Energy-Efficient NOMA with QoS-Guaranteed Power Allocation for Multi-User VLC

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***Abstract*—In this paper, we propose an energy-efficient non-orthogonal multiple access (NOMA) technique for multi-user visible light communication (VLC) systems, by adopting a low-complexity quality of service (QoS)-guaranteed power allocation strategy. From the perspective of energy saving, we design the energy-efficient NOMA-enabled multi-user VLC system with the goal to achieve maximal energy efficiency (EE). The closed-form QoS-guaranteed optimal power allocation strategy is obtained and the analytical EE of the proposed NOMA-enabled multi-user VLC system is derived. The analytical and simulation results show that, for a VLC system with ten users, the average EE can be improved by 19% when adopting the proposed NOMA in comparison to NOMA with gain ratio power allocation (GRPA), and the EE improvement becomes much more significant when the users have more diverse QoS requirements.**

***Index Terms*—Visible light communication (VLC), multi-user, non-orthogonal multiple access (NOMA), power allocation.**

I. Introduction

Due to the explosive growth of smart mobile devices (e.g., mobile phones and tablets) in our daily life, which demand data-hungry services such as high definition video streaming, low-latency gaming, virtual/augmented reality and Internet-of-things, the mobile data traffic is expected to be exponentially increased in the near future [1]. The current radio frequency (RF) systems suffer from the spectrum congestion and hence might not be able to support the ever-increasing mobile data traffic. In recent years, the wide application of white light-emitting diodes (LEDs) for general indoor illumination has made visible light communication (VLC) a potential candidate to support next-generation high-speed wireless communications [2]. Compared with traditional RF systems, VLC systems enjoy many inherent advantages such as huge and unregulated spectrum, potentially high data rate, low-cost front-ends, high security and no electromagnetic interference [3], [4]. Therefore, VLC has been considered as a promising complementary technology to traditional RF technologies, which has triggered great interest in both academia and industry.

In practical VLC systems, white LEDs serve a dual-function of simultaneous illumination and communication. Generally, a typical room can be divided into multiple optical attocells and the LED transmitter of an optical attocell needs to broadcast signal to all the users within its coverage [5], [6]. Therefore, an efficient multiple access technique is essential for the VLC system to simultaneously support multiple users. So far, several multiple access techniques have been considered for multi-user VLC systems. In [7] and [8], orthogonal frequency division multiple access (OFDMA) has been applied to support multiple users in VLC systems, where the frequency resources of the VLC system are split and allocated to different users. In [9] and [10], time division multiple access (TDMA) has been adopted in multi-user VLC systems, where different users are allocated with different time slots. Both OFDMA and TDMA can be categorized as orthogonal multiple access (OMA) techniques. In OMA-based multi-user VLC systems, the mutual interference between different users can be eliminated by allocating them with different time/frequency resources. Another category of multiple access techniques is non-orthogonal multiple access (NOMA), which allows users to share the same time/frequency resources through power domain superposition coding (SPC) and successive interference cancellation (SIC) [11]. Due to its efficient resource utilization, NOMA has been viewed as a promising solution for the fifth generation (5G) and beyond wireless networks [12].

Recently, the application of NOMA in VLC systems has attracted great attention. In [13], a gain ratio power allocation (GRPA) strategy was proposed for NOMA-based VLC systems. In [14], a theoretical framework was presented to analyze the performance of NOMA in VLC systems. In [15], user grouping and power allocation were studied in NOMA-based multi-cell VLC networks. In [16], the bit-error-rate performance of NOMA-based VLC systems with noisy and outdated channel state information was analyzed. In [17], NOMA was applied to multiple-input multiple-output VLC systems and a normalized gain difference power allocation strategy was further proposed. In [18], a SIC-free NOMA scheme based on constellation partitioning coding was proposed to mitigate error propagation caused by imperfect SIC in VLC systems. In [19], the impact of random receiver orientation on the performance of NOMA-based VLC systems was investigated. These recent works have demonstrated the superiority of NOMA over OMA in multi-user VLC systems. The key to implement NOMA is to obtain a proper power allocation strategy. In most NOMA-based VLC systems, the achievable rate is generally adopted as the performance metric and the power allocation strategy is designed to maximize the system rate. Nevertheless, energy consumption is another important issue that needs to be considered in practical VLC

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systems. Hence, it is of practical significance to design multi-user VLC systems from the perspective of energy saving.

