Joint Resource Allocation and Position Optimization in NOMA-based Multi-UAV Wireless Communication Networks

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Abstract

In this paper, we study an uplink multi-unmanned aerial vehicle (UAV) wireless communication network where multi-UAV are deployed to serve the ground users by utilizing the non-orthogonal multiple access (NOMA) technology. The goal is to minimize the total transmit power of users by jointly optimizing the user association, sub-channel assignment, power allocation and UAVs' position. The formulated problem is a mixed integer non-convex optimization that is difficult to solve in optimal approach. By applying the convex optimization tools, successive convex approximation (SCA) and Lagrange dual approaches, we solve the optimization problem then we propose an efficient iterative algorithm. Numerical results confirm that the proposed scheme can provide a better performance compared to the orthogonal multiple access (OMA), random position of UAVs in NOMA (RP-NOMA) and OMA (RP-OMA) schemes in both of the transmit power and sum-rate performance metrics.

Keywords
Unmanned aerial vehicle, Non-orthogonal multiple access, Mixed integer non-convex, Successive convex approximation, Lagrange dual.

1. Introduction

Due to exponential increase in the mobile data traffic, limitation in the wireless network capacity is a major challenge and it is expected that the current systems and techniques will not be able to meet the required capacity [1], [2]. One of the effective and promising solutions to increase the capacity and meet the various demands of users is using the unmanned aerial vehicles (UAVs) [3], [4]. UAVs can be deployed as flying base stations for surveillance and monitoring, aerial imaging, cargo delivery [5], improving the performance of the traditional cellular networks [3], [6], [7] and providing reliable and cost-effective communication links [8]. Moreover, UAVs can be used as relay nodes to improve the wireless connectivity and coverage of wireless ground devices [9]. Also, UAVs can play a useful role in collecting periodic information in the Internet of Things (IoTs). However, in order to achieve these benefits in UAV-based networks, mobility management, resource allocation, and position optimization are important challenges in these networks.

In [8], a novel framework for optimizing the performance of multi-UAV wireless networks in terms of average number of bits transmitted to users under a fair resource allocation and UAVs' flight time under load constraint is investigated. In [9], the problem of 3D trajectory, mobility management, and power optimization is studied. The authors followed minimizing the total transmit power of ground IoT devices. A downlink multi-UAV enabled wireless communication system is considered in [10] to maximize the minimum throughput of all ground users by optimizing the multi-user communication scheduling, UAVs' trajectory and power management. In [11], the authors investigated the efficient deployment of UAVs and coverage probability for UAVs in a way that the total coverage area is maximized. An optimal 3D placement algorithm for UAV-base stations is proposed in [12] that maximizes the number of covered users using the minimum required transmit power. In [13], the authors studied a new energy-efficient framework for trajectory of a fixed-wing UAV. In [14], a novel model is introduced for the UAV relaying communication system where a mobile relay is able to move at high speed. The main goal is to maximize the throughput by optimizing the relay trajectory and the source/relay power. An energy efficient cooperative relaying model, which guarantees the success rate and network lifetime for real-time applications of wireless sensor networks is addressed in [15]. The optimization problem is formulated to minimize the maximum energy consumption of the UAVs by optimizing the transmit power under a provided bit error rate. In [16], an energy-efficient UAV communication via designing the UAV trajectory is investigated. The authors considered throughput and the UAV propulsion energy consumption jointly. In [17], the authors studied user communication scheduling, UAV trajectory, and transmit power to maximize energy efficiency and satisfy user quality-of-experience (QoE) requirement.

Another potential and promising technique to achieve high spectral efficiency introduced for fifth-generation (5G) networks is non-orthogonal multiple access (NOMA) technology. In this protocol, one frequency band can be assigned to multiple users simultaneously [18], [19]. Then by applying the successive interference cancellation (SIC) technique at the receiver side, the information signals can be detected and decoded by adopting the channel gain [18-20]. Therefore, NOMA technology by using SIC technique can improve the spectral efficiency compared to the traditional orthogonal frequency division multiple access (OFDMA) [21]. In [22], a power allocation policy to maximize the sum-rate of UAV-based communication system based on NOMA technology is addressed. In [23], the authors investigated the NOMA in a UAV-based communication network by optimizing the UAV trajectory and power allocation scenario. The optimization problem is formulated for maximizing the minimum average rate of ground users. In [24], a UAV-based communication system is studied where a fixed-wing type UAV moves in a circular trajectory to coverage the ground users located outside an offloaded base station. The problem of transmit power minimization under minimum achievable rate requirements via NOMA is proposed in [25]. The optimization variables consist of the decoding order, the transmit power allocation, and the position of the UAV. In [26], the authors investigated an optimization framework for power and time resource allocation during timesharing NOMA transmission performed by an UAV.

In the papers studied above, the authors focus mainly on trajectory optimization and power allocation and the problem of sub-channel assignment and user association is not considered. This paper investigates a comprehensive framework for optimizing user association, sub-channel assignment, power allocation, and position optimization in a UAV-based wireless communication system based on NOMA. The aim is to minimize the total transmit power of ground users under minimum rate requirement, efficient SIC, and power budget. The optimization problem is a mixed integer non-convex problem. To reduce the computational complexity, we solve this problem with five steps. First, an efficient algorithm for user association is applied. Second, a linear optimization problem by using convex optimization tools is solved for sub-channel assignment. Third, the non-convex power allocation problem is approximated by applying the successive convex approximation (SCA) approach then the power allocation policy is obtained by using Lagrange dual method. Forth, the SCA approach is adopted to convert the non-convex UAVs' position problem into the convex one. Finally, we propose an efficient iterative algorithm to obtain the joint above steps.

The rest of the paper is organized as follows. Section 2 describes the system model and problem formulation. In Section 3, the optimization problem is solved based on an iterative method. The computational complexity of the proposed solution is investigated in Section 4. The numerical results are presented in Section 5. Finally, Section 6 concludes the paper.

