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Resource Allocation for Multi-User Integrated Visible Light Communication and Positioning Systems

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Abstract—In this paper, we firstly propose a joint subcarrier and power allocation approach for multi-user integrated visible light communication and positioning (VLCP) systems in the presence of practical unique optical constraints. The purpose of the proposed resource allocation approach is to maximize the sum rate of users and meanwhile guarantee the different minimum data rates and positioning accuracy requirements of users. Then, we solve the optimization problem by decomposing it into two subproblems, where a low-complexity suboptimal subcarrier allocation approach is proposed and the sequential quadratic programming (SQP) method is adopted to solve the non-linearly constrained power allocation optimization problem. Numerical results show that the proposed resource allocation approach can effectively improve the sum rate and the positioning accuracy of users compared with other resource allocation approaches.

Index Terms—Visible light communication and positioning, power allocation, subcarrier allocation, unique optical constraints.

I. INTRODUCTION

White light emitting diodes (LEDs) have achieved much attention recently for its long lifetime, low power consumption and reliability [1]. Besides illumination, LEDs are used for visible light communications (VLC) and visible light positioning (VLP), and have wide indoor applications such as homes, hospital, and industry [1], [2].

On the one hand, VLC has been identified as a promising candidate for indoor wireless communication systems due to its many attractive characteristics, such as economic, abundant bandwidth and high security [1]. So far, many researchers have presented their designs to improve the performance of VLC systems, such as multiple-input multiple-output (MIMO) [3], frequency domain equalization [4], orthogonal frequency division multiplexing (OFDM) [5], and so on. In addition, resource allocation has also been widely investigated in VLC systems [6]–[11] in order to guarantee quality-of-service (QoS) requirements of users and effectively improve the system capacity. The authors of [6] and [7] carefully designed power allocation schemes aiming to maximize the sum rate of users with practical optical power constraints. In [8], [9], the network resource optimization was investigated for hybrid VLC/radio frequency (RF) networks under users' QoS constraints. Moreover, the optimal power allocation ratio for a considerable number of multiplexed users was derived in non-orthogonal multiple access (NOMA) VLC systems by allowing users to use the same frequency resource [10]–[12].

On the other hand, VLP has become an attractive research topic recently, because it offers the high positioning accuracy compared with radio frequency (RF) based indoor positioning

systems [2], [13]–[17]. In [13], [14], the theoretical positioning accuracy by applying received signal strength (RSS) in VLP systems was derived under indoor multipath reflections, but RSS has low estimation accuracy at the edges of a room. A low-complexity time difference of arrival (TDOA) based VLP systems was proposed in [15], and the experimental results showed the effectiveness of the approach, but TDOA requires high time resolution. In [16], the authors presented a new differential phase difference of arrival (PDOA) scheme and experimental results indicated the achievable high positioning accuracy. Moreover, power allocation has been widely studied in RF based wireless positioning systems [18]–[19], but only [13] and [17] investigated the power allocation scheme among LED lamps in VLP systems.

As far as we know, most works just only focused on VLC [5]–[10] or VLP independently [2], [14]–[17]. However, practical indoor environments may require both the communication and positioning services in the same system at the same time. So far, only several works [11], [20]–[22] deployed the integration of VLC and VLP. In details, the authors in [11] and [20] combined OFDM and RSS for the integrated VLCP systems. In addition, an integrated VLCP system using filter bank multicarrier-based subcarrier multiplexing (FBMC-SCM) and PDOA was proposed in [21], [22]. Unfortunately, the above integrated VLCP models [19]–[22] did not investigate the resource allocation for both communication and positioning scenarios under practical optical constraints.

To address the above-mentioned issues, in this paper, a joint subcarrier and power allocation approach is firstly proposed for multi-user integrated VLCP systems under practical unique optical constraints, in order to maximize the system sum rate while guaranteeing the minimum data rates and positioning accuracy requirements of users. We solve the optimization problem by decomposing it into two subproblems, where a low-complexity suboptimal subcarrier allocation approach is proposed. Considering that the power allocation subproblem is non-convex with non-linear constraints, the sequential quadratic programming (SQP) method is adopted to solve the non-linearly constrained optimization problem. Numerical results verify that the feasibility of our proposed resource allocation approach for multi-user integrated VLCP systems.

The rest of this paper is organized as follows. The multi-user integrated VLCP system model and the formulation of the optimization problem are shown in Section II. The solution to the optimization problem is provided in Section III. The results and discussion are presented in Section V. Finally, Section VI concludes the article.