In this paper, we propose an energy-efficient NOMA technique for multi-user VLC systems. The proposed NOMA adopts a quality of service (QoS)-guaranteed power allocation strategy, which is derived by maximizing the energy efficiency (EE) of the multi-user VLC system while satisfying the QoS requirements of all the users. The derived QoS-guaranteed optimal power allocation strategy is given in the closed form, which can enable low-complexity power allocation for the proposed NOMA-enabled multi-user VLC systems. Monte Carlo simulations are further performed to substantiate the derived analytical results. The obtained analytical and simulation results clearly demonstrate the advantages of the proposed NOMA in comparison to OMA and NOMA with GRPA in a typical multi-user VLC system.

The rest of this paper is organized as follows. Section II describes the channel model of a typical multi-user VLC system. Multi-user VLC using the proposed NOMA technique is discussed in Section III. The analytical and simulation results are presented in Section IV. Finally, Section V concludes the paper.

II. Channel Model

In practical multi-user VLC systems, the photodiode (PD) of each user can receive both line-of-sight (LOS) and non-line-of-sight (NLOS) components of the transmitted optical signal. Nevertheless, since the NLOS component usually has much lower electrical power than that of the LOS component, it is reasonable to neglect the NLOS component during most channel conditions [20]. For simplicity, we only consider the LOS component in the following channel model. We assume that the LED is oriented vertically downwards while the PD of each user is oriented vertically upwards. Moreover, we also assume that the overall VLC system has a flat frequency response and the LED transmitter operates within its linear dynamic range.

Assuming the VLC system serves totally K users and the white LED has a Lambertian emission pattern, the LOS direct current (DC) channel gain between the LED and the k-th ($k = 1, 2, \cdots, K$) user can be calculated by [3]

$$h_k = \begin{cases} \frac{(m+1)\rho A}{2\pi d_k^2}\cos^m(\psi_k) g_f g_l \cos(\phi_k), & 0 \le \phi_k \le \Phi \\ 0, & \phi_k > \Phi \end{cases}, \tag{1}$$

where $m = -\ln 2/\ln(\cos(\Psi))$ denotes the Lambertian emission order and Ψ is the semi-angle of the LED; ρ and A are the responsivity and active area of the PD, respectively; d_k is the distance between the LED and the k-th user; ψ_k and ϕ_k denote the corresponding emission angle and incident angle, respectively; g_f and g_l represent the gains of the optical filter and lens, respectively. The gain of the optical lens is given by $g_l = \frac{n^2}{\sin^2\Phi}$, where n is the refractive index of the optical lens and Φ is the half-angle field-of-view (FOV) of the PD.

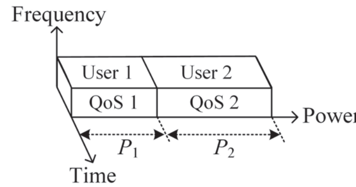

Fig. 1. Conceptual diagram of power domain energy-efficient NOMA.

The additive noise in typical VLC systems usually consists of thermal and shot noises, which are generally modeled as real-valued zero-mean additive white Gaussian noises. For simplicity, it is assumed that the additive noises of all the users have the same constant noise power spectral density (PSD) N_0. For a signal bandwidth B, the noise power is given by $N_0 B$.

III. Multi-User VLC Using Energy-Efficient NOMA

A. Principle of Energy-Efficient NOMA

Fig. 1 illustrates the conceptual diagram of the proposed power domain energy-efficient NOMA with two users, where the QoS requirements for user 1 and user 2 are represented by QoS 1 and QoS 2, respectively. Differing from conventional OMA schemes, such as OFDMA and TDMA, which split time or frequency resources to support multiple users in order to eliminate mutual interference, the proposed NOMA allows both users to utilize all the time and frequency resources. It can be seen that the transmitted data of user 1 and user 2 are superposed in the power domain and there inevitably exists mutual interference. To ensure the QoS requirements of both users, user 1 and user 2 are allocated with powers P_1 and P_2, respectively. Compared with conventional NOMA which aims to maximize the system sum rate, the proposed NOMA is designed to maximize the system EE while satisfying the QoS requirements of all the users. Therefore, the key to implement the proposed NOMA is to obtain a proper power allocation strategy. Moreover, to support a large number of users when implementing the proposed NOMA, an efficient user pairing approach is also needed.

