Enhanced Power Allocation for Sum Rate Maximization in OFDM-NOMA VLC Systems

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***Abstract*— This letter investigates the power allocation problem for the downlink of an orthogonal frequency division multiple (OFDM)-based non-orthogonal multiple access visible light communication (NOMA-VLC) system. Unlike the commonly used two-user OFDM-NOMA VLC model, in this letter, an arbitrary number of multiplexed users is considered when formulating the sum rate maximization problem. Moreover, both user-level and subcarrier-level power optimization are taken into account to improve the system performance. The corresponding theoretical analysis is presented, with the consideration of optimal decoding order and each user's required signal-to-interference-plus-noise ratio (SINR). Given a fixed power constraint on each OFDM subcarrier, we derive the optimal power ratio for an arbitrary number of multiplexed users in OFDM-NOMA VLC. Numerical results show that with a required SINR of 3 dB, the proposed enhanced power allocation algorithm has 39.59% and 40.11% sum-rate enhancement when compared to optimized fixed power allocation algorithm and gain ratio power allocation algorithm, respectively.**

***Index Terms*— VLC, OFDM, NOMA, optimal power ratio.**

I. Introduction

IN RECENT years, visible light communication (VLC) has been regarded as an alternative solution for future high-speed wireless access [1] because of its dual functionality, i.e., the primary illumination function and the high-rate data transmission. In addition, the development of multiple access technologies can help enlarge customer base and reduce cost significantly, which facilitates the commercialization of energy-efficient high-speed VLC technology.

In conventional multiple access, different users are allocated orthogonal resources in terms of time, code or frequency domains. The performance of VLC in these orthogonal systems has been evaluated in [2], [3]. However, these orthogonal methods cannot make optimal use of the resources [4]. Since the data traffic is expected to increase enormously in the following years, seeking more efficient multiple access technologies becomes very important. Non-orthogonal multiple access (NOMA) has recently attracted significant attention, which provides a higher spectral efficiency by allowing multiple users to share the same time and frequency resource [5].

The application of NOMA in VLC has been studied in prior works [3], [6]–[10]. Superiority of NOMA-VLC over OFDM-VLC was demonstrated in [3]. The performance of downlink NOMA-VLC system with one light-emitting diode (LED) serving multiple uniformly distributed users was evaluated in [6]. It was shown in [7] that the sum rate of NOMA-VLC can be further enhanced by tuning the semi-angle of LEDs and/or the field of view (FOV) of photodiodes (PDs). The authors of [8] proposed a pre-distortion scheme to alleviate the power ratio requirement of NOMA-VLC system. In addition, the sum throughput maximization problem of NOMA-VLC system subject to the constraints of user fairness and transmitted optical intensity was investigated in [9]. Besides, a sub-optimal power control method based on users' channel gain information and a power allocation scheme with fixed ratio was proposed for the downlink of NOMA-VLC networks in [7] and [10], respectively. However, most of prior works consider only the scenario of two-user multiplexed NOMA VLC. Moreover, the power allocation was generally implemented for different users without considering the subcarrier-level power allocation, resulting in sub-optimal performance.

With aforementioned observations, by considering the key feature of VLC systems, i.e., high-frequency fading, we focus on the power allocation for OFDM based NOMA-VLC system that contains arbitrary number of multiplexed users in this work. An enhanced power allocation (EPA) algorithm is proposed to maximize the sum of data rates and minimize the subcarrier loss rate of the system by considering both user-level and subcarrier-level power allocation. The closed form of the optimal power ratio of multiplexed users on each subcarrier is derived. Numerical results depict that our proposed EPA exhibits significant improvement in terms of sum rate and subcarrier loss rate when compared to the other conventional power control strategies.