II. INTEGRATED VLCP SYSTEM AND PROBLEM FORMULATION

A. Integrated VLCP System Model

We consider a downlink multi-user integrated VLCP system, which consists of M LED lamps with K users being randomly distributed in the lighting coverage area, as illustrated in Fig. 1. Besides indoor illumination, the system can also provide both communication and positioning services for users. As in [6], we assume that there exists a central controller to connect all LED lamps to simultaneously broadcast information to multiple users. We assume that the uplink feedback is offered through the Wi-Fi links and each LED lamp can share the feedback information with other LED lamps through the central controller. We assume that each user is equipped with a single photodiode (PD) and the total bandwidth is equally divided into N ($N=N_{po}+N_{co}$) subcarriers, where N_{po} subcarriers are used for positioning and the remaining N_{co} subcarriers are reserved for communication. Let $\mathcal{M}$ and $\mathcal{K}$ denote the sets of all LED lamps and users, respectively; let $\mathcal{N}_{co}$ and $\mathcal{N}_{po}$ denote the sets of the communication subcarriers and the positioning subcarriers, respectively. If one subcarrier is allocated to a user, all the LEDs will transmit the corresponding signal on the allocated subcarrier.

Fig. 1. An indoor multi-user integrated VLCP system.

All the LEDs transmit the same communication signal and thus to achieve transmit diversity [22]. At the LED lamp $m \in \mathcal{M}$, the transmitted data z_m is a linear combination of the users' communication data flow and the positioning data flow, which can be expressed as

$$z_m = \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{co}} \rho_{k,n}^{co} \sqrt{P_{n,m}^{co}} s_{k,n}^{co} + \sum_{i \in \mathcal{N}_{po}} \rho_{m,i}^{po} \sqrt{P_{i,m}^{po}} s_i^{po} + A \quad (1)$$

where $\rho_{k,n}^{co}$ denotes a binary variable, $\rho_{k,n}^{co} \in \{0,1\}$, and $\rho_{k,n}^{co}=1$ represents the n -th communication subcarrier is allocated to the user k ; otherwise, it takes the value 0. $\rho_{m,i}^{po}$ is also a binary variable, $\rho_{m,i}^{po} \in \{0,1\}$, and $\rho_{m,i}^{po}=1$ indicates the positioning signal on the i -th subcarrier is modulated into LED lamp m ; otherwise, $\rho_{m,i}^{po}=0$. $P_{n,m}^{co}$ and $P_{i,m}^{po}$ denote the allocated transmit electrical powers on the n -th communication subcarrier and on the i -th positioning subcarrier at the m -th LED lamp, respectively. $s_{k,n}^{co}$ is the communication data for the user k on the n -th subcarrier, and s_i^{po} is the positioning data on the i -th subcarrier, and we set that the mean of $s_{k,n}^{co}$ or s_i^{po} is zero, and they are in the range of $[-\sigma, \sigma]$ with $\sigma > 0$ [7], [16]. A denotes the direct current (DC) offset which is added to ensure that the transmitted signal is non-negative.

In the integrated VLCP system, the total subcarriers are divided into three groups, as shown in Fig. 1, where group 2 is used for VLP and the other two groups are used for VLC. For VLC, we apply the FBMC-SCM scheme to provide communication service due to its negligible guard band in the integrated VLCP system [22].

For VLP, we use the PDOA positioning method due to its high positioning accuracy. The main principle of PDOA can be seen in our previous work [16], where the system consists of at least three LED lamps which are used in the 2-dimensional (2D) PDOA algorithm with four different positioning frequencies (f_i, f_{i+1}, f_{i+2} and f_{i+3}), where f_i and f_{i+3} are modulated into the first LED lamp together, and f_{i+1} and f_{i+2} are modulated into the second LED lamp and the third LED lamp, respectively. All the LED lamps are synchronized. When the system gives the locations of the LED lamps, the location of the receiver can be successfully calculated, the calculation process of the PDOA scheme can be seen in [16].

After estimating the location of each user, the root square positioning error (RSE) of user k can be obtained by

$$RSE_k = \sqrt{(x_{k,e} - x_k)^2 + (y_{k,e} - y_k)^2} \quad (2)$$

where $(x_{k,e}, y_{k,e})$ and (x_k, y_k) are the estimated location and the real location of the k -th user, respectively.