B. Energy-Efficient NOMA-Enabled Multi-User VLC

In this subsection, power domain energy-efficient NOMA is introduced for multi-user VLC systems.

1) System Model: Without loss of generality, we assume that the VLC system serves $K = 2N$ users, which are divided into N user pairs. Fig. 2 shows the schematic diagram of the proposed NOMA-enabled multi-user VLC. Let $s_{i,f}$ and $s_{i,n}$ denote the modulated message signals intended for the far and near users in the i-th user pair, respectively. The superposed electrical signal of all N pairs of users to be transmitted by the LED can be expressed by

$$x = \sum_{i=1}^{N} \sqrt{p_{i,f}} s_{i,f} + \sqrt{p_{i,n}} s_{i,n} + I_{\mathrm{DC}}, \tag{2}$$

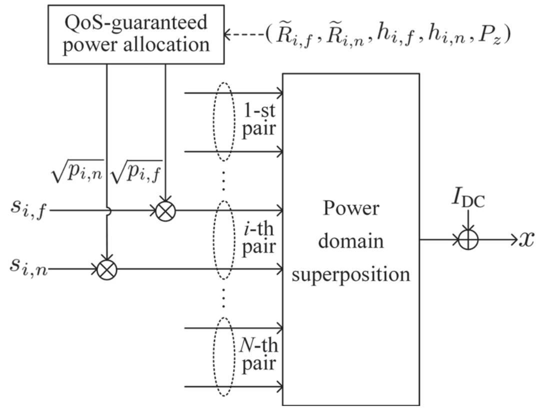

Fig. 2. Schematic of energy-efficient NOMA-enabled multi-user VLC.

where $p_{i,f}$ and $p_{i,n}$ are the electrical transmit powers allocated to the far and near users in the i-th user pair, respectively; I_{DC} is the DC bias current, which is added to simultaneously guarantee the non-negativity of the LED driving signal and ensure sufficient and stable illumination. The total electrical transmit power allocated to all N pairs of users is obtained by

$$P_{\text{elec}} = \sum_{i=1}^{N} p_{i,f} + p_{i,n}. \tag{3}$$

After removing the DC term, the received signals of the far and near users in the i-th user pair can be given by

$$\begin{cases} y_{i,f} = h_{i,f}(\sqrt{p_{i,f}}s_{i,f} + \sqrt{p_{i,n}}s_{i,n}) + z_{i,f} \\ y_{i,n} = h_{i,n}(\sqrt{p_{i,f}}s_{i,f} + \sqrt{p_{i,n}}s_{i,n}) + z_{i,n} \end{cases}, \tag{4}$$

where $h_{i,f}$ and $h_{i,n}$ denote the channel gains of the far and near users in the i-th user pair, respectively, and $h_{i,f} \leq h_{i,n}$; $z_{i,f}$ and $z_{i,n}$ are the corresponding additive noises.

To decode the intended message signals for the far and near users in the i-th user pair, the far user decodes its message signal directly by treating the intended message signal for the near user as interference, while the near user needs to decode the intended message signal for the far user first and then apply SIC to decode its own message signal without interference. As a result, (4) can be re-represented as

$$\begin{cases} y_{i,f} = \underbrace{h_{i,f}\sqrt{p_{i,f}}s_{i,f}}_{\text{signal}} + \underbrace{h_{i,f}\sqrt{p_{i,n}}s_{i,n}}_{\text{interference}} + z_{i,f} \\ y_{i,n} = \underbrace{h_{i,n}\sqrt{p_{i,f}}s_{i,f}}_{\text{SIC}} + \underbrace{h_{i,n}\sqrt{p_{i,n}}s_{i,n}}_{\text{signal}} + z_{i,n} \end{cases}. \tag{5}$$