II. System Model

The downlink of an OFDM based NOMA-VLC system with four light emitting diodes (LEDs) simultaneously serving K users is considered. The system model is shown in Fig. 1, in which the photodiodes (PDs) act as the NOMA users. We assume four LEDs are mounted on the ceiling and the vertical distance from ceiling to the receiving plane is 2.15 m. Define $\mathcal{K} \triangleq \{1, 2, \ldots, K\}$ and $\mathcal{M} \triangleq \{1, 2, 3, 4\}$ as the

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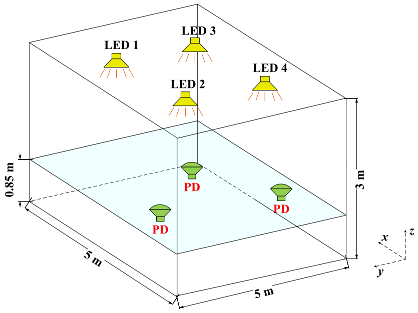

Fig. 1. The downlink NOMA-VLC system model.

index sets of all users and LEDs, respectively. For $m \in \mathcal{M}$ and $k \in \mathcal{K}$, we characterize the VLC channel property from the m-th LED transmitter to the receiver k by the corresponding impulse response [11], which is described as follows:

$$h_{m,k}(t) \triangleq h_{m,k}^{(0)}(t) + \sum_{l=1}^{\infty} h_{m,k}^{(l)}(t), \tag{1}$$

where the two items on the right side of Eq. (1) are the line-of-sight (LOS) and the non-LOS contributions, respectively.

Define $\mathcal{N} \triangleq \{1, 2, \ldots, N\}$ as the index set of all subcarriers. For $k \in \mathcal{K}$ and $n \in \mathcal{N}$, let $p_k^n \geq 0$ be the allocated power of user k on subcarrier n. In addition, for the n-th subcarrier of user k, we define g_k^n as its frequency-domain channel gain, which corresponds to the time-domain impulse response given in Eq. (1) and is directly related to the transmitted signal power. Similar to experimental investigations, the channel gains in this work are obtained via pilot-assisted channel estimation. Furthermore, let η_k^n be the received noise power of receiver k on subcarrier n. For notation simplicity, we normalize the noise power as: $\tilde{\eta}_k^n \triangleq \eta_k^n / g_k^n$.

We assume each user can use all the time-frequency resources and consider the scenario where the LED multiplexes the signals of K users on each subcarrier using superposition coding. In addition, we assume that the four LEDs transmit the same message simultaneously. Therefore, at receiver k, the received signal on subcarrier n can be expressed as:

$$y_k^n \triangleq g_k^n s_n + v_k^n, \tag{2}$$

where $k \in \mathcal{K}$ and $n \in \mathcal{N}$, s_n indicates the superposed signal of K users on subcarrier n, i.e., $s_n \triangleq \sum_{k=1}^{K} \sqrt{p_k^n} s_k^n$, in which s_k^n depicts the desired signal of user k on subcarrier n. Besides, $v_k^n \sim \mathcal{CN}(0, \sigma_{n,k}^2)$ expresses the received noise signal at user k on subcarrier n, in which $\sigma_{n,k}^2$ represents the corresponding variance containing shot noise and thermal noise contributions.

Since multiple users are multiplexed on the same subcarrier, successive interference cancellation (SIC) is applied at the receiver side to eliminate the inter-user interference. Since SIC is applied, we need to consider the optimal decoding order of users on the same subcarrier. Let Π be the set of all possible permutations of $\mathcal{K}$. For example, if $\mathcal{K} = \{1, 2, 3\}$, then

$$\Pi = \{(1, 2, 3), (1, 3, 2), (2, 1, 3), (2, 3, 1), (3, 1, 2), (3, 2, 1)\}.$$

Denote by $\boldsymbol{\pi}_n \in \Pi$ the decoding order of the users on subcarrier n. Let $\pi_n(i)$, where $i \in \mathcal{K}$, be its i-th component, which means user $\pi_n(i)$ first decodes the signals of users $\pi_n(1), \ldots, \pi_n(i-1)$, then subtracts these signals, and finally decodes its intended message by treating the signals of remaining users as noise. Note that $\boldsymbol{\pi}_n$ is a vector function of the normalized noise power [4] and is defined as follows:

$$\boldsymbol{\pi}_n \triangleq (\pi_n(1), \pi_n(2), \ldots, \pi_n(K)), \tag{3}$$

such that the following two criteria are satisfied:

1) The normalized noise power of multiplexed users on subcarrier n are arranged in descending order: $\tilde{\eta}_{\pi_n(1)}^n \geq \tilde{\eta}_{\pi_n(2)}^n \geq \cdots \geq \tilde{\eta}_{\pi_n(K)}^n$;
2) When there is a tie, we arrange those users in ascending order of their indices, i.e., if $\tilde{\eta}_{\pi_n(i)}^n = \tilde{\eta}_{\pi_n(i')}^n$, then, $\pi_n(i) < \pi_n(i')$ for $i < i'$.