At the receiver, for the communication signal, the received signal-to-noise-ratio (SNR) for user k on the n -th subcarrier is given by

$$\gamma_{k,n}^{co} = \mu^2 \sum_{m \in \mathcal{M}} P_{n,m}^{co} (h_{k,n,m})^2 / \delta^2 \quad (3)$$

where μ denotes the PD's responsivity. $h_{k,n,m}$ represents the optical channel gain from the m -th LED lamp to user k on the n -th subcarrier [3], [6]. δ^2 is the additive white Gaussian noise (AWGN) power, and we assume that the noise power of all users are equal.

For the k -th user, the achievable rate on the n -th subcarrier can be defined as

$$R_{k,n} = \frac{B_{sub}}{2} \log_2(1 + \gamma_{k,n}^{co}) \quad (4)$$

where B_{sub} is the subcarrier bandwidth and $B_{sub} = B/N$ with B being the system transmission bandwidth, and the constant $1/2$ is due to the Hermitian symmetry [6], [7].

At the receiver, for the positioning signal, when one transmitted positioning signal is modulated into the m -th LED on the positioning subcarrier i , the received SNR of user k can be given as

$$\gamma_{k,i}^{po} = \mu^2 P_{i,m}^{po} (h_{k,i \rightarrow m})^2 / \delta^2 \quad (5)$$

where $h_{k,i \rightarrow m}$ is the channel gain between the m -th LED lamp and the k -th user on the i -th positioning subcarrier.

B. VLCP System Constraints

In practical integrated VLCP systems, some certain constraints should be considered in the optimization problem, which are discussed and analyzed as follows:

1) *Power Constraint*: Differing from the RF systems, two unique issues for power allocation must be taken account into VLCP systems due to the inherent characteristics of white LEDs based VLCP systems: (1) the transmitted signals should be non-negative; (2) the optical power must be operated in the limited linear optical power range due to the non-linearity of LEDs and the maximum permissible optical intensity for the eye safety [1], [7], [16]. Then, the transmitted signal at each LED lamp should satisfy

$$A_{\min} \leq z_m \leq A_{\max} \quad (6)$$

where $A_{\min}$ and $A_{\max}$ denote the minimum and maximum values of the LED lamp driving currents in the linear region of $[A_{\min}, A_{\max}]$, and $A_{\min}$ is non-negative due to the non-negativity of the transmitted signals in VLCP system. In addition, $A_{\max}$ should satisfy the maximum optical intensity limitation for the eye safety.

Then, combining (1) and (6), we can get the constraint on the allocated electrical power of each LED lamp, which is given by

$$\frac{A_{\min} - A}{\sigma} \leq \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} \sqrt{P_{n,m}^{\text{co}}} + \sum_{i \in \mathcal{N}_{\text{po}}} \rho_{i,m}^{\text{po}} \sqrt{P_{i,m}^{\text{po}}} \quad (7a)$$

$$\sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} \sqrt{P_{n,m}^{\text{co}}} + \sum_{i \in \mathcal{N}_{\text{po}}} \rho_{i,m}^{\text{po}} \sqrt{P_{i,m}^{\text{po}}} \leq \frac{A_{\max} - A}{\sigma} \quad (7b)$$

In addition, the electrical power allocated to the associated users across all subcarriers should be less than the maximum electrical power $P_{\max}$ of each LED lamp, which can be expressed as

$$\sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} P_{n,m}^{\text{co}} + \sum_{i \in \mathcal{N}_{\text{po}}} \rho_{i,m}^{\text{po}} P_{i,m}^{\text{po}} \leq P_{\max} \quad (8)$$

2) *QoS Constraints of VLC*: One of the key purposes of the VLCP system is to provide the communication services for the users, so the minimum transmission data rates of these users must be satisfied in the performance optimization design. Thus, the resulting constraint is expressed by

$$R_k = \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} R_{k,n} \geq R_k^{\min} \quad (9)$$

where $R_k^{\min}$ is the minimum data rate requirement of user k .

