Subchannel Assignment and Power Optimization in Caching based UAV Networks With NOMA

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***Abstract*—This paper intends to study the energy efficiency in caching based UAV networks, where fog radio access network (FRAN) and non-orthogonal multiple access (NOMA) are considered meanwhile. Taking full account of the impact of caching, subchannel assignment, and power allocation in UAV enabled wireless networks, we formulate the problem of maximizing energy efficiency. In order to better solve the proposed non-convex problem, we propose a subchannel assignment algorithm and a power allocation algorithm applying alternating direction method of multipliers (ADMM). The final simulation section verifies the fast convergence of the algorithm and compares the advantages with existing algorithms.**

I. Introduction

The diversification of unmanned aerial vehicles (UAVs) application scenarios has led to the rapid development of UAV communication technology in the past years. However, the heat of UAVs research is not diminished although there have been many related studies and it is predicted that worldwide shipments of UAVs will increase at a rate of ten times to 67.7 million in 2021 [1]. The promising potentiality in UAVs is inseparable from its rapid deployment, cost-effectiveness, and miniaturization. Meanwhile, the popularization of caching [2] and non-orthogonal multiple access (NOMA) technology [3] in UAV networks will be more eye-catching to better alleviate the transmission pressure of the cellular network with the promotion of fifth-generation (5G) networks.

There have been many studies on UAVs in academia. In [4], researchers mainly optimize the UAV relays placement based on the evaluation standard of power loss and communication outage. Also in the scenario of relay, the paper [5] studied the reliable data link transmission which can support relay control and situational awareness with the consideration of security issues. In particular, by location optimization and performance analysis, the comparisons between multi-hop and dual-hop link in multiple-UAVs system were given in [6]. Considering the diversification of them, the authors in [7] studied the group utility in social networks through power control. In addition, In [8], the authors proposed to research the secrecy rate which is in worst-case through jointly users scheduling and trajectory plan. In [9], a beam tracking method was given in UAV enabled satellite wireless networks.

Although there have been many research results about UAV relay or flying base stations, and power control in NOMA-based cellular network has been researched in [11], the resource allocation in caching based moving UAV with NOMA technology has not been researched systematically. In this paper, we mainly research the subchannel assignment and power optimization in UAV-enabled fog wireless networks considering the circular trajectory which is denoted by the angle between the UAV and the horizontal direction.

The structure of this paper is organized as follows. In Section I, we researched some articles on the existing UAV technology. Section II is about the system model where a caching based UAV wireless network with fixing circular trajectory is proposed. Section III mainly describes the algorithm for subchannel assignment and power optimization. The simulation results are shown and analyzed in Section IV. Finally, a summary is drawn in Section V.

II. System Model and Problem Formulation

A. System Model

A fixed-wing UAV which works as a flying base station is considered in Fig. 1. Meanwhile, F-RAN is integrated into the system to reduce the cost of the fronthaul link and make full use of the storage and computing capacity of edge devices [10]. In order to improve the coverage of the communication, we assume the flight path of the UAV is a fixing circle whose radius is denoted by r_{UAV}. The i-th user being served on the ground can be represented by $i \in \{1, 2, \cdots, I\}$, and there are n subchannels in the downlink NOMA wireless networks where $n \in \{1, 2, \cdots, N\}$. The users in subchannel n is denoted by I_n. Let $I_n \leq \alpha_n$, where α_n denotes the maximum number of users on each subchannel.

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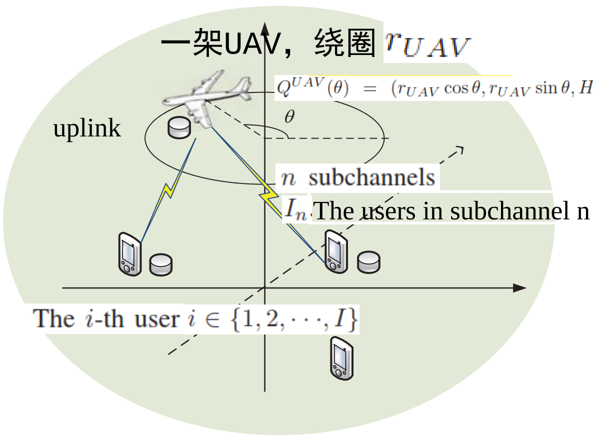

Fig. 1. Proposed UAV Wireless Networks.