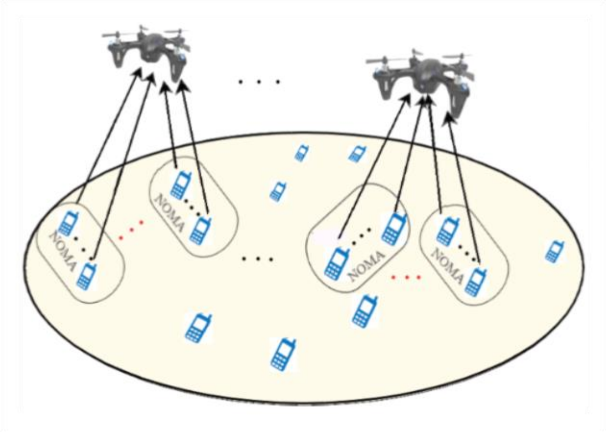

Fig. 1. Example of the considered system model

2. System Model and Problem Formulation

As shown in Figure 1, we consider an uplink communication network consists of U UAVs and M ground users where $\mathcal{U} = \{1,2,\dots,U\}$ and $\mathcal{M} = \{1,2,\dots,M\}$ denote the sets of UAVs and users, respectively. $\mathcal{M}_m$ denotes the set of associated users with UAV m where $M_m = |\mathcal{M}_m|$ and $\bigcup_{m=1}^{U} \mathcal{M}_m = M$. UAVs and all users are equipped with a single antenna. We assume that all users have the full knowledge of channel state information (CSI). The total system bandwidth of BW Hz is shared between all UAVs, which is divided into a set of NOMA-based sub-channels denoted by $\mathcal{N} = \{1,2,\dots,N\}$. The bandwidth of each sub-channel is equal to B=BW/N, and is assumed to be much less than the coherent bandwidth. Let $\alpha_{m,i}^{n}$ be the sub-channel assignment parameter, where $\alpha_{m,i}^{n} = 1$ if sub-channel n is assigned to user i associated with UAV m and 0 otherwise.

Due to flexibility and mobility, UAVs typically have high possibilities of line-of-sight (LoS) air-to-ground communication links. Therefore, similar to [10] and [13], we assume that the communication links from the UAV to the ground users is dominated by the LOS. Let $g_{m,i}$ be the channel gain between the UAV m and the user $i \in \mathcal{M}_m$, which is calculated based on free-space path loss model as follows

$$g_{m,i} = \rho_0 d_{m,i}^{-2} = \frac{\rho_0}{{h_m}^2 + \|W_m - Q_i\|^2} \qquad (1)$$

where ρ_0 is the channel gain at the reference distance $d_0 = 1$, $d_{m,i} = \sqrt{{h_m}^2 + \|W_m - Q_i\|^2}$ is the distance between UAV m and user i, h_m is the altitude of UAV m, and $W_m = [x_m, y_m]^T$ and $Q_i = [x_i, y_i]^T$ are two-dimensional (2D) positions of UAV m and user i, respectively.

Based on the NOMA protocol, a sub-channel can be assigned to multiple users at a same time. Moreover, in this paper, an uplink communication network is considered, which each UAV reveals its users' information signals. Without loss of generality, assume that $\mathcal{L}_m^n$ users in UAV m are allocated to sub-channel n and $g_{m,1} \geq g_{m,2} \geq \cdots \geq g_{m,i} \geq \cdots \geq g_{m,\mathcal{L}_m^n}$. By allocating proper powers and applying SIC technique in uplink transmission, UAV m is able to successfully decode the messages of the users $1, \dots, i-1$, and interference from users $i+1, \dots, \mathcal{L}_m^n$ appear as noise on the UAV m during the decoding operation [27].

Now, the signal-to-interference-plus-noise ratio (SINR) of user i served by UAV m on sub-channel n can be expressed as

$$\Gamma_{m,i}^n = \frac{P_{m,i}^n g_{m,i}}{\sigma^2 + \sum_{k=i+1}^{\mathcal{L}_m^n} P_{m,k}^n g_{m,k} + \sum_{l\in\mathcal{U}\backslash m} \sum_{b\in\mathcal{M}_l} P_{l,b}^n g} \tag{2}$$

where $P_{m,i}^n$ is the transmit power of user i to UAV m over sub-channel n and σ^2 is the noise power spectral density. In the denominator of (2), the second and third expressions are the received interferences from the uplink NOMA and users of other UAVs, respectively.

The achievable data rate of the user i on sub-channel n in UAV m can be calculated as

$$R_{m,i}^n = B \, log_2(1 + \Gamma_{m,i}^n) \tag{3}$$

Since UAV m receives the all transmitted messages, the power allocation mechanism for efficient SIC in uplink NOMA system is essential. For this purpose, the following constraint is considered as

$$\alpha_{m,i}^n P_{m,i}^n g_{m,i} - \left(\sum_{k=i+1}^{\mathcal{L}_m^n} \alpha_{m,k}^n P_{m,k}^n g_{m,k} + \sum_{l\in\mathcal{U}\backslash m} \sum_{b\in\mathcal{M}_l} \alpha_{l,b}^n P_{l,b}^n g_{m,b} \right) \geq p_{tol}, \forall m \in \mathcal{U}, n \in \mathcal{N}, i \in \mathcal{M}_m \tag{4}$$

where p_{tol} is the minimum power difference needed to successfully reveal between the desired message and remaining non-decoded messages and interference power from the users of other UAVs.

We define $\boldsymbol{A} = \{\alpha_{m,i}^n, \forall i, m, n\}$, $\boldsymbol{P} = \{P_{m,i}^n, \forall i, m, n\}$ and $\boldsymbol{W} = \{W_m, \forall m\}$ as sub-channel assignment matrix, power allocation matrix and 2D position of UAVs, respectively. Our objective is to minimize the total transmit power of users by optimizing the variables $\boldsymbol{A}$, $\boldsymbol{P}$, $\boldsymbol{W}$, and user association. The optimization problem is formulated as

$$\min_{\boldsymbol{A},\boldsymbol{P},\boldsymbol{W}} \sum_{m\in\mathcal{U}} \sum_{i\in\mathcal{M}_m} \sum_{n\in\mathcal{N}} \alpha_{m,i}^n P_{m,i}^n \tag{5a}$$

s.to:

Eq.(4),

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^n R_{m,i}^n \geq R_{i,min}, \forall m \in \mathcal{U}, i \in \mathcal{M}_m \tag{5b}$$

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^n P_{m,i}^n \leq P_{i,max}, \forall m \in \mathcal{U}, i \in \mathcal{M}_m \tag{5c}$$

$$\sum_{i\in\mathcal{M}_m} \alpha_{m,i}^n \leq D, \forall n \in \mathcal{N}, m \in \mathcal{U} \tag{5d}$$

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^n \leq G, \forall m \in \mathcal{U}, i \in \mathcal{M}_m \tag{5e}$$

$$\alpha_{m,i}^n \in \{0,1\}, \forall m \in \mathcal{U}, i \in \mathcal{M}_m, n \in \mathcal{N} \tag{5f}$$

$$0 \leq P_{m,i}^n \leq P_{m,i}^{n,mask}, \forall m \in \mathcal{U}, i \in \mathcal{M}_m, n \in \mathcal{N} \tag{5g}$$

(5b) is the data rate constraint for each user guarantying the data rate of user i in all sub-channels to be more than or equal to $R_{i,min}$. (5c) defines a power budget constraint for each user in all sub-channels. (5d) ensures that NOMA-based sub-channels can be assigned to at most D users in each UAV. (5e) guarantees that each user in all UAVs can only occupy at most G sub-channels. (5f) shows the sub-channel assignment parameter takes binary values, and finally (5g) defines the spectral mask.

