$ and $g_n = \ln\left(\sigma^2\right) - \ln\left(h_n^2\right)$, $n = 1, \ldots, N$.

Proof: Please refer to the Appendix.

On the basis of Appendix, the convexity of the new transformed problem (17) can be shown by proving that Hessian matrix of the objective function (17a) is positive definite. And then it is converted into the standard form of convex programming. Finally the optimal power control solution can be obtained by using CVX solver and standard interior point method [27].

IV. NUMERICAL RESULTS

In this section, Monte-Carlo simulation is used to evaluate the performance of the proposed MFOPA strategy in NOMA-VLC system. We consider a 7 m×7 m×3 m room with one transmitting LED and three users. The maximal transmitted power and noise power spectral density is $P = 20$mW and $N_0 = 10^{-24}$W/Hz, respectively. The required SINR (T) of each user is set from 1 dB to 4.5 dB in order to analyze and demonstrate the sum rate and user fairness performance of the proposed MFOPA scheme. Additionally, the power allocation factor of SPA (α) is assumed to be 0.3 and 0.4 and the interference cancellation factor ε is set to be 0, 0.01 and 0.02, respectively. The main simulation parameters about LED and PD settings in NOMA-VLC are summarized in Table 1. And we compare the performance of our MFOPA strategy with SPA (with different power control factors 0.3 and 0.4) and GRPA in terms of achievable sum rate, cumulative distribution function(CDF) of rate and user fairness, respectively.

TABLE 1. Simulation parameters.

Parameter	Symbol	Value
Optical filter gain	$T(\phi)$	1
Refractive index	n	1.5
Area of PD	A	1 cm^2
FOV of PD	ϕ_{FOV}	90 deg
Semi angle at half power	$\varphi_{1/2}$	60 deg
LED height	H	3 m
User height	z	0.85 m
Signal bandwidth	B	10 MHz
Noise power spectral density	N_0	10^{-24} W/Hz
Required SINR of user	T	1 dB to 4.5 dB
Max. Transmitted Power	P	20 mW
Power allocation factor	α	0.3, 0.4
DC-offset	C	$30\sqrt{dBm}$
Peak optical intensity	D	$40\sqrt{dBm}$
Interference cancellation factor	ε	0, 0.01, 0.02

Firstly, we investigate the sum rate of the new MFOPA criterion in NOMA-VLC systems with respect to the required SINR (T) of the user, where the interference cancellation factor ε is set to 0, 0.01 and 0.02, as shown in Figure 3(a). Simulation results show that when ε is fixed, the measured sum rate of the proposed MFOPA remains high values approximately