Considering the actual scenario, we model the communication process in a three-dimensional Cartesian coordinate system. Users are randomly distributed in a circular range with a radius of 200 meters, and their coordinates can be expressed as $u_i = (x_i, y_i, 0), i \in I$.

The UAV flies in a counterclockwise direction, and the horizontal angle with the x-axis is θ. So the position of the UAV can be expressed as $Q^{UAV}(\theta) = (r_{UAV}\cos\theta, r_{UAV}\sin\theta, H_{UAV})$ where the fixing H_{UAV} denotes the flying height of the UAV.

The distance between user i and UAV can be expressed as

UAV位置 用户位置

$$D_{UAV,i}(\theta) = \left\| Q^{UAV}(\theta) - u_i \right\|_2. \tag{1}$$

Without loss of generality, the channel characteristics in UAV-enabled wireless networks are determined by line of sight (LoS) links. At the same time, assuming that the signal transmission will experience small-scale fading and large-scale path loss, the Doppler effect brought by the flight of the UAV can be compensated at the receiving end. Let $PL^{-1}(d)$ and $g_{l,n}$ denote the path loss function and Rayleigh fading channel gain of l-th user on subchannel n, where d is the distance. So the signal-to-interference-plus-noise ratio (SINR) user can be written by

$$SINR_{l,n} = \frac{p_{l,n}\left|g_{l,n}\ PL^{-1}(D_{UAV,l}(\theta))\right|^2}{\sigma_n^2 + \sum\limits_{i=1, i\neq l}^{I_n} p_{i,n}\left|g_{l,n}\ PL^{-1}(D_{UAV,l}(\theta))\right|^2} \tag{2}$$

干扰只来自于channel gain比当前用户差的用户

where $SINR_{l,n}$ donotes the SINR of l-th user on subchannel n, $p_{l,n}$ and $p_{i,n}$ denote the power of l-th and i-th user on subchannel n, σ_n^2 represents the additive white Gaussian noise (AWGN) [12].

The data rate of user l can be written by

$$r_{l,n} = B\log_2(1 + SINR_{l,n}) \tag{3}$$

The power consumed by the entire UAV wireless network can be written by

$\mathrm{P} = \{p_{i,n}, \forall i, n\}$

$$UT_i(a, p) = p_c + \sum^{N}\sum_{i}^{I_n} a_{i,n}\boxed{p_{i,n}} \tag{4}$$

UAV 消耗的总能量

where p_c represents the power consumed by circuit, $a_{i,n}$ is a binary parameter and $\boxed{a_{i,n} \in \{0, 1\}}$. If user i is allocated to subchannel n, $a_{i,n} = 1$; otherwise $a_{i,n} = 0$. $\mathrm{A} = \{a_{i,n}, \forall i, n\}$

As for the caching strategy, it can be denoted by a binary variable $\boxed{\xi_{UAV,i} \in \{0, 1\}}$. If the UAV caches the requested data by user i, $\xi_{UAV,i} = 1$; otherwise $\xi_{UAV,i} = 0$. For simplicity, the reward of caching strategy of user i can be denoted by $C_i = q_i \xi_{UAV,i}\phi_i$, where q_i denotes the rate of content which the user i is interested in, ϕ_i represents the gain due to the caching strategy. The brought gain can be viewed as the alleviation of bandwidth. $\Im = \{\xi_{UAV,i}, \forall i\}$

The reward of caching strategy of all users can be written by

$$C_{cache} = \sum_{i \in I} C_i = \sum_{i \in I} q_i \boxed{\xi_{UAV,i}}\phi_i \tag{5}$$

UAV是否存储了i需要的文件

However, the content which is cached through the caching strategy can not exceed the maximum cache size C_{UAV} that the UAV has. Let s_i denote content size which requested by user i. So,

$$\sum_{i=1}^{I} \xi_{UAV,i} s_i \leq C_{UAV} \tag{6}$$

content size

B. Problem Formulation

In this subsection, the energy efficiency is formulated as an optimization problem with the consideration of caching strategy, subchannel assignment, and power allocation. Then, the energy efficiency in the fog UAV wireless network can be written by $EE = \sum_I \sum_N \left[(a_{i,n} r_{i,n} + a_{i,n} C_{cache})/UT_i(a,p)\right]$.