Remark 1: In this work, only the UAV position optimization is investigated whereas the UAV trajectory design is not considered. This is because we focus on the cases that a UAV serves multi-delay-sensitive users simultaneously instead of sequentially [28]. Moreover, the UAV trajectory problem can be considered as UAV position optimization. Our research is also useful for the tethered UAV enabled. This means that the UAV is connected to a ground control center by cable/wire, i.e., Facebook's "Tether-Tenna" and AT&T's "flying cell-on-wings (COWs)" [28], [29].

Problem (5) is a mixed-integer non-convex optimization problem due to the non-convex constraint in (5b) with respect to transmit power of users $\boldsymbol{P}$ and 2D position of UAVs $\boldsymbol{W}$, non-linear constraint in (3) due to the existence of $\boldsymbol{W}$ in the channel gain equation, and binary value in constraint (5f). Therefore, there is no proper method to obtain the optimal solution.

Table I. User association algorithm

```
Initialize: i=1 and $\mathcal{M} \leftarrow \{1,2,\dots,M\}$
1. while $|\mathcal{M}| > 0$
2.     calculate $g_{m,i}$ based on (1) for all $m \in \mathcal{U}$
3.     $g_{m,i} = max\{g_{1,i}, g_{2,i} \dots, g_{U,i}\}$
4.     associate the user i to UAV m, namely $M_m \leftarrow i$
5.     $\mathcal{M} \leftarrow \mathcal{M} - \{i\}$
6.     i=i+1
7. end while
```

3. Proposed Solution

In order to reduce the computational complexity, we solve this problem in four stages: 1) users association, 2) sub-channel assignment, 3) power allocation policy, and 4) determining the optimal position of UAVs. Then, an iterative algorithm is applied to solve the problem (5).

3.1. User Association

Firstly, we need to associate users with the UAVs. In our algorithm, each user is connected to the nearest UAV, which is a well-known method in communication networks. This process is summarized in Table I. Assume the position of UAVs are known. Channel gain between each user and all UAVs can be calculated based on (1). Then, each user is associated to the UAV that provides the maximum channel gain (or has the minimum distance). It is cleared that our algorithm converges to the local optimum, but it provides low computational complexity. Then, the following sub-problems (sub-channel assignment, power allocation, and position optimization) are solved based on the user association algorithm presented in Table I and its corresponding constraints. This process is stopped when the convergence is obtained.

3.2. *Sub-channel Assignment*

By assuming fixed power vector and known 2D position of UAVs, the sub-channel assignment problem is written as follows.

$$\min_{\boldsymbol{A}} \sum_{m\in\mathcal{U}} \sum_{i\in\mathcal{M}_m} \sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} P_{m,i}^{n,z-1} \tag{6a}$$

s.to:

$$\alpha_{m,i}^{n,z} P_{m,i}^{n,z-1} g_{m,i} - \left(\sum_{k=i+1}^{\mathcal{L}_m^n} \alpha_{m,k}^{n,z} P_{m,k}^{n,z-1} g_{m,k} + \sum_{l\in\mathcal{U}\backslash m} \sum_{b\in\mathcal{M}_l} \alpha_{l,b}^{n,z} P_{l,b}^{n,z-1} g_{m,b} \right) \geq p_{tol}, \forall m\in\mathcal{U}, n\in\mathcal{N}, i\in\mathcal{M}_m \tag{6b}$$

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} R_{m,i}^{n} \geq R_{i,min}, \forall m\in\mathcal{U}, i\in\mathcal{M}_m \tag{6c}$$

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} P_{m,i}^{n,z-1} \leq P_{i,max}, \forall m\in\mathcal{U}, i\in\mathcal{M}_m \tag{6d}$$

$$\sum_{i\in\mathcal{M}_m} \alpha_{m,i}^{n,z} \leq D, \forall n\in\mathcal{N}, m\in\mathcal{U} \tag{6e}$$

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} \leq G, \forall m\in\mathcal{U}, i\in\mathcal{M}_m \tag{6f}$$

$$\alpha_{m,i}^{n,z} \in \{0,1\}, \forall m\in\mathcal{U}, i\in\mathcal{M}_m, n\in\mathcal{N} \tag{6g}$$

where z is iteration index. Similar to [30], problem (6) is a linear optimization problem that can be solved optimally using integer linear programming such as CVX optimizer [31].

3.3. *Power Allocation Policy*

By considering obtained sub-channel assignment vector in z^{th} iteration and known position of UAVs, the power allocation problem is

$$\min_{\boldsymbol{P}} \sum_{m\in\mathcal{U}} \sum_{i\in\mathcal{M}_m} \sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} P_{m,i}^{n,z} \tag{7a}$$

s.to:

Eq. (4),

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} R_{m,i}^{n} \geq R_{i,min}, \forall m\in\mathcal{U}, i\in\mathcal{M}_m \tag{7c}$$

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} P_{m,i}^{n,z} \leq P_{i,max}, \forall m\in\mathcal{U}, i\in\mathcal{M}_m \tag{7d}$$

$$0 \leq P_{m,i}^{n,z} \leq P_{m,i}^{n,mask}, \forall m\in\mathcal{U}, i\in\mathcal{M}_m, n\in\mathcal{N} \tag{7e}$$