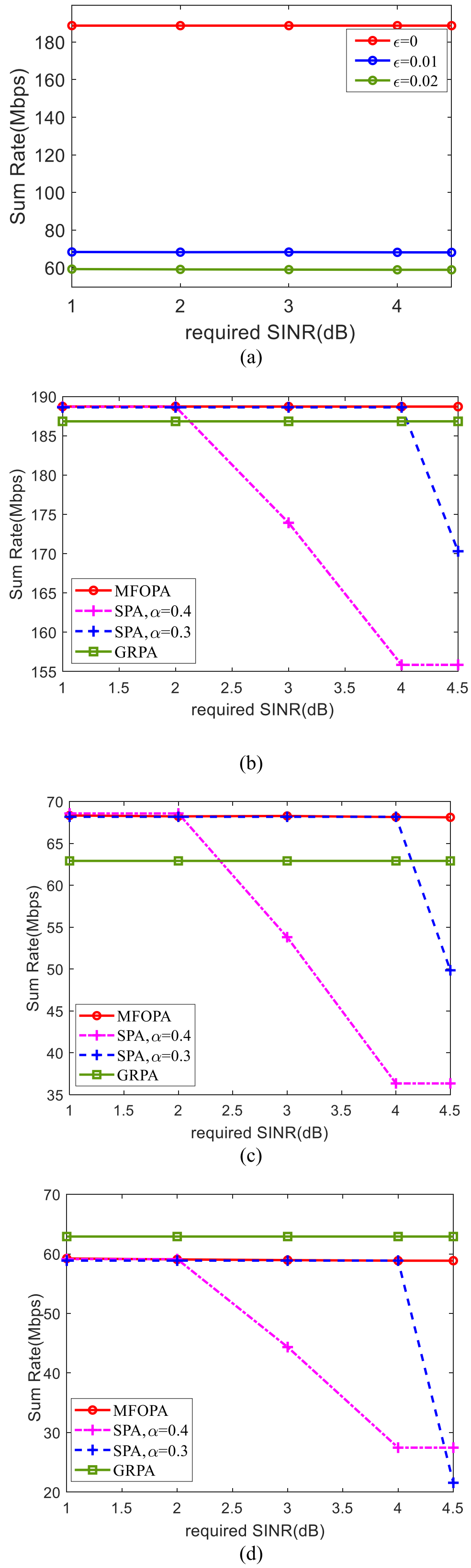

FIGURE 3. The maximized sum user rate comparison vs required SINR for different power allocation schemes. (a) MFOPA with different ε; (b) MFOPA, SPA and GRPA with $\varepsilon = 0$; (c) MFOPA, SPA and GRPA with $\varepsilon = 0.01$; (d) MFOPA, SPA and GRPA with $\varepsilon = 0.02$.