Let $\mathrm{A} = \{a_{i,n}, \forall i, n\}$, $\Im = \{\xi_{UAV,i}, \forall i\}$, and $\mathrm{P} = \{p_{i,n}, \forall i, n\}$. This paper mainly aims to optimize the energy efficiency through A, $\Im$, and P, for the purpose of getting an energy-efficient scheme, the optimization problem can be written by

non-convex optimization problem.

$$
\begin{aligned}
\max_{\mathrm{A},\Im,\mathrm{P}} EE = \max \sum_I \sum_N & \frac{\overbrace{\boxed{a_{i,n} r_{i,n}}}^{\text{总data-rate}} + \overbrace{\boxed{a_{i,n} q_i \xi_{UAV,i} \phi_i}}^{\text{cache带来的收益}}}{UT_i(a,p)} \\
s.t. \quad & C1: \xi_{UAV,i} \in \{0,1\}, \forall i \\
& C2: a_{i,n} \in \{0,1\}, \forall i, n \\
& C3: p_{i,n} > 0, \forall i, n \\
& C4: r_{i,n} \geq r_{\min}, \forall i, n \quad \text{minimum data rate of users} \\
& C5: \sum_{n=1}^{N} \sum_{i=1}^{I_n} a_{i,n} p_{i,n} \leq p_{\max} \\
& C6: \sum_{i=1}^{I} \xi_{UAV,i} s_i \leq C_{UAV}
\end{aligned}
\tag{7}
$$

Constraint $C1$ and $C2$ in problem (7) represent the factor of cache strategy and subchannel assignments. Constraint $C3$ limits the minimum power of the user i. Constraint $C4$ guarantees the minimum data rate of users. Constraint $C5$ gives the maximum power limit of total UAV wireless network which is denoted by $p_{\max}$. Constraint $C6$ ensures that the cache strategy is limited to a fixed range that UAV has.

The above optimization problem can not be solved directly. Firstly, there are two binary variables $a_{i,n}$ and $\xi_{UAV,i}$, which cause integer constraints; secondly, if the binary constraint problem is solved, the power allocation of the UAV is still a non-convex optimization problem. Therefore, problem (7) is a non-convex problem including integer which can be solved through the following sections.

III. Proposed Algorithm

For simplicity, each user can cache assuming the network has enough space for cache. And it can be denoted by $\xi_{UAV,i} = 1, \forall i$. Let $\tilde{C}_{cache}$ denote the reward when $\xi_{UAV,i} = 1, \forall i$. And the problem (7) can be rewritten by

忽略缓存空间限制不太合理

$$
\begin{aligned}
\max_{\mathrm{A},\mathrm{P}} EE = \max \sum_I \sum_N & \frac{a_{i,n} r_{i,n} + a_{i,n} \tilde{C}_{cache}}{UT_i(a,p)} \\
s.t. \quad & C2, C3, C4, C5
\end{aligned}
\tag{8}
$$

The above relaxation of binary variable solves the problem of integer constraints in $C1$. Then the next two subsections mainly study subchannel assignments A and power allocation scheme P.

A. Subchannel Assignment in UAV Wireless Networks

The subchannel assignment scheme in the traditional NOMA-based wireless networks is suitable for the NOMA-based UAV wireless networks, but unlike the traditional scheme, this paper proposes a matching and swapping algorithm to give a better subchannel allocation scheme with an acceptable complexity.

Considering a total of I users and N subchannels in proposed UAV wireless networks, let α_n limit the maximum number of users allocated to each subchannel to reduce the algorithm complexity, so $I = \sum_N \alpha_n$. Let I_n denotes the users number matched with subchannel n.

This algorithm consists of two parts: *matching process* and *swapping process*. This means that users are matched firstly according to the preference list, and then swapped according to the principle of *swapping process*.