3) *Positioning Accuracy Constraints of VLP*: In addition to the QoS constraint in (9) of VLC, VLCP systems should guarantee that the positioning accuracy requirement of each user k ; in other words, its current positioning error must be below its given positioning error threshold $RSE_k^{\max}$. Hence, we have the constraint: $RSE_k \leq RSE_k^{\max}$. In PDOA based VLP systems, when the clock offset, LEDs' locations and other relevant parameters of PDOA are given, the positioning accuracy depends on the received SNR on the positioning subcarriers [2], [16], thus we can transform the constraint ($RSE_k \leq RSE_k^{\max}$) as follows

$$\gamma_{k,i}^{\text{po}} \geq \gamma_{k,\min}^{\text{po}} \quad (10)$$

where $\gamma_{k,\min}^{\text{po}}$ denotes the minimum SNR requirement of the user k on each positioning subcarrier when the user has the

corresponding maximum positioning error threshold $RSE_k^{\max}$.

C. Problem Formulation

In the multi-user integrated VLCP system, the objective of the proposed resource allocation approach is to globally maximize the sum rate of all users, while considering the above mentioned constraints in Section III.B: maintaining the transmit electrical power of LEDs in the lower and upper bound constraints, satisfying the minimum data rate requirements of users and guaranteeing the positioning accuracy of users. The problem of the resource allocation for multi-user integrated VLCP systems is formulated as follows

$$\underset{\mathbf{p}_{\text{co}}, \mathbf{P}_{\text{co}}, \mathbf{P}_{\text{po}}}{\text{maximize}} \quad \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} R_{k,n} \quad (11a)$$

$$\text{s.t.} \quad (7), (8), (9), (10); \quad (11b)$$

$$\rho_{k,n}^{\text{co}} \in \{0, 1\}, \forall k, n; \quad \rho_i^{\text{po}} \in \{0, 1\}, \forall i; \quad (11c)$$

$$\sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} + \sum_{i \in \mathcal{N}_{\text{po}}} \rho_i^{\text{po}} \leq N \quad (11d)$$

where $\mathbf{p}_{\text{co}}$ and $\mathbf{p}_{\text{po}}$ denote the set of subcarrier allocation variables for communication and positioning, respectively. $\mathbf{P}_{\text{co}} = [P_1^{\text{co}}, \dots, P_{N_{\text{co}}}^{\text{co}}]^T$ and $\mathbf{P}_{\text{po}} = [P_1^{\text{po}}, \dots, P_4^{\text{po}}]^T$ are the set of transmit electrical power allocation vectors for communication and positioning, respectively. In (11), (11d) is used to ensure that the sum of allocated subcarriers should be less than the number of the available subcarriers.

III. SOLUTION FOR THE RESOURCE ALLOCATION PROBLEM

Clearly, the optimization problem in (11) is a mixed-integer programming problem due to the binary variables $\mathbf{p}_{\text{co}}$, as well as the non-negative variables $\mathbf{P}_{\text{co}}$ and $\mathbf{P}_{\text{po}}$ are involved. In addition, it is also a NP-hard problem [23], so it cannot be solved directly. Hence, in this section, we solve the joint optimization problem in (11) by decomposing it into two subproblems: a subcarrier allocation problem and a power allocation problem. Consequently, after solving these two subproblems alternately, we can achieve the suboptimal solution of the joint optimization problem in (11) by using an iterative algorithm.

A. Suboptimal Subcarrier Allocation

We can observe that the resource allocation problem in (1) is a combinatorial problem in terms of subcarrier allocation, which has a prohibitive computational complexity if we solve it by using the exhaustive search for all possible cases. Hence, we propose a low-complexity approach to achieve the suboptimal subcarrier allocation under the constraints (9), (10) and (11d).

The main principle of the proposed suboptimal subcarrier allocation approach is based on the users' channel quality and their QoS requirements, which can be presented by the following analysis. Searching the user whose current rate is the farthest away from its target QoS requirement can be allocated the high-quality subcarriers to guarantee its QoS requirement first. After satisfying the all users' minimum data rate

requirements, we allocate the remaining communication subcarriers to optimize the overall sum rate of users.

The detailed algorithm for the suboptimal subcarrier allocation is shown in **Algorithm 1**. Let Ω_k denotes the set of subcarriers allocated to user k .

Algorithm 1. Suboptimal Subcarrier Allocation

1: **Initialization:** $\mathcal{N}_{\text{co}} = \{1, \dots, N_{\text{co}}\}$, $\mathcal{K} = \{1, \dots, K\}$, set $R_k = 0$ and $\Omega_k = \emptyset$ for $\forall k \in \mathcal{K}$.