In practical VLC systems, compared to the receiver amplifier noise and background noise of the electrical circuit, the signal-dependent shot noise is negligible. Therefore, in this work, we assume the noise in the VLC system is Gaussian and signal-independent [12], and the Shannon formula, which has been widely applied in VLC [6], [13], is used to characterize the capacity of a VLC link with both LOS and non-LOS components taken into account. For $k \in \mathcal{K}$, and $n \in \mathcal{N}$, let R_k^n be the achievable data rate of user k on subcarrier n. Once the decoding order is determined by the normalized receiver noise power, R_k^n can be obtained as follows:

$$R_k^n \triangleq W_n \log_2\Big(1 + \frac{p_k^n}{\sum_{j=\pi_n^{-1}(k)+1}^{K} p_{\pi_n(j)}^n + \tilde{\eta}_k^n}\Big), \tag{4}$$

where W_n indicates the bandwidth of subcarrier n, $\pi_n^{-1}(k)$ represents the decoding order of user k in $\boldsymbol{\pi}_n$. More precisely, $\pi_n^{-1}(k) = i$ if $\pi_n(i) = k$. Since there are totally K users in our system, both k and i belong to the set $\mathcal{K}$.

For $i \in \mathcal{K}$ and $n \in \mathcal{N}$, let $\alpha_{\pi_n(i)}^n$ be the power ratio of user $\pi_n(i)$ on subcarrier n, i.e., $p_{\pi_n(i)}^n \triangleq \alpha_{\pi_n(i)}^n P_n$, in which P_n is the total power constraint of subcarrier n. In addition, let $\hat{\eta}_{\pi_n(i)}^n \triangleq \tilde{\eta}_{\pi_n(i)}^n / P_n$. Therefore, the sum rate of the multiplexed users on subcarrier n is obtained as follows:

$$R_{\text{sum}}^n \triangleq \sum_{i=1}^{K} W_n \log_2\Big(1 + \frac{\alpha_{\pi_n(i)}^n}{\sum_{j=i+1}^{K} \alpha_{\pi_n(j)}^n + \hat{\eta}_{\pi_n(i)}^n}\Big), \tag{5}$$

where $\frac{\alpha_{\pi_n(i)}^n}{\sum_{j=i+1}^{K} \alpha_{\pi_n(j)}^n + \hat{\eta}_{\pi_n(i)}^n}$ denotes the signal-to-interference-plus-noise ratio (SINR) of user $\pi_n(i)$.

III. EPA Algorithm for Multiplexed Users

The objective of this work is to maximize the sum of data rates while satisfying the required SINRs of users. Once the power constraint of each subcarrier is given, the problem can be transformed into a power control problem for sum rate maximization on each subcarrier. Without loss of generality, we take subcarrier n, $n \in \mathcal{N}$ as an example. Therefore, the sum rate maximization problem for multiplexed receivers on subcarrier n can be mathematically formulated as follows:

$$\text{maximize} \quad R_{\text{sum}}^n, \tag{6}$$

$$\begin{aligned} C1: &\quad \frac{\alpha_{\pi_n(i)}^n}{\sum_{j=i+1}^{K} \alpha_{\pi_n(j)}^n + \hat{\eta}_{\pi_n(i)}^n} \geq \gamma_{\pi_n(i)}, \quad i \in \mathcal{K} \\ C2: &\quad \sum_{i=1}^{K} \alpha_{\pi_n(i)}^n = 1, \\ C3: &\quad \alpha_{\pi_n(i)}^n \geq 0, \ i \in \mathcal{K}, \end{aligned} \tag{7}$$

where $\gamma_{\pi_n(i)}$, $i \in \mathcal{K}$ represents the required SINR of user $\pi_n(i)$ for successful message detection. In addition, $C2$ and $C3$ is used to guarantee the total power constraint and the non-negativity of power ratios, respectively. Note that the sum rate maximization problem for the general case of OFDM is not considered in the current work. With aforementioned definitions, we have the following lemma:

Lemma 1: The optimal power ratio of user $\pi_n(1)$ for maximization problem (6) *is* $\hat{\alpha}^n_{\pi_n(1)} = \frac{\gamma_{\pi_n(1)}(1+\hat{\eta}^n_{\pi_n(1)})}{1+\gamma_{\pi_n(1)}}$.