The power allocation is a non-convex optimization problem due to the existence interference power term in SINR of users. In this paper, we use the Successive Convex Approximation for Low complExity (SCALE) method [30]. In this method, the achievable data rate of users in constraint (7c) can be approximated as [30], [32]

$$\hat{R}_{m,i}^{n} = B \times \left(\xi_{m,i}^{n,z} + \beta_{m,i}^{n,z}\, log_2\left(\Gamma_{m,i}^{n,z}\right)\right) \tag{8}$$

where $\xi_{mi}^{n,z}(z) = \log_2\left(1+\Gamma_{m,i}^{n,z-1}\right) - \beta_{m,i}^{n} \log_2\left(\Gamma_{m,i}^{n,z-1}\right)$ and $\beta_{m,i}^{n,z} = \frac{\Gamma_{m,i}^{n,z-1}}{1+\Gamma_{m,i}^{n,z-1}}$. $\xi_{m,i}^{n,z}$ and $\beta_{m,i}^{n,z}$ are fixed values that obtain in pervious iteration. However, the power allocation problem is still non-convex. By changing the variable $\widehat{\boldsymbol{P}} = \log_2(\boldsymbol{P})$, we have the convex optimization problem with respect to $\widehat{\boldsymbol{P}}$ as follows

$$\min_{\widehat{\boldsymbol{P}}} \sum_{m\in\mathcal{U}} \sum_{i\in\mathcal{M}_m} \sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} e^{\hat{P}_{m,i}^{n,z}} \tag{9a}$$

s.to:

$$\alpha_{m,i}^{n,z} e^{\hat{P}_{m,i}^{n,z}} g_{m,i} - \left(\sum_{k=i+1}^{\mathcal{L}_m^n} \alpha_{m,k}^{n,z} e^{\hat{P}_{m,k}^{n,z}} g_{m,k} + \sum_{l\in\mathcal{U}\backslash m} \sum_{b\in\mathcal{M}_l} \alpha_{l,b}^{n,z} e^{\hat{P}_{l,b}^{n,z}} g_{m,b} \right) \geq p_{tol}, \forall m \in\mathcal{U}, n\in\mathcal{N}, i\in\mathcal{M}_m \tag{9b}$$

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z}\, \hat{R}_{m,i}^{n}\left(e^{\hat{P}_{m,i}^{n,z}}\right) \geq R_{i,min}, \forall m\in\mathcal{U}, i \in\mathcal{M}_m \tag{9c}$$

$$\sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} e^{\hat{P}_{m,i}^{n,z}} \leq P_{i,max}, \forall m\in\mathcal{U}, i\in\mathcal{M}_m \tag{9d}$$

$$0 \leq e^{\hat{P}_{m,i}^{n,z}} \leq P_{m,i}^{n,mask}, \forall m\in\mathcal{U}, i\in\mathcal{M}_m, n \in\mathcal{N} \tag{9e}$$

Since log-sum-exp is convex [33], power allocation problem in (9) is a convex optimization problem that can be solved effectively by Lagrange dual approach. The Lagrange function of problem (9) with Lagrange multipliers $\left\{\varphi_{m,i}^{n}, \lambda_{m,i}, \omega_{m,i}, \forall m\in\mathcal{U}, i\in\mathcal{M}_m, n\in\mathcal{N}\right\}$ is written as follows.

$$L\left(\hat{P}_{m,i}^{n,z}, \varphi_{m,i}^{n}, \lambda_{m,i}, \omega_{m,i}\right) = \sum_{m\in\mathcal{U}} \sum_{i\in\mathcal{M}_m} \sum_{n\in\mathcal{N}} \alpha_{m,i}^{n,z} e^{\hat{P}_{m,i}^{n,z}} - \sum_{m\in\mathcal{U}} \sum_{i\in\mathcal{M}_m} \lambda_{m,i} \left(\sum_{n=1}^{N} \alpha_{m,i}^{n,z}\, \hat{R}_{m,i}^{n}\left(e^{\hat{P}_{m,i}^{n,z}}\right) - R_{i,min} \right)$$

$$-\sum_{m\in\mathcal{U}}\sum_{i\in\mathcal{M}_m}\sum_{n\in\mathcal{N}}\varphi_{m,i}^{n}\left(\alpha_{m,i}^{n,z}e^{\hat{P}_{m,i}^{n,z}}g_{m,i}-\sum_{k=i+1}^{\mathcal{L}_m^n}\alpha_{m,k}^{n,z}e^{\hat{P}_{m,k}^{n,z}}g_{m,k}-\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}\alpha_{l,b}^{n,z}e^{\hat{P}_{l,b}^{n,z}}g_{m,b}-p_{tol}\right)-\sum_{m\in\mathcal{U}}\sum_{i\in\mathcal{M}_m}\omega_{m,i}\left(P_{i,max}-\sum_{n=1}^{N}\alpha_{m,i}^{n,z}e^{\hat{P}_{m,i}^{n,z}}\right) \tag{10}$$

Then the dual problem is $\min_{\varphi_{m,i}^{n},\lambda_{m,i},\omega_{m,i}}\max_{\hat{\boldsymbol{P}}}L\left(\hat{P}_{m,i}^{n,z},\varphi_{m,i}^{n},\lambda_{m,i},\omega_{m,i}\right)$. Now, by applying the standard optimization techniques and the Karush- Kuhn-Tucker (KKT) conditions, $\frac{\partial L\left(\hat{P}_{m,i}^{n,z},\lambda_{m,i},\varphi_{m,i}^{n},\omega_{m,i}\right)}{\partial\hat{P}_{m,i}^{n,z}}=0$, the transmit power of user *i* to UAV *m* over sub-channel *n* is calculated as

$$P_{m,i}^{n}=\left[\frac{\lambda_{m,i}\alpha_{m,i}^{n}\beta_{m,i}^{n}B\times\frac{1}{ln\,2}}{F_{m,i}^{n}-\alpha_{m,i}^{n}+Y_{m,i}^{n}+\omega_{m,i}\alpha_{m,i}^{n}}\right]_0^{P_{m,i}^{n,mask}} \tag{11}$$

where $[x]_0^t=\max(0,\min(x,t))$ and

$$F_{m,i}^{n}\triangleq Bg_{m,i}\times\sum\nolimits_{e=1}^{i-1}\frac{\lambda_{m,e}\alpha_{m,e}^{n}\beta_{m,e}^{n}(ln\,2)^{-1}}{\sigma^2+\sum_{k=e+1}^{\mathcal{L}_m^n}\alpha_{m,k}^{n}P_{m,k}^{n}g_{m,k}+\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}\alpha_{l,b}^{n}P_{l,b}^{n}g_{m,b}}$$

$$Y_{m,i}^{n}=-\alpha_{m,i}^{n,z}g_{m,i}\left(\varphi_{m,i}^{n}-\sum_{e=1}^{i-1}\varphi_{m,e}^{n}\right)$$

Finally, using the sub-gradient method the Lagrange multipliers can be updated as follows [34]

$$\varphi_{m,i}^{n,z+1}=\left[\varphi_{m,i}^{n,z}+\psi_1^z\left(p_{tol}-\alpha_{m,i}^{n,z}P_{m,i}^{n,z}g_{m,i}+\sum_{k=i+1}^{\mathcal{L}_m^n}\alpha_{m,k}^{n,z}P_{m,k}^{n,z}g_{m,k}+\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}\alpha_{l,b}^{n,z}P_{l,b}^{n,z}g_{m,b}\right)\right]^{+} \tag{12}$$

$$\lambda_{m,i}^{z+1}=\left[\lambda_{m,i}^{z}+\psi_2^z\left(R_{i,min}-\sum_{n\in\mathcal{N}}\alpha_{m,i}^{n,z}\hat{R}_{m,i}^{n}\right)\right]^{+} \tag{13}$$

$$\omega_{m,i}^{z+1}=\left[\omega_{m,i}^{z}-\psi_3^z\left(P_{i,max}-\sum_{n=1}^{N}\alpha_{m,i}^{n,z}P_{m,i}^{n,z}\right)\right]^{+} \tag{14}$$

where $[x]^+=\max(0,x)$ and ψ_1^z, ψ_2^z, and ψ_3^z are step size for updating the iterative algorithm.