Following (5), the achievable rates of the far and near users in the i-th user pair can be given by

$$\begin{cases} R_{i,f} = \frac{1}{2}\log_2\left(\frac{h_{i,f}^2 p_{i,f}}{h_{i,f}^2 p_{i,n} + P_z}\right) \\ R_{i,n} = \frac{1}{2}\log_2\left(\frac{h_{i,n}^2 p_{i,n}}{P_z}\right) \end{cases}, \tag{6}$$

where the scaling factor $\frac{1}{2}$ is due to the Hermitian symmetry [14] and $P_z = N_0 B$ is the power of the additive noises. In addition, the achievable rate for the near user to decode the far user's message signal is obtained by

$$R_{i,n\to f} = \frac{1}{2}\log_2\left(\frac{h_{i,n}^2 p_{i,f}}{h_{i,n}^2 p_{i,n} + P_z}\right). \tag{7}$$

In practical multi-user VLC systems, different users might have different QoS requirements. Generally, we can define the QoS requirement of a specific user as its required achievable rate per bandwidth, i.e., spectral efficiency [14]. Let $\widetilde{R}_{i,f}$ and $\widetilde{R}_{i,n}$ denote the rate requirements of the far and near users in the i-th user pair, respectively. To meet their rate requirements, the following conditions need to be satisfied:

$$\begin{cases} R_{i,f} \geq \widetilde{R}_{i,f} \\ R_{i,n} \geq \widetilde{R}_{i,n} \\ R_{i,n\to f} \geq \widetilde{R}_{i,f} \end{cases}. \tag{8}$$

According to (8), the power requirements of two users can be given by

$$\begin{cases} p_{i,f} \geq 2^{2\widetilde{R}_{i,f}}\left(p_{i,n} + \frac{P_z}{h_{i,f}^2}\right) \\ p_{i,n} \geq 2^{2\widetilde{R}_{i,n}}\frac{P_z}{h_{i,n}^2} \\ p_{i,f} \geq 2^{2\widetilde{R}_{i,f}}\left(p_{i,n} + \frac{P_z}{h_{i,n}^2}\right) \end{cases}. \tag{9}$$

Using $h_{i,f} \leq h_{i,n}$, we can obtain the power requirements to satisfy the QoS requirements of both the far and near users in the i-th user pair:

$$\begin{cases} p_{i,f} \geq 2^{2\widetilde{R}_{i,f}}\left(2^{2\widetilde{R}_{i,n}}\frac{P_z}{h_{i,n}^2} + \frac{P_z}{h_{i,f}^2}\right) \\ p_{i,n} \geq 2^{2\widetilde{R}_{i,n}}\frac{P_z}{h_{i,n}^2} \end{cases}. \tag{10}$$

Hence, the total electrical transmit power requirements of all N pairs of users is given by

$$P_{\text{elec}} \geq \sum_{i=1}^{N} 2^{2\widetilde{R}_{i,f}}\left(2^{2\widetilde{R}_{i,n}}\frac{P_z}{h_{i,n}^2} + \frac{P_z}{h_{i,f}^2}\right) + 2^{2\widetilde{R}_{i,n}}\frac{P_z}{h_{i,n}^2}. \tag{11}$$

It can be found that the QoS requirements of the far and near users in the i-th user pair can be guaranteed with mutual interference by allocating them with proper powers.

2) QoS-Guaranteed Optimal Power Allocation: For the efficient implementation of the proposed NOMA in multi-user VLC systems, a QoS-guaranteed optimal power allocation strategy is proposed. In this work, we design the proposed NOMA-enabled multi-user VLC systems from the energy consumption perspective. Therefore, the goal to design the proposed-enabled multi-user VLC systems is to maximize the EE through a QoS-guaranteed optimal power allocation strategy. The EE (η) can be defined as the ratio of the achievable sum rate (R) to the total electrical power consumption (P_{elec}):

$$\eta = \frac{R}{P_{\text{elec}}}, \tag{12}$$

where the unit of EE is bits/J/Hz.

For the proposed NOMA-enabled multi-user VLC system with N pairs of users, the achievable sum rate of the system can be calculated by

$$R = \sum_{i=1}^{N} \widetilde{R}_{i,f} + \widetilde{R}_{i,n}. \tag{13}$$

Considering the fact that each user in the multi-user VLC system normally has its fixed QoS requirement during a period of time, the achievable sum rate R given in (13) can be viewed as a fixed value. Hence, the EE maximization problem can be transformed into a power minimization problem.