Proof: According to $C1$ and $C2$, we have

$$\frac{\alpha^n_{\pi_n(1)}}{1-\alpha^n_{\pi_n(1)}+\hat{\eta}^n_{\pi_n(1)}} \geq \gamma_{\pi_n(1)}, \tag{8}$$

which further indicates

$$\alpha^n_{\pi_n(1)} \geq \frac{\gamma_{\pi_n(1)}(1+\hat{\eta}^n_{\pi_n(1)})}{1+\gamma_{\pi_n(1)}}. \tag{9}$$

Now, we only need to show that the optimal power ratio of user $\pi_n(1)$, if exists, satisfies the inequality constraint in (9) with equality. We prove this by contradiction and suppose $\boldsymbol{\alpha}^* = (\alpha^{*n}_{\pi_n(1)}, \alpha^{*n}_{\pi_n(2)}, \ldots, \alpha^{*n}_{\pi_n(K)})$ is the optimal solution to problem (6), in which $\alpha^{*n}_{\pi_n(1)} > \frac{\gamma_{\pi_n(1)}(1+\hat{\eta}^n_{\pi_n(1)})}{1+\gamma_{\pi_n(1)}}$.

According to (5), we have

$$\begin{aligned} R^n_{\text{sum}} &= W_n \log_2\Big(\frac{1+\hat{\eta}^n_{\pi_n(1)}}{\sum_{j=2}^K \alpha^n_{\pi_n(j)}+\hat{\eta}^n_{\pi_n(1)}}\Big) \\ &\quad + W_n \log_2\Big(\frac{\sum_{j=2}^K \alpha^n_{\pi_n(j)}+\hat{\eta}^n_{\pi_n(2)}}{\sum_{j=3}^K \alpha^n_{\pi_n(j)}+\hat{\eta}^n_{\pi_n(2)}}\Big) \\ &\quad + \cdots + W_n \log_2\Big(\frac{\alpha^n_{\pi_n(K)}+\hat{\eta}^n_{\pi_n(K)}}{\hat{\eta}^n_{\pi_n(K)}}\Big) \\ &= W_n \log_2\Big(\frac{1+\hat{\eta}^n_{\pi_n(1)}}{\hat{\eta}^n_{\pi_n(K)}}\Big) \\ &\quad + W_n \log_2\Big(1+\frac{\hat{\eta}^n_{\pi_n(2)}-\hat{\eta}^n_{\pi_n(1)}}{\sum_{j=2}^K \alpha^n_{\pi_n(j)}+\hat{\eta}^n_{\pi_n(1)}}\Big) \\ &\quad + \cdots + W_n \log_2\Big(1+\frac{\hat{\eta}^n_{\pi_n(K)}-\hat{\eta}^n_{\pi_n(K-1)}}{\alpha^n_{\pi_n(K)}+\hat{\eta}^n_{\pi_n(K-1)}}\Big). \end{aligned} \tag{10}$$

Since $\hat{\eta}^n_{\pi_n(1)} \geq \hat{\eta}^n_{\pi_n(2)} \geq \cdots \geq \hat{\eta}^n_{\pi_n(K)}$, based on (10), we see that R^n_{sum} is a monotonicity increasing function of $\alpha^n_{\pi_n(K)}$. Therefore, we can strictly reduce the value of $\alpha^{*n}_{\pi_n(1)}$ to $\alpha^{'n}_{\pi_n(1)} = \frac{\gamma_{\pi_n(1)}(1+\hat{\eta}^n_{\pi_n(1)})}{1+\gamma_{\pi_n(1)}}$ and increase the value of $\alpha^{*n}_{\pi_n(K)}$ to $\alpha^{'n}_{\pi_n(K)}$ such that $||\boldsymbol{\alpha}'||_1 = 1$, in which $\boldsymbol{\alpha}' = (\alpha^{'n}_{\pi_n(1)}, \alpha^{*n}_{\pi_n(2)}, \ldots, \alpha^{*n}_{\pi_n(K-1)}, \alpha^{'n}_{\pi_n(K)})$ and $||\boldsymbol{x}||_1$ indicates the l_1 norm of vector $\boldsymbol{x}$. Obviously, under the power allocation ratio $\boldsymbol{\alpha}'$, R^n_{sum} is larger than that under $\boldsymbol{\alpha}^*$, which contradicts with that $\boldsymbol{\alpha}^*$ is the optimal solution. □