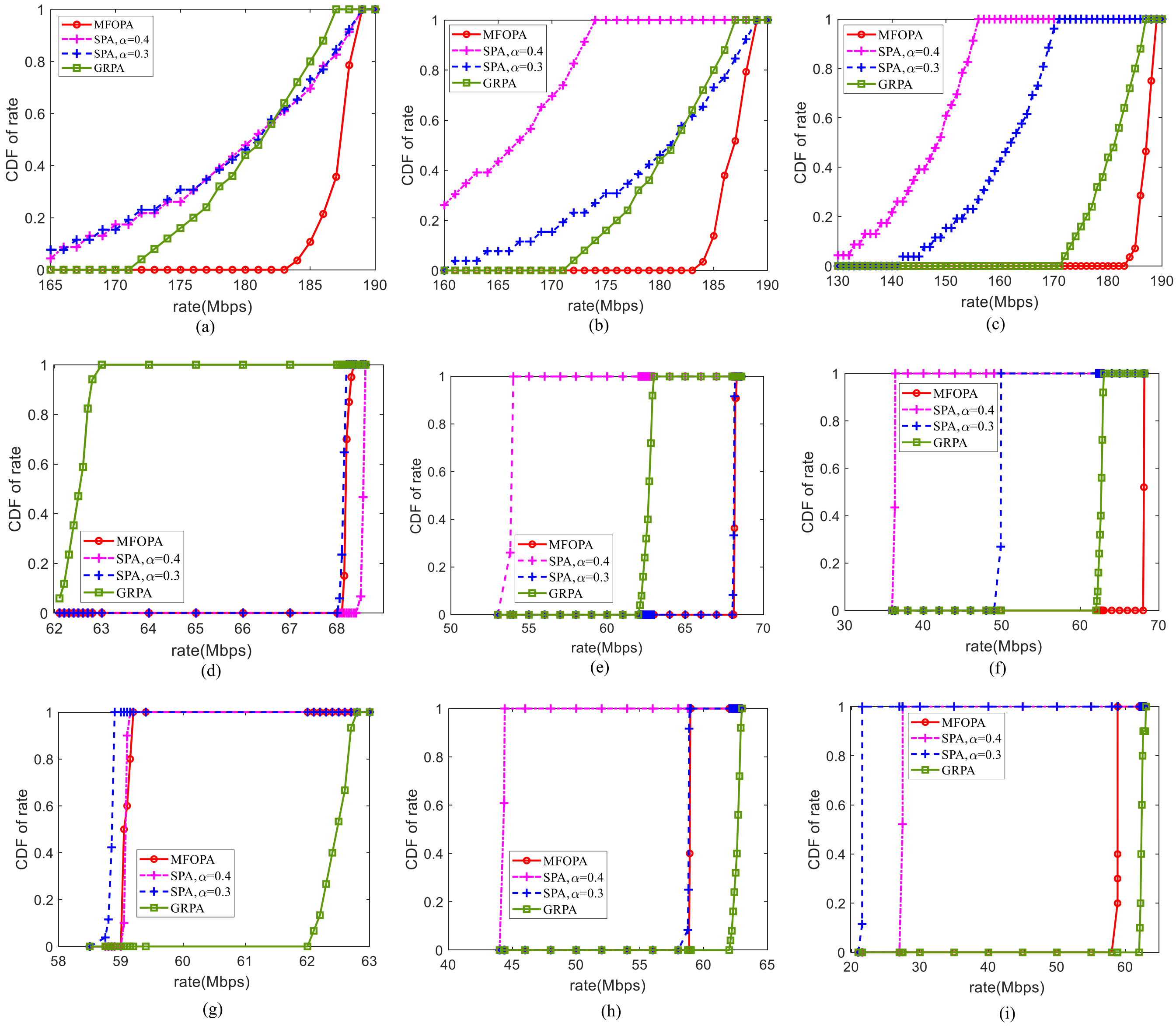

FIGURE 4. CDF of rate for different power allocation schemes with various T and ε. (a) $T = 1$ dB, $\varepsilon = 0$; (b) $T = 3$ dB, $\varepsilon = 0$; (c) $T = 4.5$ dB, $\varepsilon = 0$; (d) $T = 1$ dB, $\varepsilon = 0.01$; (e) $T = 3$ dB, $\varepsilon = 0.01$; (f) $T = 4.5$ dB, $\varepsilon = 0.01$; (g) $T = 1$ dB, $\varepsilon = 0.02$; (h) $T = 3$ dB, $\varepsilon = 0.02$; (i) $T = 4.5$ dB, $\varepsilon = 0.02$.

with the increase of T. However, it will decline when ε gradually increases. As a result, we can observe that the residual interference which is not entirely cancelled within the process of SIC has a great negative impact on system performance. When $\varepsilon = 0$, for example, the sum rate of three users in the illumination area can achieve about 188.72 Mbps, and it will be decreased to 68.3 Mbps and 59.2 Mbps when ε is up to 0.01 and 0.02, respectively.

Fig. 3(b) to 3(d) present the sum rate comparison among MFOPA and SPA as well as GRPA strategies when different ε are taken. It is straightforward to see that the proposed MFOPA outperforms the other two strategies significantly, especially when the required SINR T is high. For example, when $\varepsilon = 0$, the maximal sum rate of MFOPA achieves 188.72 Mbps and almost invariable with the increase of T, while GRPA remains about 186.8 Mbps, and SPA ($\alpha = 0.4$ and 0.3) achieves the sum rate of 188.69 Mbps and 188.62 Mbps at $T = 1$ dB, respectively. But when T increases to 4.5 dB, the sum rate of SPA will be reduced by 32.9 Mbps and 18.32 Mbps in comparison to its original rates, while MFOPA still keeps high rate, i.e., 188.71 Mbps. This is because all of these four power control criteria are able to ensure the Qos of each user for lower T in NOMA-VLC, which is reasonable that the sum rate of all methods make small difference at the beginning. Nevertheless, with the gradual increase of T, both of SPA and GRPA can no longer guarantee the lowest targeted rate of all users simultaneously, thus there is a sharp decline in the sum rate performance in these two strategies when T becomes higher.

It is worth noting that although the sum rate of GRPA appears optimistic for $\varepsilon = 0.01$ and 0.02 based on Fig. 3(b) and Fig. 3(c), in fact the user's Qos cannot be pledged from $T = 1$ dB through a large number of simulation data, which means the sum rate of GRPA is only depended on the single user that can meet the targeted SINR. For the remaining two users in the system, we consider it to be disconnected with LED since the actual achievable rate measured is not satisfied with its targeted T. Additionally and similarly, for arbitrary ε, the Qos requirement cannot be satisfied from $T = 3$ dB and $T = 4.5$ dB in SPA with $\alpha = 0.4$ and SPA with $\alpha = 0.3$, respectively. In contrast, the Qos requirement and user fairness are always considered to be partial of the sufficient conditions in our proposed MFOPA model to maximize the objective utility function, thus not only a higher achievable sum user rate can be obtained, but fairness among users can also be guaranteed consequently. And the comparison of user fairness among MFOPA, SPA with $\alpha = 0.4$ and 0.3 as well as GRPA is shown in Fig. 5.