Step 1: satisfy users' minimum rate requirements

- 2: For any user k satisfying $R_k < R_k^{\text{tar}}$;
- 3: Find the user k' satisfying $R_k^{\text{tar}} - R_k \leq R_{k'}^{\text{tar}} - R_{k'}$ for $\forall k' \in \mathcal{K}$;
- 4: For the user k' , find n' satisfying $\sum_{m \in \mathcal{M}} (h_{k', n', m})^2 \geq \sum_{m \in \mathcal{M}} (h_{k, n', m})^2$ for $n' \in \mathcal{N}_{\text{co}}$;
- 5: Let $\Omega_{k'} = \Omega_{k'} \cup \{n'\}$, $\mathcal{N}_{\text{co}} = \mathcal{N}_{\text{co}} - \{n'\}$, and update $R_{k'}$;

Step 2: maximize the system sum rate

- 6: while $\mathcal{N}_{\text{co}} \neq \emptyset$
 - 7: find the user k' and the subcarrier n' satisfying $\sum_{m \in \mathcal{M}} (h_{k', n', m})^2 \geq \sum_{m \in \mathcal{M}} (h_{k, n', m})^2$;
 - 8: For k' and n' , let $\Omega_{k'} = \Omega_{k'} \cup \{n'\}$; $\mathcal{N}_{\text{co}} = \mathcal{N}_{\text{co}} - \{n'\}$ and update $R_{k'}$.
 - 9: **end**
-

The optimal subcarrier allocation can be achieved if we adopt the exhaustive search for all the possible subcarrier allocation cases. In our multi-user integrated VLCP system with the K -user N_{co} -communication-subcarrier, it is prohibitive to search the optimum due to the high computational complexity, since the exhaustive search method has $O(K^{N_{\text{co}}})$ possible subcarrier allocations. However, the complexity of our proposed suboptimal subcarrier allocation is $O(K \times N_{\text{co}})$, which is greatly lower than that of the exhaustive search method.

B. Power Allocation with Given Subcarrier Allocation

After allocating the subcarrier according to Algorithm 1, here, we present an optimal power allocation approach for given suboptimal subcarrier allocation $\mathbf{p}_{\text{co}}$. The optimization problem in (11) now reduces to sum rate maximization with the communication power allocation $\mathbf{P}_{\text{co}}$ and positioning power allocation $\mathbf{P}_{\text{po}}$ while maintaining the constraints (7)-(9). Hence, the problem in (11) is formulated to the following form.

$$\begin{aligned} & \underset{\mathbf{P}_{\text{co}}, \mathbf{P}_{\text{po}}}{\text{maximize}} \quad \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} R_{k,n} \\ & \text{s.t.} \quad (7), (8), (9), (10). \end{aligned} \quad (13)$$

Clearly, the problem in (13) is a non-convex and non-linear programming problem in $\mathbf{P}_{\text{co}}$ and $\mathbf{P}_{\text{po}}$ [23], which makes the global optimal solution intractable. In order to solve it, we adopt the Sequential Quadratic Programming (SQP) method [24] to obtain the global optimal solution $\mathbf{P}_{\text{co}}$ and $\mathbf{P}_{\text{po}}$, which is capable of solving the non-linearly constrained optimization problems [24]. Due to the non-linear constraints (7), (9) and (10), the SQP method is an effective approach to solve our formulated optimization problem in (13) by converting it into the choice of quadratic sub-problems with a quadratic objective function.

The Lagrangian function of the optimization problem in (13) can be expressed as

$$\begin{aligned} \mathcal{L}(\mathbf{P}_{\text{co}}, \mathbf{P}_{\text{po}}, \boldsymbol{\lambda}) = & \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} R_{k,n} + \sum_{m \in \mathcal{M}} \lambda_m^{\text{c1}} \alpha_m(\mathbf{P}) + \sum_{m \in \mathcal{M}} \lambda_m^{\text{c2}} \beta_m(\mathbf{P}) \\ & + \sum_{m \in \mathcal{M}} \lambda_m^{\text{c3}} \mu_m(\mathbf{P}) + \sum_{k \in \mathcal{K}} \lambda_k^{\text{c4}} \nu_k(\mathbf{P}) + \sum_{i \in \mathcal{N}_{\text{po}}} \sum_{k \in \mathcal{K}} \lambda_{k,i}^{\text{c5}} \omega_{k,i}(\mathbf{P}) \end{aligned} \quad (14)$$