For $i \in \mathcal{K}$, denote by $\hat{\alpha}^n_{\pi_n(i)}$ the optimal power ratio of problem (6). Then, we have the following theorem:

Theorem 2: If the sum rate maximization problem (6) *is feasible, the closed form of the optimal power ratio on subcarrier n is given by*

$$\hat{\alpha}^n_{\pi_n(i)} = \frac{\gamma_{\pi_n(i)}(1+\hat{\eta}^n_{\pi_n(i)}-\sum_{j<i}\hat{\alpha}^n_{\pi_n(j)})}{1+\gamma_{\pi_n(i)}}, \quad i \in \mathcal{K}\setminus\{K\}, \tag{11}$$

$$\hat{\alpha}^n_{\pi_n(K)} = 1-\sum_{i=1}^{K-1}\hat{\alpha}^n_{\pi_n(i)}. \tag{12}$$

Proof: First, we prove (11). Based on Lemma 1, (11) holds for $i = 1$.

Then, for $L \in \{2, 3, \ldots, K-1\}$, let

$$\sum_{j'=L+1}^K \alpha^n_{\pi_n(j')} \triangleq 1-\sum_{j<L}\hat{\alpha}^n_{\pi_n(j)}-\alpha^n_{\pi_n(L)}$$

and substitute it into $C1$, we achieve that

$$\alpha^n_{\pi_n(L)} \geq \frac{\gamma_{\pi_n(L)}(1+\hat{\eta}^n_{\pi_n(L)}-\sum_{j<L}\hat{\alpha}^n_{\pi_n(j)})}{1+\gamma_{\pi_n(L)}}. \tag{13}$$

With the similar argument to that in Lemma 1, for $L = \{2, 3, \ldots, K-1\}$, we show that the optimal ratio of user $\pi_n(L)$ achieve when the inequalities in (13) satisfy with equalities, i.e., $\hat{\alpha}^n_{\pi_n(L)} = \frac{\gamma_{\pi_n(L)}(1+\hat{\eta}^n_{\pi_n(L)}-\sum_{j<L}\hat{\alpha}^n_{\pi_n(j)})}{1+\gamma_{\pi_n(L)}}$. This completes the proof of (11).

According to $C2$, it is easy to get the optimal power ratio of user $\pi_n(K)$, i.e., $\hat{\alpha}^n_{\pi_n(K)} = 1-\sum_{i=1}^{K-1}\hat{\alpha}^n_{\pi_n(i)}$. □

IV. Simulation Results

This section evaluates the performance of the proposed EPA algorithm. We compare the performance of our enhanced power control method with fixed power allocation (FPA) (with different power control factors) and gain ratio power allocation (GRPA), respectively. FPA and GRPA are two sub-optimal power allocation strategies [7], [10]. The difference between these two existing power allocation schemes and the proposed EPA scheme is that the FPA and GRPA schemes only consider user-level power allocation. In contrast, the proposed EPA takes into account both user- and subcarrier-level power allocations, resulting in significant transmission performance enhancement. We note that the power allocation for multi-carrier NOMA can also be optimized by solving the non-convex optimization problem via Lagrangian duality or monotonic optimization programming, however, these schemes exhibit much higher computational complexity, and thus are not preferable for VLC. The power allocation factor of FPA, α_{FPA}, is assumed to be 0.2, 0.3 and 0.4, respectively. We assume $\gamma_{\pi_n(i)} = \gamma$ for $i \in \mathcal{K}$. Additionally, Monte Carlo method that is used in [14] is utilized to model the multi-reflection NOMA-VLC channel. The main simulation parameters are summarized in Table I, and the other parameter values, e.g., LED and PD settings, are the same as in [11]. In theory, the proposed EPA could be applied to arbitrary values of K. In this section, we consider the scenario where $K = 2$, which is commonly used in practical NOMA system from implementation point of view [15].