Secondly, the CDF of rate under various required SINR ($T = 1$ dB, 3 dB and 4.5 dB) and interference cancellation factor ($\varepsilon = 0$, 0.01 and 0.02) for different power allocation schemes is shown in Figure 4. Numerical results demonstrates that the proposed MFOPA always performs better than SPA and GRPA in terms of the CDF of rate with different ε. In Fig. 4(a) to Fig. 4(f), e.g., when $\varepsilon = 0$ and 0.01, the CDF curve of MFOPA is always at the bottom compared to the other strategies. Furthermore, it can be found that for $\varepsilon = 0$ and $T = 1$ dB, there is little difference in CDF between SPA with $\alpha = 0.4$ and SPA with $\alpha = 0.3$, where the targeted rate of each user can get effectively ensured. When T is up to 3 dB, SPA with $\alpha = 0.3$ can still exhibits well whereas only two users' Qos is guaranteed in SPA with $\alpha = 0.4$. However, when T increases to 4.5 dB, both of their CDF performance will degrade since only single user and two users in NOMA-VLC access the network normally in SPA with $\alpha = 0.4$ and SPA with $\alpha = 0.3$, respectively. As a consequence, the CDF performance of SPA with $\alpha = 0.4$ is inferior to that of SPA with $\alpha = 0.3$ from Fig. 4(a) to Fig. 4(c) and Fig. 3(b). In addition, when ε takes 0 and T takes from 1 dB to 4.5 dB, the CDF and sum rate performance of GRPA perform only second to the proposed MFOPA. This is because the detected rates of all users in systems are satisfied with their required SINR at this time. What's more, it is worth noting that when ε is 0.02, the CDF of MFOPA still performs best rather than GRPA in which only user 1's required Qos can be satisfied and the other users are failed to connect with LED through a great deal of experimental data, therefore the three green lines in Fig. 4(g) to Fig. 4(i) make little sense actually. According to the principle of SPA and GRPA, only partial of the key factors that influence system performance are considered, which is not comprehensive enough, resulting in communication interruption of some users in the network as a consequence.

Fig. 5 investigates the variance of user rate with regard to various required SINR for the purpose of illustrating the fairness among users for MFOPA in comparison to SPA and GRPA schemes. And the corresponding rate variance among all users in the system at the maximal sum utility for different required SINR is presented in Fig. 5(a) to Fig. 5(c). We can see that the proposed MFOPA has better user fairness performance in which the variance of user rate is smaller and more stable than SPA and GRPA strategy, especially when T and ε are high, respectively. For example, when T is 4.5 dB and ε is 0, MFOPA has 36.73% and 21.35% user fairness performance enhancement compared to that of SPA with $\alpha = 0.4$ and SPA with $\alpha = 0.3$. And when T is set to 4.5 dB and ε increases to 0.01, the rate variance enhancement is calculated as 94.38% for SPA with $\alpha = 0.4$, 89.31% for SPA with $\alpha = 0.3$ and 98.12% for GRPA. Furthermore, the user fairness performance in GRPA seems superior to that in MFOPA when $\varepsilon = 0$ based on Fig. 5(a), however, its sum rate is still lower than that of MFOPA according to Fig. 3(b). For $\varepsilon = 0.01$ and

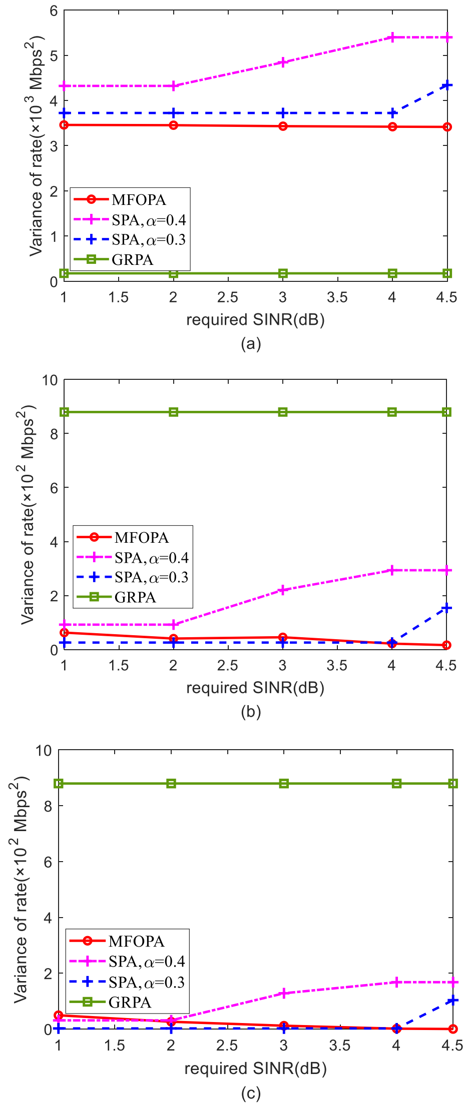

FIGURE 5. **The variance of rate vs required SINR (T) for different power allocation schemes with various ε. (a) $\varepsilon = 0$; (b) $\varepsilon = 0.01$; (c) $\varepsilon = 0.02$.**