1) Matching Process: The matching here is a many-to-many matching process. Assuming that user i generates a preference list $List^i_{prefer}$ based on subchannel state information, user i will first match with subchannel n if this subchannel is in $List^i_{prefer}$. The matching process traverses all users. If the number of matching users of a subchannel has exceeded the maximum limit α_n, then system will choose the two most suitable users who send the request. The termination condition of the above process is

$$
\{List^{users}_{unmatch}\} = 0 \tag{9}
$$

where $\{List^{users}_{unmatch}\}$ denotes unmatched users.

2) Swapping Process: The swapping is on the basis of *matching process*. There will be α_n users on each subchannel after the *matching process*. However, these results are not optimal. Through the following introduction, we will give a better assignment.

Definition 1: Assuming that the users matched with subchannel N_1 are $\{x_1, x_2 \cdots x_{\alpha_n}\}$ and the users matched with subchannel N_2 are $\{y_1, y_2 \cdots y_{\alpha_n}\}$, user x_1 and y_1 can form a swapping pair $\Psi(x_1 y_1)$ if the following conditions are met after the swapping:

(1) $r^s_{x_1,N_2} \geq r_{x_1,N_1}$.
(2) $r^s_{y_2,N_1} \geq r_{y_2,N_2}$.
(3) $r^s_{x_\alpha,N_1} \geq r_{x_\alpha,N_1}$.
(4) $r^s_{y_\alpha,N_2} \geq r_{y_\alpha,N_2}$.

where $\alpha \in \{1, 2, \cdots, \alpha_n\}$. Condition (1) and (2) ensure that the data rate of the two users after the swapping is improved. Condition (3) and (4) indicate that the swapping will not make the data rate of users on co-channels smaller. Only the above four conditions are

Algorithm 1 Matching and Swapping Algorithm for Subchannel Assignment in UAV Wireless Networks

Initialize preference lists of all users: $List^{i}_{prefer}$,$\forall i \in I$.
Step 1: ***Matching Process***
while Equation (9) is not satisfied **do**
  for each $\forall i \in I$ **do**
    Match with the subchannel in $List^{i}_{prefer}$.
    if $I_n < \alpha_n$ **then**
      The user is matched successfully.
    end if
    if $I_n = \alpha_n$ **then**
      Choose α_n users which can yield maximum EE.
    end if
  end for
end while
Get suboptimal results of users matching.
Step 2: ***Swapping Process***
repeat
  Calculate and count swapping pairs.
  Exchange two users in a swapping pair Ψ.
until $\Psi_{all} = 0$

met at the same time, the swapping pair will be formed and the swapping will proceed.

This definition implies that if there is any swapping pair, the rate of swapped and un-swapped users will not decrease at least. The collection of all swapping pairs is denoted by Ψ_{all}. Only the above two conditions are met at the same time, the swapping pair will be formed and the swapping will proceed. These conditions imply that if there is any swapping pair, the rate of swapped and un-swapped users will not decrease at least. Then exchange users until the swapping pair is 0. Based on the above discussion, the process of subchannel assignment is summarized as algorithm 1.

B. Power Optimization via ADMM

The subchannel assignment matrix A can be gotten in the previous subsection. Then, let $\Delta\tilde{C}$=$\tilde{a}_{i,n}r_{i,n} + \tilde{a}_{i,n}\tilde{C}_{cache}$, and the problem (8) can be rewritten by

$$\begin{aligned} \max_{\mathrm{P}} EE = \max \sum_{I}\sum_{N} \frac{\Delta\tilde{C}}{UT_i(\tilde{a},p)} \\ s.t. \quad \sum_{n=1}^{N}\sum_{i=1}^{I_n} \tilde{a}_{i,n}p_{i,n} \le p_{\max} \\ C3, C4 \end{aligned} \tag{10}$$

Due to the quick convergence, ADMM is a very good solution for convex optimization problems such as power allocation and optimization in this paper. It is usually used to solve problems as is shown below.