where

$$\begin{aligned} \alpha_m(\mathbf{P}) &= P_{\text{max}} - \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} P_{n,m}^{\text{co}} - \sum_{i \in \mathcal{N}_{\text{po}}} \rho_{i,m}^{\text{po}} P_{i,m}^{\text{po}}; \\ \beta_m(\mathbf{P}) &= \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} \sqrt{P_{n,m}^{\text{co}}} + \sum_{i \in \mathcal{N}_{\text{po}}} \rho_{i,m}^{\text{po}} \sqrt{P_{i,m}^{\text{po}}} - \frac{A_{\text{min}} - A}{\sigma}; \\ \mu_m(\mathbf{P}) &= \frac{A_{\text{max}} - A}{\sigma} - \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} \sqrt{P_{n,m}^{\text{co}}} - \sum_{i \in \mathcal{N}_{\text{po}}} \rho_{i,m}^{\text{po}} \sqrt{P_{i,m}^{\text{po}}}; \\ \nu_k(\mathbf{P}) &= \sum_{n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} R_{k,n} - R_k^{\text{min}}; \\ \omega_{k,i}(\mathbf{P}) &= \gamma_{k,i}^{\text{po}} - \gamma_{k,\text{min}}^{\text{po}}. \end{aligned}$$

where $\boldsymbol{\lambda} = (\lambda^{\text{c1}}, \lambda^{\text{c2}}, \lambda^{\text{c3}}, \lambda^{\text{c4}}, \lambda^{\text{c5}})$ is the dual Lagrange variable matrix for the constraints (7)-(10).

The SQP method needs a finite number of iterations to coverage the optimal point of the optimization problem in (13), and the t -th iteration of the function (14) is formulated by a quadratic programming sub-problem with an approximate solution $\mathbf{P}(t) = [\mathbf{P}^{\text{co}}(t) \ \mathbf{P}^{\text{po}}(t)]^T$. And the initial approximation solution is $\mathbf{P}(0) = [\mathbf{P}^{\text{co}}(0) \ \mathbf{P}^{\text{po}}(0)]^T$. In order to solve the formulated problem in the SQP format, we define the SQP vector of the constraints (7)-(10) as

$$\mathbf{F}(\mathbf{P}) = [\boldsymbol{\alpha}(\mathbf{P}), \boldsymbol{\beta}(\mathbf{P}), \boldsymbol{\mu}(\mathbf{P}), \mathbf{v}(\mathbf{P}), \boldsymbol{\omega}(\mathbf{P})] \quad (15)$$

where $\boldsymbol{\alpha}(\mathbf{P}) = [\alpha_1(\mathbf{P}), \dots, \alpha_M(\mathbf{P})]^T$, $\boldsymbol{\beta}(\mathbf{P}) = [\beta_1(\mathbf{P}), \dots, \beta_M(\mathbf{P})]^T$, $\boldsymbol{\mu}(\mathbf{P}) = [\mu_1(\mathbf{P}), \dots, \mu_M(\mathbf{P})]^T$, $\mathbf{v}(\mathbf{P}) = [\nu_1(\mathbf{P}), \dots, \nu_K(\mathbf{P})]^T$ and $\boldsymbol{\omega}(\mathbf{P}) = [\omega_1(\mathbf{P}), \dots, \omega_K(\mathbf{P})]^T$ are the SQP format matrices.

To solve (13), at each iteration t , the SQP method improves the estimate solution $(\mathbf{P}(t), \mathbf{F}(t))$ with a correction vector $\mathbf{s}(t) = [\mathbf{s}_P^T(t) \ \mathbf{s}_F^T(t)]^T$. The correction vector $\mathbf{s}$ is achieved by solving the following quadratic programming problem

$$\min \frac{1}{2} \langle \mathbf{s}, \nabla^2 [\mathcal{L}(\mathbf{P})] \mathbf{s} \rangle + \langle \nabla [\mathcal{L}(\mathbf{P})], \mathbf{s} \rangle \quad (16a)$$

$$\text{s.t.} \quad \nabla [\mathbf{F}(\mathbf{P})] \mathbf{s} + \mathbf{F}(\mathbf{P}) \geq 0 \quad (16b)$$

where $\nabla[\cdot]$ and $\nabla^2[\cdot]$ are the first-order and second-order partial derivatives, respectively, and $\nabla^2[\cdot]$ is also the Hessian operator. The SQP method updates the pair of solution $(\mathbf{P}(t), \mathbf{F}(t))$ at each iteration to minimize the function (16a). In other words, the allocated electrical power and the dual Lagrange variables are estimated by finding the correction vector $\mathbf{s}(t)$ at the t -th iteration, which are expressed as follows