0.02 in Fig. 5(b) and Fig. 5(c), the minimal Qos requirement of all users except for user 1 cannot be assured for any given T (from 1 dB $\sim$ 4.5 dB) in GRPA, resulting in the highest rate variance and thus worst user fairness consequently. For traditional SPA, it is implemented just considering the power allocation factor α to allocate different power values to users in the illumination area mechanically, without taking any other key factors into account that may have an influence on system performance. For traditional GRPA, it only adds the channel gain values h on the basis of SPA. Therefore, the effectiveness to the user fairness issue of the proposed MFOPA is verified and demonstrated through the tremendous increase in rate variance performance compared to SPA and GRPA.

V. CONCLUSION

This paper investigates the power control problem for indoor downlink NOMA-VLC networks equipped with one LED and multiple users. We propose an optimal power allocation strategy based on multi-factor control (MFOPA), aiming to optimize the system's sum rate performance subject to ensuring each user's Qos, fairness and illumination requirement simultaneously. And then considering the imperfect SIC, we take the interference cancellation factor into account in the proposed MFOPA for the purpose of investigating the impact on system performance. Then the optimal power control solution of the proposed MFOPA strategy can be obtained by using convex optimization theory and CVX solver. Numerical results show that compared to the existing SPA and GRPA schemes, MFOPA exhibits significant performance enhancement in terms of sum rate and user fairness on condition that all users' Qos and eye safety can be pledged whether the residual interference exists in SIC, especially in the case of high demand for required SINR.

APPENDIX

PROOF OF TRANSFORMATION FROM NONCONVEX PROBLEM (16) TO CONVEX PROBLEM (17)

In this part, we prove that the non-convex problem (16) is equivalent to the convex problem (17). We firstly introduce auxiliary variables β_n, and the problem (16) can be written as

$$\max_{\mathbf{p},\beta} \sum_{n=1}^{N} \log_2\left[\log_2\left(1+\beta_n\right)\right] \tag{18a}$$

$$\text{s.t. } \beta_n \le \frac{h_n^2 p_n}{h_n^2 \sum\limits_{k=n+1}^{N} p_k + \varepsilon \cdot h_n^2 \sum\limits_{k=1}^{n-1} p_k + \sigma^2} \tag{18b}$$

$$\sum_{n=1}^{N} p_n \le P \tag{18c}$$

$$\sum_{n=1}^{N} \sqrt{p_n} \le C \tag{18d}$$

$$\sum_{n=1}^{N} \sqrt{p_n} + C \le D \tag{18e}$$

$$B \log_2\left[1 + \frac{h_n^2 p_n}{h_n^2 \sum\limits_{k=n+1}^{N} p_k + \varepsilon \cdot h_n^2 \sum\limits_{k=1}^{n-1} p_k + \sigma^2}\right] \ge T_n \tag{18f}$$

$$\mathbf{p} \ge \mathbf{0} \tag{18g}$$

where $\beta = (\beta_1, \beta_2, \ldots, \beta_N)$. To deal with concave (18a) and nonconvex constraints (18d) (18e) and (18f), we definite $p_n = e^{c_n}$, $\beta_n = e^{f_n}$, $\frac{\sigma^2}{h_n^2} = e^{g_n}$, $T_n = e^{v_n}$, $n = 1, \ldots, N$. Then (18a), (18c), (18d), (18e) and (18g) can be written as (17a), (17c), (17d), (17e) and (17g), respectively. For (18b), we can get

$$e^{f_n} \le \frac{h_n^2 e^{c_n}}{h_n^2 \sum\limits_{k=n+1}^{N} e^{c_k} + \varepsilon \cdot h_n^2 \sum\limits_{k=1}^{n-1} e^{c_k} + \sigma^2}, \tag{18b$_1$}$$

which is equivalent to

$$e^{f_n - c_n + g_n} + \sum_{k=n+1}^{N} e^{f_n - c_n + c_k} + \varepsilon \cdot \sum_{i=1}^{n-1} e^{f_n - c_n + c_i} \le 1. \tag{18b$_2$}$$