3.4. Determining position of the UAVs

For any obtained sub-channel assignment matrix, ***A***, and transmit power matrix, ***P***, the UAV's position problem can be formulated as

$$\min_{\boldsymbol{W}}\sum_{m\in\mathcal{U}}\sum_{i\in\mathcal{M}_m}\sum_{n\in\mathcal{N}}\alpha_{m,i}^{n,z}P_{m,i}^{n,z} \tag{15a}$$

s.to:

$$\alpha_{m,i}^{n,z}P_{m,i}^{n,z}\frac{\rho_0}{{h_m}^2+\|W_m-Q_i\|^2}-\sum_{k=i+1}^{\mathcal{L}_m^n}\alpha_{m,k}^{n,z}P_{m,k}^{n,z}\frac{\rho_0}{{h_m}^2+\|W_m-Q_k\|^2}-\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}\alpha_{l,b}^{n,z}P_{l,b}^{n,z}\frac{\rho_0}{{h_m}^2+\|W_m-Q_b\|^2}\ge p_{tol},\forall m\in\mathcal{U},n\in\mathcal{N},i\in\mathcal{M}_m \tag{15b}$$

$$\sum_{n\in\mathcal{N}}\alpha_{m,i}^{n,z}R_{m,i}^{n}\ge R_{i,min},\forall m\in\mathcal{U},i\in\mathcal{M}_m \tag{15c}$$

The original position optimization is a non-convex optimization due to the non-convex constraints in (15b) and (15c). Hence, there is no proper solution to solve this problem optimally. To cope with non-convexity, we convert the non-convex constraints in (15b) and (15c) into the convex forms. Hence, the achievable data rate of users, $R_{m,i}^{n}$, in constraint (15c) can be written as the difference of two functions, i.e., $V_{m,i}^{n}$ and $E_{m,i}^{n}$ as follows

$$R_{m,i}^{n}=B\log_2(1+\Gamma_{m,i}^{n})=B\left(V_{m,i}^{n}-E_{m,i}^{n}\right) \tag{16}$$

where

$$V_{m,i}^{n}=\log_2\left(\sigma^2+\sum_{k=i}^{\mathcal{L}_m^n}P_{m,k}^{n,z}\frac{\rho_0}{{h_m}^2+\|W_m-Q_k\|^2}+\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}P_{l,b}^{n,z}\frac{\rho_0}{{h_m}^2+\|W_m-Q_b\|^2}\right) \tag{17}$$

$$E_{m,i}^{n}=\log_2\left(\sigma^2+\sum_{k=i+1}^{\mathcal{L}_m^n}P_{m,k}^{n,z}\frac{\rho_0}{{h_m}^2+\|W_m-Q_k\|^2}+\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}P_{l,b}^{n,z}\frac{\rho_0}{{h_m}^2+\|W_m-Q_b\|^2}\right) \tag{18}$$

It is cleared that the constraint (15c) is still non-convex because $V_{m,i}^{n}$ is concave and $-E_{m,i}^{n}$ is a convex function with respect to W_m. Hence, by changing the variable $\{T_{m,i}=\|W_m-Q_i\|^2,\forall m,i\}$, the optimization problem is converted into

$$\min_{\boldsymbol{W},\boldsymbol{T}}\sum_{m\in\mathcal{U}}\sum_{i\in\mathcal{M}_m}\sum_{n\in\mathcal{N}}\alpha_{m,i}^{n,z}P_{m,i}^{n,z} \tag{19a}$$

s.to:

$$\alpha_{m,i}^{n,z}P_{m,i}^{n,z}g_{m,i}-\sum_{k=i+1}^{\mathcal{L}_m^n}\alpha_{m,k}^{n,z}P_{m,k}^{n,z}\frac{\rho_0}{{h_m}^2+T_{m,k}}-\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}\alpha_{l,b}^{n,z}P_{l,b}^{n,z}\frac{\rho_0}{{h_m}^2+T_{m,b}}\ge p_{tol},\forall m\in\mathcal{U},n\in\mathcal{N},i\in\mathcal{M}_m \tag{19b}$$

$$\sum_{n=1}^{N}\alpha_{m,i}^{n,z}B\Big(V_{m,k}^{n}-\log_2(\sigma^2+\sum_{k=i+1}^{\mathcal{L}_m^n}P_{m,k}^{n,z}\frac{\rho_0}{{h_m}^2+T_{m,k}}+\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}P_{l,b}^{n,z}\frac{\rho_0}{{h_m}^2+T_{m,b}})\Big)\geq R_{i,min},\forall m\in\mathcal{U},i\in\mathcal{M}_m \tag{19c}$$

$$T_{m,i}\leq\|W_m-Q_i\|^2,\forall m\in\mathcal{U},i\in\mathcal{M}_m \tag{19d}$$

Problem (19) still has a non-convex form with respect to $\boldsymbol{W}$ and $\boldsymbol{T}$ due to the non-convex terms in (19b), (19c), and (19d). To cope with the non-convexity of the problem, we follow the following steps.

- First, $V_{m,k}^n$ should be concave. However, it is neither convex nor concave with respect to W_m, and it is convex with respect to $T_{m,i}$. To solve the problem, the first-order Taylor approximation is applied. With the definition of W_m^{z-1} as 2D position of UAV m at iteration z-1, the lower bound of $V_{m,k}^n$ can be expressed as [35]

$$\begin{aligned}V_{m,i}^n(T_{m,i})\geq\tilde{V}_{m,i}^n(T_{m,i})&=-(\|W_m^z-Q_i\|^2-\|W_m^{z-1}-Q_i\|^2)\\&\times\nabla {B_{m,i}^n}^T(\|W_m^{z-1}-Q_i\|^2)\\&+V_{m,k}^n(\|W_m^{z-1}-Q_i\|^2)\end{aligned} \tag{20}$$

where $\nabla {B_{m,i}^n}^T(T_{m,i})=\frac{P_{m,k}^n\rho_0}{({h_m}^2+T_{m,i})^2}\Big[\ln 2\Big(\sigma^2+\sum_{k=i+1}^{\mathcal{L}_m^n}\frac{P_{m,k}^n\rho_0}{{h_m}^2+T_{m,k}}+\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}\frac{P_{l,b}^{n,z}\rho_0}{{h_m}^2+T_{m,b}}\Big)\Big]^{-1}$.