$$\mathbf{P}(t+1) = \mathbf{P}(t) + \varepsilon_P(t) \mathbf{s}_P(t), \text{ and } \mathbf{F}(t+1) = \mathbf{F}(t) + \varepsilon_F(t) \mathbf{s}_F(t) \quad (17)$$

respectively, where $\varepsilon_P(t)$ and $\varepsilon_F(t)$ are the non-negative step

sizes. We obtain the correction vector $\mathbf{s}(t)$ as [24]

$$\begin{bmatrix} \nabla^2[\mathcal{L}(\mathbf{P}(t))] & \nabla[\mathbf{F}(\mathbf{P}(t))]^T \\ \nabla[\mathbf{F}(\mathbf{P}(t))] & \mathbf{0} \end{bmatrix} \times \begin{bmatrix} \mathbf{s}(t) \\ -\mathbf{s}(t) \end{bmatrix} = - \begin{bmatrix} \nabla[\mathcal{L}(\mathbf{P}(t))] \\ \mathbf{F}(\mathbf{P}(t)) \end{bmatrix} \quad (18)$$

In (18), the Karush–Kuhn–Tucker (KKT) condition is used to solve the SQP quadratic problem in (15) by taking $\nabla[\mathbf{F}(\mathbf{P}(t))]\mathbf{s} + \mathbf{F}(\mathbf{P}(t)) = \mathbf{0}$, so that the set of constraints (7)-(10) are active constraints at each iteration [24]. At each iteration, the SQP method provides a better estimated solution towards to the optimal solution point when the convergence is guaranteed within a finite number of iterations [25]. In addition, the step size parameters $\varepsilon_{\mathbf{p}}(t)$ and $\varepsilon_{\mathbf{F}}(t)$ are chosen by applying a merit function $\Phi(\cdot)$ [25], and the step size $\varepsilon_{\mathbf{p}}(t)$ is selected to decrease the value of the merit function. The process is measured by a merit function $\Phi(\cdot)$, and when $\Phi(\cdot)$ is minimized by the selection of the step size $\varepsilon_{\mathbf{p}}(t)$, that is, $\Phi(\mathbf{P}(t) + \beta_{\mathbf{p}}(t)\mathbf{s}(t))$ is sufficiently smaller than $\Phi(\mathbf{P}(t))$. The step sizes $\varepsilon_{\mathbf{p}}(t)$ and $\varepsilon_{\mathbf{F}}(t)$ usually set to 1 [25], the solution details can be found in [25].

Finally, according to (14)-(18), we can get the optimal power allocation in the multi-user integrated VLCP system by applying the SQP method.

D. Resource Allocation in Multi-user Integrated VLCP Systems

Accordingly, we present the solution process for the resource allocation in the multi-user integrated VLCP system, as shown in **Algorithm 2**. The algorithm iteratively updates the subcarrier allocation and the transmit electrical power allocation, in order to coverage to the optimized solution point.

Algorithm 2. Resource Allocation in Multi-user Integrated VLCP Systems

- 1: **Initialization:** Set the iteration $j=0$, initialize $\mathbf{p}(0)$ and $\mathbf{P}(0)$, the maximum tolerance $\varsigma > 0$.
- 2: **Repeat**
- 3: Update $\mathbf{p}(j+1)$ by **Algorithm 1** with given $\mathbf{P}(0)$;
- 4: Update $\mathbf{P}(j+1)$ by solving (13) using the SQL method with given $\mathbf{p}(j+1)$;
- 5: Update $j \leftarrow j+1$;
- 6: Calculate $R_{\text{total}}(\mathbf{p}(j), \mathbf{P}(j)) = \sum_{k \in \mathcal{K}, n \in \mathcal{N}_{\text{co}}} \rho_{k,n}^{\text{co}} R_{k,n}$;
- 7: Until $|R_{\text{total}}(\mathbf{p}(j), \mathbf{P}(j)) - R_{\text{total}}(\mathbf{p}(j-1), \mathbf{P}(j-1))| \leq \varsigma$;
- 8: **End**
- 9: **Output:** $\mathbf{p}^* \leftarrow \mathbf{p}(j)$, and $\mathbf{P}^* \leftarrow \mathbf{P}(j)$.