Let $\mathcal{P}_i = \{p_{i,f}, p_{i,n}\}$ denote the power allocation set for the far and near users in the i-th user pair. To obtain a QoS-guaranteed optimal power allocation strategy, i.e., optimal $\mathcal{P}_i$ with $i = 1, 2, \cdots, N$, the power minimization problem of the multi-user VLC system can be formulated as

$$\begin{aligned} \min_{\{\mathcal{P}_1, \cdots, \mathcal{P}_N\}} \quad & P_{\text{elec}} \\ \text{s.t.} \quad & \text{a: } (10) \\ & \text{b: } P_{\text{elec}} \leq P_{\max}. \end{aligned} \tag{14}$$

In (14), constraint "a" is used to guarantee the power requirements of all the users so as to meet their QoS requirements and constraint "b" is that the total electrical transmit power of the LED should not exceed its maximum value $P_{\max}$.

By observing (10), we can find that the optimal solution for the power minimization problem is that the far and near users in the i-th user pair are allocated with minimum powers to satisfy their QoS requirements. As a result, the closed-form optimal power allocation set $\mathcal{P}_i^{\text{opt}} = \{p_{i,f}^{\text{opt}}, p_{i,n}^{\text{opt}}\}$ can be obtained by

$$\begin{cases} p_{i,f}^{\text{opt}} = 2^{2\widetilde{R}_{i,f}} \left(2^{2\widetilde{R}_{i,n}} \dfrac{P_z}{h_{i,n}^2} + \dfrac{P_z}{h_{i,f}^2} \right) \\ p_{i,n}^{\text{opt}} = 2^{2\widetilde{R}_{i,n}} \dfrac{P_z}{h_{i,n}^2} \end{cases}. \tag{15}$$

Using (15), the minimum total electrical transmit power of all the N pairs of users is given by

$$P_{\text{elec,min}} = \sum_{i=1}^{N} 2^{2\widetilde{R}_{i,f}} \left(2^{2\widetilde{R}_{i,n}} \frac{P_z}{h_{i,n}^2} + \frac{P_z}{h_{i,f}^2} \right) + 2^{2\widetilde{R}_{i,n}} \frac{P_z}{h_{i,n}^2}. \tag{16}$$

Substituting (13) and (16) into (17) yields the EE of the multi-user VLC system using the proposed NOMA:

$$\eta_{\text{EE}} = \frac{\sum_{i=1}^{N} \widetilde{R}_{i,f} + \widetilde{R}_{i,n}}{\sum_{i=1}^{N} 2^{2\widetilde{R}_{i,f}} \left(2^{2\widetilde{R}_{i,n}} \frac{P_z}{h_{i,n}^2} + \frac{P_z}{h_{i,f}^2} \right) + 2^{2\widetilde{R}_{i,n}} \frac{P_z}{h_{i,n}^2}}. \tag{17}$$

Based on the above analysis, we can find that the proposed NOMA can be considered as a special case of NOMA in which the total electrical transmit power is minimized by adopting the QoS-guaranteed optimal power allocation strategy. It should also be noticed that the QoS-guaranteed optimal power allocation strategy is obtained based on the assumption that all the $2N$ users are divided into N user pairs. Therefore, efficient user pairing should be performed before executing the QoS-guaranteed optimal power allocation strategy in pairs.

3) Channel-Based User Pairing: By selecting a pair of users to perform the proposed NOMA, the computational complexity of the multi-user VLC system can be substantially reduced, which results in a hybrid multiple access scheme consisting of both NOMA and OMA techniques. More specifically, the proposed NOMA is adopted for the two users within each user pair, while OMA is applied for different user pairs.

In this work, channel-based user pairing is adopted to divide all the users into pairs [14], [21]. The key to implement channel-based user pairing is to pair the two users which have more distinctive channel conditions. For channel-based user pairing, all the $2N$ users can be sorted based on their channel gains in the ascending order:

$$h_1 \leq \cdots \leq h_k \leq \cdots \leq h_{2N}, \tag{18}$$

where h_k is given in (1). After that, the sorted $2N$ users are divided into two groups: the first group G_1 contains the first half of the sorted users starting from user 1 to user N; the second group G_2 consists of the second half starting from user $N+1$ to user $2N$. Based on the obtained two user groups, user pairing can be performed in the following manner: $U_i = \{G_1(i), G_2(i)\}$, i.e., the i-th user pair U_i contains both the i-th user in G_1 and the i-th user in G_2 with $i = 1, 2, \cdots, N$.