Denote $l_n = f_n - c_n + g_n$, $u_{nk} = f_n - c_n + c_k$ for $n = 1, \ldots, N-1$ and $k = n+1, \ldots, N$, and $z_{ni} = f_n - c_n + c_i$ for $n = 2, \ldots, N$ and $i = 1, \ldots, n-1$. As a result, (18b$_2$) can be simplied as (17b). Similarly, (18f) is equivalent to

$$-e^{c_n} + \sum_{k=n+1}^{N} e^{v_n + c_k} + \varepsilon \cdot \sum_{i=1}^{n-1} e^{v_n + c_i} \le -e^{g_n + v_n}. \tag{18f$_1$}$$

Denote $w_{nk} = v_n + c_k$ for $n = 1, \ldots, N-1$ and $k = n + 1, \ldots, N$, $\lambda_{ni} = v_n + c_i$ for $n = 2, \ldots, N$ and $i = 1, \ldots, n-1$, and $t_n = v_n + g_n$. Thus (18f) can be formulated as (17f). Now, we get the new transformed problem (17) and prepare to show the convexity of it by deriving the Hessian matrix of the objective function (17a), which is given by

$$\begin{aligned}
&\frac{\partial^2 \log_2\left[\log_2\left(1+e^{f_n}\right)\right]}{\partial f_n^2} \qquad (19)\\
&= \frac{\partial\left[\frac{1}{\ln 2 \cdot \log_2\left(1+e^{f_n}\right)} \cdot \frac{e^{f_n}}{\left(1+e^{f_n}\right)\cdot \ln 2}\right]}{\partial f_n}\\
&= \frac{\partial\left[\frac{e^{f_n} \cdot \ln 2}{(\ln 2)^2 \cdot \left(1+e^{f_n}\right)\ln\left(1+e^{f_n}\right)}\right]}{\partial f_n}\\
&= \frac{1}{\ln 2} \cdot \frac{\partial\left[\frac{e^{f_n}}{\left(1+e^{f_n}\right)\ln\left(1+e^{f_n}\right)}\right]}{\partial f_n}\\
&= \frac{1}{\ln 2}
\end{aligned}$$

$$\cdot \frac{e^{f_n}\left(1+e^{f_n}\right)\ln\left(1+e^{f_n}\right)-e^{f_n}\left[\begin{array}{c} e^{f_n}\ln\left(1+e^{f_n}\right)+\left(1+e^{f_n}\right) \\ \times \dfrac{e^{f_n}}{\left(1+e^{f_n}\right)}\end{array}\right]}{\left(1+e^{f_n}\right)^2\left[\ln\left(1+e^{f_n}\right)\right]^2}$$

$$= \frac{1}{\ln 2}\cdot \frac{e^{f_n}\ln\left(1+e^{f_n}\right)+e^{2f_n}\ln\left(1+e^{f_n}\right)-e^{2f_n}\ln\left(1+e^{f_n}\right)-e^{2f_n}}{\left(1+e^{f_n}\right)^2\left[\ln\left(1+e^{f_n}\right)\right]^2}$$

$$= \frac{1}{\ln 2}\cdot\frac{e^{f_n}\left[\ln\left(1+e^{f_n}\right)-e^{f_n}\right]}{\left(1+e^{f_n}\right)^2\left[\ln\left(1+e^{f_n}\right)\right]^2} < 0, \qquad (20)$$

$$\frac{\partial^2 \log_2\left[\log_2\left(1+e^{f_n}\right)\right]}{\partial f_n \partial f_m} = 0, \quad \forall n \neq m. \qquad (21)$$

Based on (19), (20) and (21), we can see that the Hessian matrix of problem (17) is positive definite and each constraint is convex, therefore the new problem (17) is convex.

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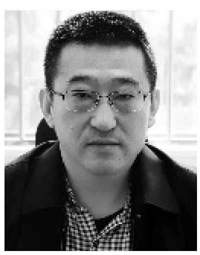

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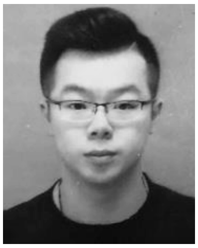

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