$$\min_{\mathrm{X,Z}} f(\mathbf{x}) + g(\mathbf{z}) \tag{11}$$

Algorithm 2 Power Allocation of Users in UAV Wireless Networks

Initialize the subchannel assignment matrix A in NOMA-based UAV wireless networks, set $t = 0$, and initialize $\mathbf{x}^0_{UAV}, \mathbf{z}^0_{UAV}, \mu^0_{UAV}$, initialize the threshold of algorithm stop criterion ς.
repeat
  Calculate and update $\mathbf{x}^{t+1}_{UAV}$through equation (19).
  Calculate and update $\mathbf{z}^{t+1}_{UAV}$ through equation (20).
  Calculate and update μ^{t+1}_{UAV} through equation (21).
  $t \leftarrow t + 1$
until $\left\|\mathbf{x}^{t+1}_{UAV} - \mathbf{x}^{t}_{UAV}\right\|_2 \le \varsigma$

$$s.t. \ \mathrm{A}\mathbf{x} + \mathrm{B}\mathbf{z} = \mathbf{c} \tag{12}$$

In order to convert to the scaled form of ADMM, we introduce auxiliary matrixes $\mathbf{x}_{UAV}, \mathbf{z}_{UAV}$. The matrix $\mathbf{x}_{UAV}$ consists of power allocation values of each users, and the relationship between $\mathbf{x}_{UAV}$ and $\mathbf{z}_{UAV}$ is a one-to-one correspondence. Introducing function f_{UAV} and $g(\mathbf{z}_{UAV})$ here,

$$f_{UAV} = -\left[\sum_{I}\sum_{N}\left(\tilde{a}_{i,n}r_{i,n} + \tilde{a}_{i,n}q_i\phi_i\right)\right]/UT(\tilde{a},p). \tag{13}$$

$$g(\mathbf{z}_{UAV}) = \left\{ \begin{array}{l} 0, \mathbf{z} \in \Phi \\ +\infty, otherwise \end{array} \right\} \tag{14}$$

where

$$\Phi = \left\{ \begin{array}{l} p_{i,n} > 0, \forall i, n \\ r_{i,n} \ge r_{\min}, \forall i, n \\ \sum\limits_{I}\sum\limits_{N} \tilde{a}_{i,n}p_{i,n} \le p_{\max}, \forall i, n \end{array} \right\} \tag{15}$$

Then the power allocation problem in this subsection can be transformed into:

$$\min_{\mathbf{x}_{UAV},\mathbf{z}_{UAV}} \left\{ f_{UAV}(\mathbf{x},\tilde{\mathbf{A}}) + g(\mathbf{z}) \right\} \tag{16}$$

$$s.t. \ \mathbf{x} - \mathbf{z} = 0 \tag{17}$$

The scaled augmented Lagrangian can be given as equation (18) and iterative steps of power allocation can be denoted by equation (19), (20), and (21), where μ is the scaled dual variable.

Based on the proposed iterative steps, the algorithm 1 of power optimization in NOMA-based UAV wireless networks can be obtained.

$$L_\rho(\mathbf{x},\mathbf{z},\mu) = -\left[\sum_I \sum_N (\tilde{a}_{i,n} r_{i,n} + \tilde{a}_{i,n} q_i \phi_i)\right] / UT(\tilde{a},p) + g(\mathbf{z}) - (\rho/2)\|\mu\|^2 + (\rho/2)\left\|\mathbf{x} - \mathbf{z} + \mu\right\|_2^2 \tag{18}$$

$$\mathbf{x}_{UAV}^{t+1} = \arg\min_{\mathbf{x}_{UAV}} \left\{ -\left[\sum_I \sum_N (\tilde{a}_{i,n} r_{i,n} + \tilde{a}_{i,n} q_i \phi_i)\right] / UT(\tilde{a},p) + (\rho/2)\left\|\mathbf{x}_{UAV} - \mathbf{z}_{UAV}^t + \mu_{UAV}^t\right\|_2^2 \right\} \tag{19}$$

$$\mathbf{z}_{UAV}^{t+1} = \arg\min \left\{ g(\mathbf{z}_{UAV}) + (\rho/2)\left\|\mathbf{x}_{UAV}^t - \mathbf{z}_{UAV} + \mu_{UAV}^t\right\|_2^2 \right\} \tag{20}$$

$$\mu_{UAV}^{t+1} = \mu_{UAV}^t + \mathbf{x}_{UAV}^{t+1} - \mathbf{z}_{UAV}^{t+1} \tag{21}$$

IV. Simulation Results

In this section, the data and results of simulation experiments through MATLAB are presented. In addition, we also give some parameters about UAV in this simulation and analyze the simulation data to see the rationality and superiority of the proposed solution. The flying height of UAV keeps unchanged at $H_{UAV} = 100$ m. The radius of the flight trajectory of the UAV is $r = 100$ m.