IV. Analytical and Simulation Results

In this section, Monte Carlo simulations are performed to substantiate the analytical expressions derived above, and the EE of a typical multi-user VLC system using different multiple access techniques are evaluated and compared. Specifically, the following three multiple access techniques are considered: (i) the proposed NOMA, (ii) NOMA with GRPA [13] and (iii) OMA. The EE values adopting NOMA with GRPA and OMA are calculated based on the condition that all the QoS

TABLE I
SIMULATION PARAMETERS

Parameter name	Value
Vertical separation	2.5 m
Maximum horizontal separation	3 m
LED semi-angle	70°
Maximum LED transmit power	1 W
PD responsivity	0.4 A/W
PD active area	1 cm^2
PD half-angle FOV	70°
Optical filter gain	0.9
Optical lens refractive index	1.5
Signal bandwidth	20 MHz
Noise PSD	10^{-22} A^2/Hz

requirements of all the users are satisfied. The key simulation parameters are summarized in Table I. The vertical separation between the LED and the receiving plane is 2.5 m. The maximum horizontal separation between the LED and the users is 3 m. The LED semi-angle is 70° and the maximum LED transmit power is 1 W. The responsivity and the active area of PD are 0.4 A/W and 1 cm^2, respectively. The half-angle FOV of PD is 70°. The optical filter gain is 0.9. The refractive index of optical lens is 1.5. The signal bandwidth and noise PSD are 20 MHz and 10^{-22} A^2/Hz, respectively.

A. Two-User Case

We first investigate the EE performance of a two-user VLC system using different multiple access techniques. Fig. 3 shows the EE versus the horizontal separation of two users with $\widetilde{R}_f = \widetilde{R}_n = 1$ bit/s/Hz, where the near user is located under the LED and the horizontal separation between the near user and the far user is ranging from 0.5 to 3 m. It can be observed that the simulation results agree well with the analytical results, which can verify the fidelity of our analytical derivations obtained in Section III.

For the two-user VLC system using OMA, the EE is gradually reduced with the increase of the horizontal separation. However, when NOMA with GRPA is adopted, the EE first increases and then decreases with the increase of the horizontal separation. A maximum EE of 408.1 bits/J/Hz is obtained at the horizontal separation of 1 m. As can be seen from Fig. 3, NOMA with GRPA obtains a lower EE than OMA at the horizontal separation of 0.5 m, which suggests that the advantage of NOMA cannot be fully exploited if two users have similar channel conditions. Compared with OMA and NOMA with GRPA, the proposed NOMA always achieves the highest EE. More specifically, the proposed NOMA significantly outperforms NOMA with GRPA when the horizontal separation is relatively small, and the EE improvement becomes less significant when the horizontal separation is larger than 2 m.

B. Multi-User Case

In the next, we evaluate and compare the EE performance of the VLC system with multiple users using different multiple access techniques. In this multi-user case, the users are randomly distributed within the receiving plane and the QoS requirement of each user is randomly selected from a given QoS set $\widetilde{R}$ where the unit of its elements is bits/s/Hz. In order to obtain a stable EE value under random user locations and QoS requirements, the average EE value is adopted over 10000 independent trials.

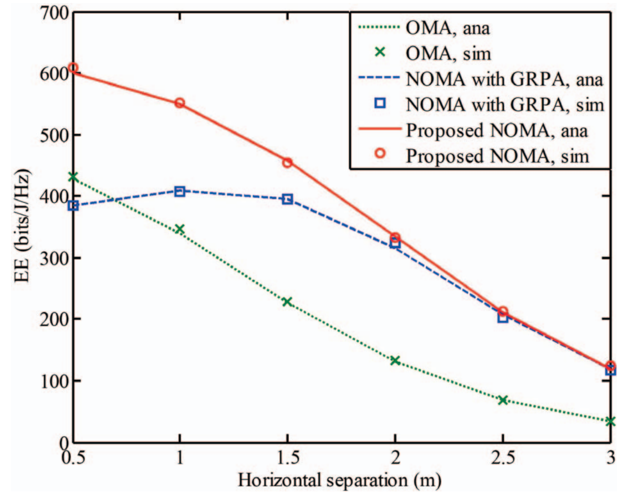

Fig. 3. EE vs. horizontal separation of two users with $\widetilde{R}_f = \widetilde{R}_n = 1$ bit/s/Hz.