- Second, in constraint (19b) $g_{m,i}=\frac{\rho_0}{{h_m}^2+T_{m,i}}$ is a convex function with respect to $T_{m,i}$ while it should be concave. By applying the linear approximation to $g_{m,i}^n$ at the given $T_{m,i}^{z-1}$ we have

$$\begin{aligned}g_{m,i}(T_{m,i})\geq\tilde{g}_{m,i}(\|W_m-Q_i\|^2)&=g_{m,i}(\|W_m^{z-1}-Q_i\|^2)\\+\nabla {g_{m,i}}^T(\|W_m^{z-1}-Q_i\|^2)(\|W_m^z-Q_i\|^2&-\|W_m^z-Q_i\|^2)\end{aligned} \tag{21}$$

where $\nabla {g_{m,i}}^T(\|W_m^{z-1}-Q_i\|^2)=\frac{-\rho_0}{\left({h_m}^2+\|W_m^{z-1}-Q_i\|^2\right)^2}$.

- Finally, expression $\|W_m-Q_i\|^2$ is a convex function with respect to W_m while it should be concave. By applying the first approximation at W_m^{z-1}, we have the following equation

$$\begin{aligned}\|W_m-Q_i\|^2\geq&\|W_m^{z-1}-Q_i\|^2\\&+(2(W_m^{z-1}-Q_i))^T(W_m^z-W_m^{z-1})\end{aligned} \tag{22}$$

Thus, the position optimization problem is transformed into

$$\min_{\boldsymbol{W},\boldsymbol{T}}\sum_{m\in\mathcal{U}}\sum_{i\in\mathcal{M}_m}\sum_{n\in\mathcal{N}}\alpha_{m,i}^{n,z}P_{m,i}^{n,z} \tag{23a}$$

s.to:

$$\alpha_{m,i}^{n,z}P_{m,i}^{n,z}\tilde{g}_{m,i}-\sum_{k=i+1}^{\mathcal{L}_m^n}\alpha_{m,k}^{n,z}P_{m,k}^{n,z}\frac{\rho_0}{{h_m}^2+T_{m,k}}-\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}\alpha_{l,b}^{n,z}P_{l,b}^{n,z}\frac{\rho_0}{{h_m}^2+\|W_m-Q_b\|^2}\geq p_{tol},\forall m\in\mathcal{U},n\in\mathcal{N},i\in\mathcal{M}_m \tag{23b}$$

$$\sum_{n\in\mathcal{N}}\alpha_{m,i}^{n,z}B\Bigg[\tilde{V}_{m,i}^n-\log_2(\sigma^2+\sum_{k=i+1}^{\mathcal{L}_m^n}P_{m,k}^n\frac{\rho_0}{{h_m}^2+T_{m,k}}+\sum_{l\in\mathcal{U}\backslash m}\sum_{b\in\mathcal{M}_l}P_{l,b}^{n,z}\frac{\rho_0}{{h_m}^2+T_{m,b}})\Bigg]\geq R_{i,min},\forall m\in\mathcal{U},i\in\mathcal{M}_m \tag{23c}$$

$$T_{m,i}\leq\|W_m(z-1)-Q_i\|^2+\big(2(W_m(z-1)-Q_i)\big)^T\times\big(W_m(z)-W_m(z-1)\big),\forall m\in\mathcal{U},i\in\mathcal{M}_m \tag{23d}$$

Now, problem (23) has the convex optimization feature with respect to $\{\boldsymbol{W},\boldsymbol{T}\}$ that can be solved optimally and effectively by using the CVX solver.

3.5. *Iterative method*

Table II presents the iterative algorithm procedure to solve our optimization problem in (5). In this regard, the problem is solved in the four stages: user association, sub-channel assignment, power allocation, and UAVs' position. In the proposed algorithm, first, initial values for $\boldsymbol{P}$, $\boldsymbol{W}$ and Lagrange multipliers are defined. Then, the above mentioned stages are solved to get the sub-channels, powers and UAVs' position consequently, until the power allocation converges or $\|\boldsymbol{P}^z-\boldsymbol{P}^{z-1}\|\leq\Delta$ where $\Delta\ll 1$.

Table II. Iterative algorithm to solve (5).

```
1. Initialization: z=1, $\boldsymbol{P}^0$, $\boldsymbol{W}^0$, $\varphi^0$, $\lambda^0$, and $\omega^0$
User association
2. Perform the user association according to Table I
Sub-channel assignment
3. Perform the sub-channel assignment based on problem (4) by using CVX and obtain $\boldsymbol{\Gamma}^z$
Power allocation
4. Calculate the transmit power of users based on (11) and obtain $\boldsymbol{P}^z$
UAVs' position
5. Calculate $E_{m,i}^n$ and $\tilde{V}_{m,i}^n$ based on (18) and (20), respectively
6. Compute $\tilde{g}_{m,i}^n$ and approximation of $\|W_m-Q_i\|^2$ based on (21) and (22), respectively
7. Calculate the new position of UAVs by solving the optimization problem (25) and obtain $\boldsymbol{W}^z$
Update
8. Update $\varphi$, $\lambda$ and $\omega$ based on (12), (13) and (14), respectively
9. if $\|\boldsymbol{P}^z-\boldsymbol{P}^{z-1}\|\leq\Delta$
       stop
   else
       Set z=z+1, update the transmit power of users and UAV's position and go back to step 2
10. Output: $\boldsymbol{\Gamma}^z$, $\boldsymbol{P}^z$ and $\boldsymbol{W}^z$
```

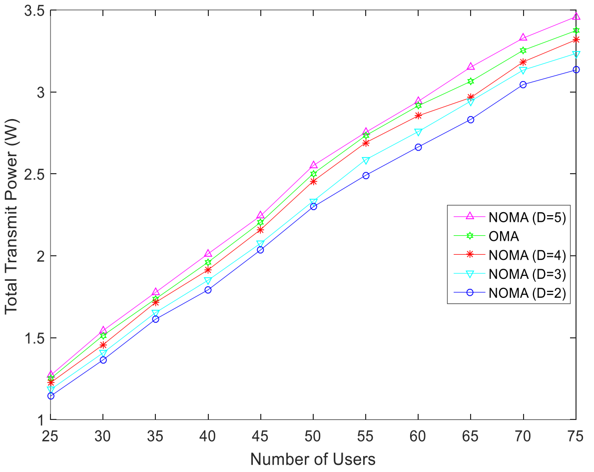

Fig. 2. Total transmit power vs. the number of users.