Here, we analyze the complexity of **Algorithm 2**. As analyzed in Section IV.B, updating the subcarrier allocation $\mathbf{p}$ needs the complexity of $O(K \times N_{\text{co}})$. In addition, the complexity for calculating the power allocation $\mathbf{P}$ is $O(M(N)^3 \log(1/\varsigma))$ [25]. Then, the overall complexity of **Algorithm 2** is $O(M(N)^3 \log(1/\varsigma) + K \times N_{\text{co}})$.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we evaluate the performance of the proposed resource allocation approach (Proposed RA) and compare it with the following approaches: 1. resource allocation approach (Optimal); 2. power allocation with equal subcarrier allocation

(PA-ESA), where the power allocation is adopted by Section III.C and the communication subcarriers are equally allocated to users; 3. subcarrier allocation with equal power allocation (SA-EPA), where the subcarrier allocation is adopted by Section III.B and the transmit electrical power is equally allocated to each communication subcarrier and each positioning subcarrier. We define the mean positioning error of all users as the mean RSE (MSER): $MRSE = (\sum_{k \in \mathcal{K}} RSE_k) / K$.

We consider a 5 m×5 m×3 m indoor room with three LED lamps are attached below the indoor ceiling and the receiving plane is 0.5 m above the floor. The locations of three LED lamps are (0, -0.175, 3), (0.25, 0.075, 3) and (-0.25, 0.075, 3), where the units are all meters. The LED lamp's semi-angle at half power is 60°, and the area of the PD is 0.5 cm² and the field of view (FOV) is 120°. The optical filter gain and the PD's responsivity are 1.0 and 0.5 A/W, respectively. The transmission bandwidth B is 20 MHz. The total number of subcarriers is 128 (Hermittian symmetry), and the number of data subcarriers is 64. The noise power spectral density is $N_0 = 10^{-20}$ A²/Hz. The positioning error threshold and the minimum data rate requirement of each user are 4.5cm and 8 Mbps. The overlapping factor in FBMC is 4. The four positioning frequencies are in the range between 5.0 to 5.47 MHz with the frequency gap of 0.156 MHz. Other relevant parameters can be seen in [6].

Figs. 2(a) and (b) show the average sum rate and positioning accuracy performance of users against the maximum electrical power P_{max} per LED lamp when $K=5$. In Fig. 2, with the increase of P_{max} , both the sum rate and positioning accuracy performance of all approaches improve due to the enhanced received SNR. In addition, the three power allocation approaches outperform the SA-EPA approach because they are capable of dynamically allocating the transmit electrical power according to the different channel gains from LED lamps to users, which can effectively improve the communication and positioning performance. Moreover, in Fig. 2, the positioning error is constant in the high maximum power regions ($P_{\text{max}} > 70$ mW), because the extra power will be allocated to maximize the sum rate of users once the positioning accuracy requirements is guaranteed in the high power regions.

Fig. 2. (a) Average sum rate and (b) positioning accuracy performance versus the maximum transmit electrical power P_{max} per LED lamp.

Figs. 3(a) and (b) plot the average sum rate and positioning accuracy with different numbers of users when the maximum

transmit electrical power per lamp is 50 mW. We can see that the sum rate performance of the four approaches improves as the number of users increases, because the system has the more probability of searching users having good channel gains to enhance the sum rate of users. In contrast, the positioning error of the SA-EPA approach increases as the increased number of users, while other three approaches almost maintains the positioning error at a horizontal level (may be with a slight increase). The reason can be explained as follows. The larger number of users leads to a wide range of channel gains from LED lamps to users; hence the equal power allocation strategy of the SA-EPA approach fails to allocate the positioning power under the complex channel gains' environment, while other two approaches are capable of adjusting their power allocation strategy to optimize the positioning accuracy.

Fig. 3. (a) Average sum rate and (b) positioning accuracy performance versus different numbers of users.

V. CONCLUSION

This paper has studied the resource allocation approach in multi-user integrated VLCP systems to address the issues of joint subcarrier and power allocation problem under the unique optical constraints, the minimum data rate and the positioning accuracy requirements. As the optimization problem is a mixed-integer one and NP-hard with non-linear constraints, we decompose it into two subproblems, where a low-complexity suboptimal subcarrier approach is proposed and the SQP method is exploited to address the non-linearly power allocation optimization problem. Numerical results showed that the proposed resource allocation approach can effectively improve the sum rate and the positioning accuracy of the integrated VLCP system compared with other resource allocation approaches. In the future, we will pay more attention to the VLCP system in vehicular networks to support real-time vehicle communications [26].

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