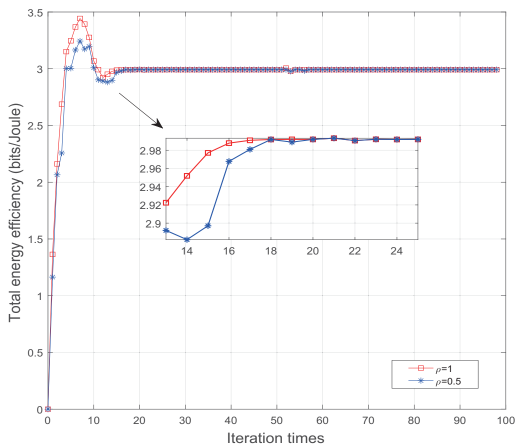

Fig. 2. Comparison of algorithm convergence with different ρ.

Fig. 2 presents the convergence when $\rho = 1$ and $\rho = 0.5$. It can be seen that both schemes can achieve convergence after satisfying a certain number of iterations. In terms of speed, the former is approaching convergence sooner.

In Fig. 3, we compare the proposed ADMM-based algorithm with the existing algorithm. The optimized

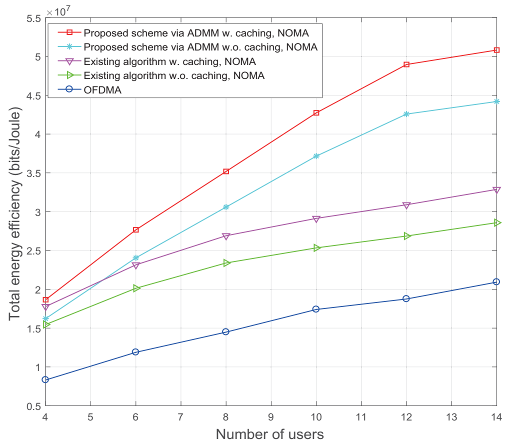

Fig. 3. Total energy efficiency with users of different number, $\rho = 1$, $\theta = \pi$ and the power of UAV is 8 Watt.

power allocation scheme by ADMM can improve the energy efficiency of the total networks, and the effect after adding the cache will be better. As the number of users increases, the energy efficiency will increase gradually. Fig. 4 shows the energy efficiency when the angle changes from 0 to 2π. It can be seen that the proposed algorithm can improve energy efficiency at all angles. The slight decrease in the curve at the middle position is because of the increased path loss which is caused by the remote location between the UAV and the user.

V. Conclusions

This paper investigated a caching based UAV networks with NOMA technology where the UAV flies along a circular trajectory. Specifically, the subchannel

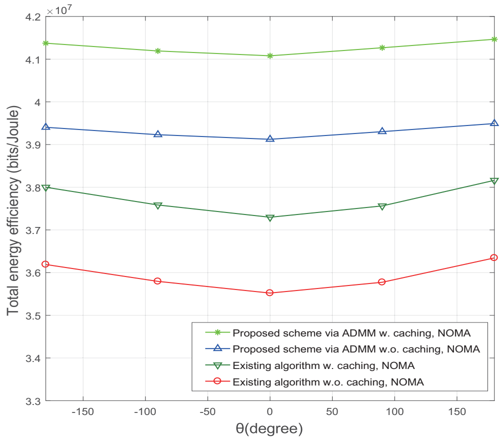

Fig. 4. Total energy efficiency about different θ, the number of users is 10 and the power of UAV is 8 Watt.

assignment, power allocation and caching strategy are considered through maximizing the total energy efficiency in proposed UAV wireless networks. In order to solve the problem, we proposed a new matching and swapping algorithm based on the existing matching theory to allocate subchannels and used ADMM scheme to optimize the power. Finally, the simulation were used to prove the rationality and superiority of the scheme proposed in this paper.

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