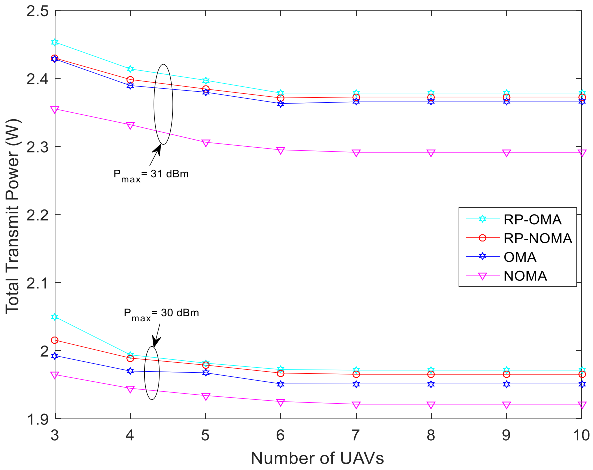

Fig. 3. Total transmit power of users vs. the number of UAVs.

4. Computational Complexity

In this section, we investigate the computational complexity of our proposed iterative algorithm presented in Table II. The proposed optimization algorithm in (5) is divided into four sub-problems: 1) user association based on Table 1, 2) determining the optimal sub-channel assignment, 3) solving power allocation policy problem based on SCALE, 4) determining position of UAVs. For user association, we applied the presented algorithm in Table 1 with $M \times U$ computational complexity. We used CVX optimizer to allocate the sub-channels, which the number of required iterations for this method is $\frac{\log\left((3M+MN+NU)/t^0\varrho\right)}{\log(\xi)}$ where $3M+MN+NU$ is the total number of constraints of the problem (6), t^0 is the initial point for approximated the accuracy of interior point method (IPM), $0<\varrho\ll 1$ is the stopping criterion for IPM and ξ s applied for updating the accuracy of IPM [33].

We applied SCALE approach for the power allocation policy, which power allocation is obtained from (11) with $O(MN)$ computational complexity. For updating the Lagrange multipliers, where the sub-gradient method is applied, the computational complexity is equal to $O(M(N+2))$. Thus, the total computational complexity of the power allocation policy is $M^2N(N+2)$.

When CVX optimization solver is used for UAVs' position, the number of required iterations for this approach is $\frac{\log\left((M(N+1))/t^0\varrho\right)}{\log(\xi)}$ where $M(N+1)$ is the total number of constraints of the problem (23).

5. Numerical Results

In this section, we evaluate the performance of the proposed scheme through the simulations and compare its performance with OMA-based scheme and random position of UAVs in NOMA (RP-NOMA) and OMA (RP-OMA) schemes. We consider a 2D area of 1×1 km^2 where $M=40$ ground users are randomly distributed inside the coverage of the area. The number of UAVs is $U=4$ and assumed to fly at a fixed altitude $h=250$ m. The number of sub-channels and users which can be assigned to each sub-channel are $N=20$ and $D=3$, respectively. We set the maximum power of each user, $P_{i,max}=P_{max}$, to 30dBm, the minimum required data rate for each user, $R_{i,min}$, to 1Kbps, the bandwidth of each sub-channel, B, to 180 kHz, maximum number of sub-channels allocated to each user, G, to 1, channel gain at reference distance $d_0 = 1$ m, ρ_0, to 0.5×10^{-6}, noise power, σ^2, to -125 dB and spectral mask is equal to $P_{m,i}^{n,mask}=P_{i,max}/N$.

To illustrate the impact of the maximum number of users shared on each sub-channel on transmit power of users, in Fig. 2 we provide the total transmit power of users versus the number of users. Generally, by increasing the number of users the total transmit power increases for both proposed and OMA schemes. Also, we can find out that by increasing the number of users shared on each sub-channel, *D*, the transmit power of the proposed scheme increases due to the increased interference so that excessive increase in *D*, e.g., *D*=5, can lead to performance degradation of the NOMA scheme than the OMA scheme. The proposed scheme presents a better performance compared to the OMA in *D* = 2, 3, and 4 in terms of transmit power.

Fig. 3 shows the total transmit power of users versus the number of UAVs for two levels of maximum transmit power. We can see that the total transmit power decreases when the number of UAVs increases from $U=3$ to U=6. This is due to the distance reduction between the users and the UAVs. Also, it is observed that the proposed scheme provide lower power consumption compared to the OMA, RP-NOMA and RP-OMA schemes. Moreover, by increasing the number of UAVs from 6 to 10, the total transmit power is fixed because some UAVs are not used in the system.

The total transmit power of users versus the altitude of UAVs for the proposed, OMA, RP-NOMA, and RP-OMA schemes is illustrated in Fig. 4. It can be observed that transmit power approaches to the allowable maximum transmit power in high altitude.

Fig. 5 shows the total transmit power of users versus the minimum required data rate for each user, $R_{i,min}$ for both proposed and OMA schemes. Generally, the total transmit power increases as the minimum data rate increases for all plotted graphs. Also, increase in the maximum power of users, $P_{i,max}$, the total power consumption increases.

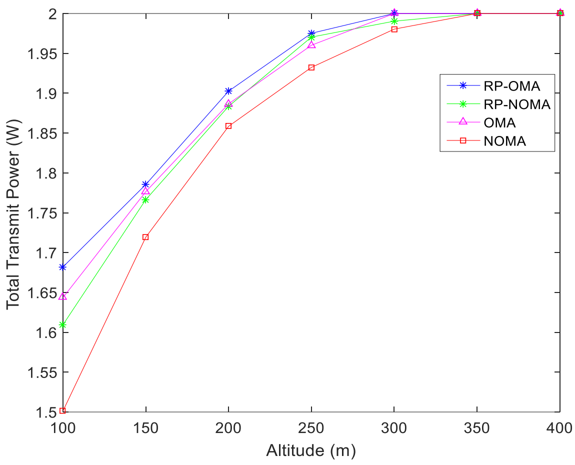

Fig. 4. Total transmit power vs. the altitude of UAVs.