In the following, we consider two system-level performance metrics: the sum of data rates and the subcarrier loss rate.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Room size	$5 \times 5 \times 3$ m^3
LED locations (in meter)	(3.5,3.5,3); (1.5,3.5,3); (3.5,1.5,3); (1.5,1.5,3)
PD location (in meter)	(2.5,2.5,0.85); (0.5,0.5,0.85)
Reflection coefficient	(walls, floor, ceiling) = (0.83, 0.63, 0.4)
Vertical distance from ceiling to receiving plane	2.15 m
LED power	3 watt
Power constraint of each subcarrier	Equal distribution
Maximum reflection order	5
Subcarrier number, N	127
Signal bandwidth	30 MHz
Throughput calculation	Shannon's capacity formula
Required SINR of user, γ	0.5 dB to 3 dB
Power allocation factor, α_{FPA}	0.2, 0.3, 0.4

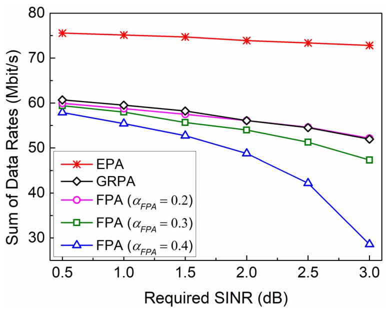

Fig. 2. Sum rate versus required SINR, γ.

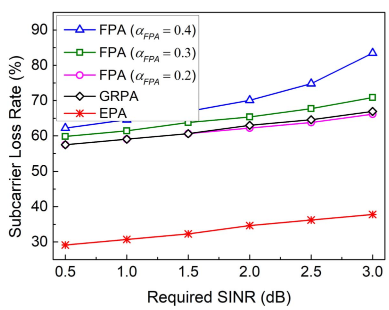

Fig. 3. Subcarrier loss rate versus required SINR, γ.

A. Sum of Data Rates

Fig. 2 depicts the sum rate performance of different schemes versus the required SINR. The conventional FPA scheme with different power allocation factors, as well as the GRPA scheme are implemented to evaluate the performance of the proposed EPA algorithm. For each required γ, the data point of each scheme is obtained by summating the data rate of K users on feasible subcarriers. It can be seen that the sum of data rates of all the five power control methods will decrease when the required SINR increases. Besides, for different α_{FPA}, FPA achieves different performance and $\alpha_{FPA} = 0.2$ has the best performance among three FPA strategies. This is because more power will be assigned to the weak user with the decreasing of α_{FPA}, which will improve the performance of NOMA to some extent. It is worth noting that FPA with $\alpha_{FPA} = 0.2$ has approximate performance to that of GRPA. Additionally, it is straightforward to see that the proposed EPA outperforms the other schemes significantly, especially when the required SINR is high. For example, when γ is set to 3 dB, EPA has 155%, 54%, 39.59% and 40.11% sum-rate enhancement compared to that of FPA with $\alpha_{FPA} = 0.4$, FPA with $\alpha_{FPA} = 0.3$, FPA with $\alpha_{FPA} = 0.2$ and GRPA, respectively.

B. Subcarrier Loss Rate

Fig. 3 compares the subcarrier loss rate of all five power allocation schemes. Given the required SINR, the subcarrier loss rate, defined as the ratio of the number of infeasible subcarriers to the number of total subcarrier, is used as the metric for performance evaluation. We can see that when the required SINR increases, the subcarrier loss rates of all the five schemes increase. Besides, for any given γ, FPA with $\alpha_{FPA} = 0.2$ has the lowest subcarrier loss rate among three different FPA strategies and comparable performance when compared to that of GRPA. In addition, for any given required SINR γ, the proposed EPA always has the best subcarrier-loss-rate performance among all the schemes.

V. CONCLUSION

This letter studies the power control problem for an OFDM-NOMA VLC system with arbitrary number of multiplexed users. The goal is to maximize system's sum rate with any given required SINR of each user. Based on theoretical derivations of the closed form of the optimal power ratio for the multiplexed users, an efficient EPA algorithm is proposed to realize both user- and subcarrier-level power allocation, and thus maximizing the achievable sum rate of OFDM-NOMA VLC. Numerical results show that, in terms of sum rate and subcarrier loss rate, the proposed EPA algorithm exhibits significant performance improvement compared to the optimized FPA strategy and the conventional GRPA scheme.

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