Figs. 4 and 5 show the average EE versus the number of users with the QoS sets $\widetilde{R} = 1$ and $\widetilde{R} = \{1, 2\}$, respectively. As we can see, the simulation results are consistent with the analytical results. For $\widetilde{R} = 1$, the average EE of the multi-user VLC system using OMA gradually decreases when more users are served in the system. The same trends can be found when using NOMA with GRPA and the proposed NOMA. It can also be seen that NOMA with GRPA achieves substantially improved average EE than OMA, which demonstrates the superiority of NOMA against OMA. Nevertheless, when the proposed NOMA with QoS-guaranteed optimal power allocation is applied, the average EE can be further enhanced. When the number of users is 10, the average EEs using NOMA with GRPA and the proposed NOMA are about 190 and 209 bits/J/Hz, suggesting a 10% improvement of EE. Moreover, for $\widetilde{R} = \{1, 2\}$, the average EEs using NOMA with GRPA and the proposed NOMA for ten users are about 74 and 88 bits/J/Hz, which indicates a EE improvement of 19%. Hence, the EE improvement by using the proposed NOMA in comparison to NOMA with GRPA becomes much more significant when the users have more diverse QoS requirements.

V. Conclusion

In this paper, we have proposed and investigated a power domain energy-efficient NOMA technique for multi-user VLC systems. In the proposed NOMA, the QoS requirements of different users are guaranteed by allocating them with proper powers, by adopting a QoS-guaranteed optimal power allocation strategy to minimize the total electrical transmit power and hence maximize the EE of the multi-user VLC system. The obtained Monte Carlo simulation results successfully verify

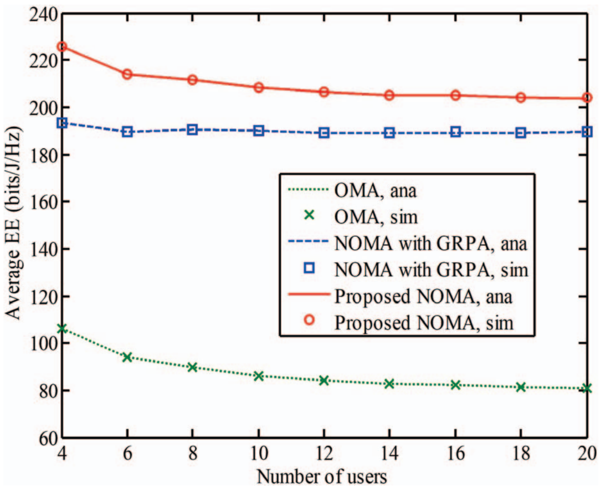

Fig. 4. Average EE vs. number of users with QoS set $\widetilde{R} = 1$.

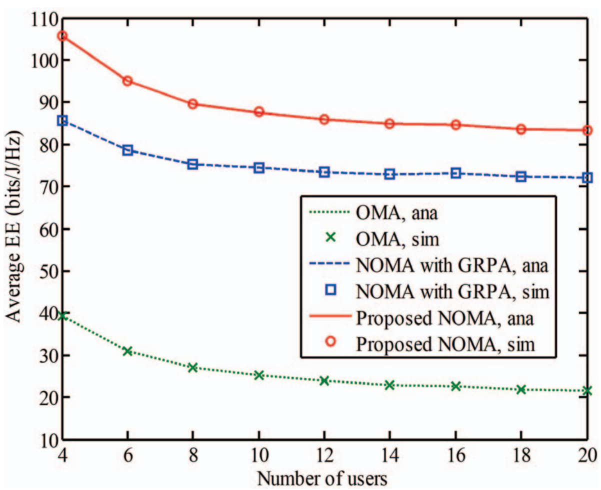

Fig. 5. Average EE vs. number of users with QoS set $\widetilde{R} = \{1, 2\}$.

the fidelity of the analytical derivations. Our results show that the EE of the multi-user VLC system can be greatly improved by using the proposed NOMA in comparison to NOMA with GRPA, especially when diverse QoS are required by the users.

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