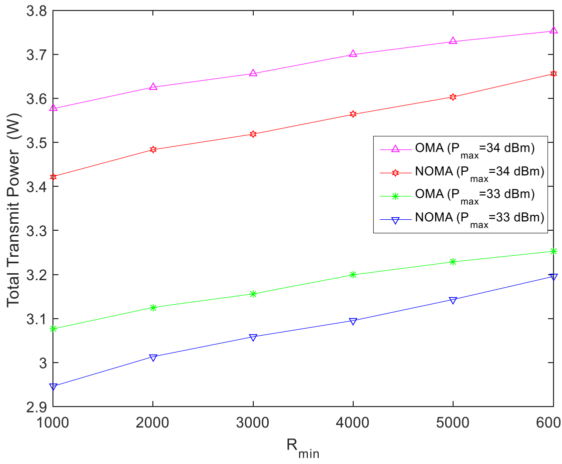

Fig. 5. Total transmit power vs. the minimum required data rate.

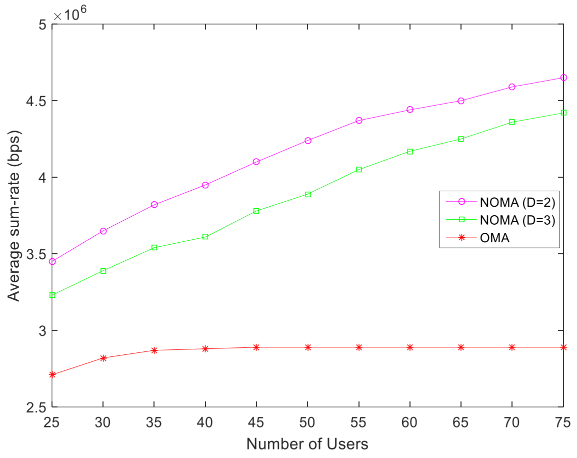

Fig. 6. Average sum-rate vs. the number of users

Fig. 6 illustrates the sum-rate performance versus the number of users where N=10 and U=3. A general observation is that the sum-rate increases as the number of users increases for both NOMA and OMA schemes. Also, we find out that by increasing the maximum number of users shared on each sub-channel, the sum-rate decreases due the increased interference. In addition, it can be seen that the NOMA scheme can support more users compared to the OMA-based scheme.

The sum-rate performance versus the altitude of UAVs for NOMA, OMA and RP-NOMA is shown in Fig. 7. As the altitude of UAVs increases, the distance between the users and UAVs increases, resulting in a reduction in the sum-rate of users. Also, we can see that the proposed scheme by determining the optimal position of UAVs Outperforms the traditional OMA and RP-NOMA schemes in terms of sum-rate performance.

Fig. 8 shows the energy efficiency of the system versus the number of UAVs. It can be observed that by increasing the number of UAVs, the energy efficiency grows from U=3 to U=5 due to decreasing the total transmit power. Then, from U=6 to U=7, the energy efficiency is fixed because the sum-rate and total transmit power are almost fixed.

Finally, in Fig. 9, the convergence of the proposed iterative algorithm presented in Table II for different number of users is provided.

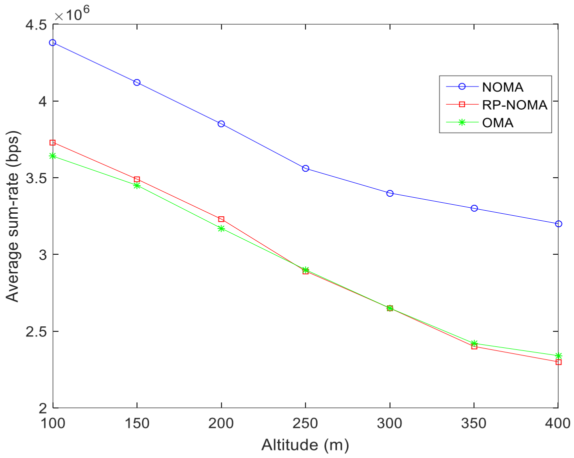

Fig. 7. Average sum-rate vs. the altitude of UAVs

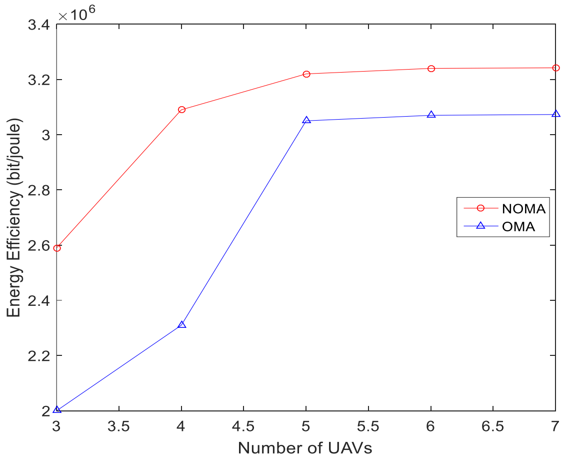

Fig. 8. Energy efficiency vs. the number of UAVs

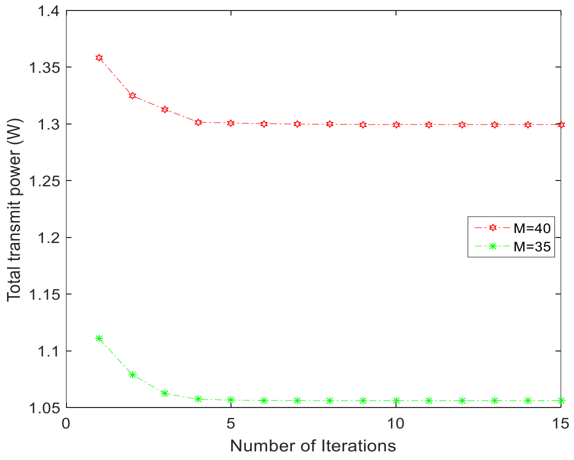

Fig. 9. Convergence behavior of the proposed iterative algorithm

6. Conclusion

In this paper, we studied a NOMA-based multi-UAV wireless communication network. Specifically, the user association, sub-channel assignment, power allocation and UAVs' position were jointly optimized with the objective of the minimizing the transmit power of users subject to NOMA, minimum required data rate, efficient SIC, and transmit power constraints. By utilizing SCA approach and Lagrange dual method, we solved the mixed integer non-convex optimization problem and then an efficient iterative algorithm was proposed. Numerical results showed that the proposed scheme outperforms the traditional OMA, RP-NOMA and RP-OMA schemes in both of the transmit power and sum-rate performance metrics.

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