Resource Allocation for Optimizing Energy Efficiency in NOMA-based Fog UAV Wireless Networks

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Abstract

Due to their advantages in rapid deployment and miniaturization, unmanned aerial vehicles (UAVs) have been widely used in various fields, especially for disaster scenarios which require emergency communications. This article considers a fog UAV wireless network and focuses on improving the energy efficiency through subchannel assignment and power allocation. Specifically, in order to make better use of the limited spectrum resources, this article considers integrating non-orthogonal multiple access (NOMA) which is widely recognized as an emerging transmission technology into UAV wireless networks. On the basis of the proposed UAV network architecture, a two-sided matching and swapping algorithm is proposed to optimize subchannel assignment. Besides, we provide a power allocation method to maximize energy efficiency. Simulation results show that the proposed UAV system architecture, as well as the resource allocation method can prominently improve the energy efficiency of fog UAV wireless networks.

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I. Introduction

Unmanned aerial vehicles (UAVs) have been unprecedentedly developed and received much attention in both industry and academia. Initially, the emergence of UAVs was used to detect or destroy enemy in military affairs. But the quick development of their miniaturization, lower cost of construction, and better controllability make UAVs increasingly applicable in disaster and civilian field [1]. However, there are some constraints such as limited spectrum resources and data traffic in wireless networks, most existing techniques can not solve these problems properly. In this article, we study the resource allocation in a fog UAV wireless network, where the UAV serves as a temporary mobile base station (BS) to achieve a movement of the wireless network coverage area and the fog can bring gain in data rate or network traffic [2] [3]. It is noted that fog UAV wireless networks are becoming more adaptable than fixed BSs, thanks to the flexibility in deployment, as well as the low cost of construction [4].

As an enhanced evolutionary scheme for cloud radio access network (CRAN), fog radio access network (FRAN) pays more attention to storage and computing functions of edge devices which are close to users [5]. The fog computing aims to reduce response time through processing units located in the edge of network, which can better alleviate latency and support various applications in next generation networks [6] [7].

A lot of transmission schemes in UAV wireless network for multiple users have been proposed, mainly for an orthogonal transmission. Significantly improving the spectrum efficiency of network seems to be particularly vital for the new wireless communication system. To accommodate the demand of spectrum resources, the appearance of non-orthogonal multiple access (NOMA) [8] and multiple-input multiple-output (MIMO) [9] are considered as a method for effectively utilizing limited spectrum resources and can yield a better effect in terms of sum-rate, energy efficiency, and coverage. A subchannel in NOMA can be occupied by multiple communication equipments which is different from orthogonal frequency division multiple access (OFDMA) systems. The basic idea of NOMA is to adopt the non-orthogonal transmission mode to transmit signals and then eliminate the interference at the receiver through the successive interference cancellation (SIC) technology. In this way, the downlink NOMA network using SIC technology can not only improve the network capacity but also has a better throughput performance.

Although there are some studies concentrating on the UAV wireless network, what they mainly study is about mobile relay [10] or path planning [11]. The authors in [10] considered a UAV as a flying relay to provide communication service for two users on the ground and achieve significant throughput gains over static relaying. The authors in [11] provided an operational path planning method for UAVs by using a parallel implementation. In particular, the authors in [12] considered the flight safety and security of UAVs which work as fog nodes in a fog UAV wireless network. NOMA technology is applied to UAV wireless networks in [13], where the authors considered resource allocation in wireless backhaul to optimize the sum rate. However, the energy consumption problem in UAV wireless networks has become increasingly important with the increase of network traffic. Therefore, how to achieve communication under the premise of energy conservation is a top priority. To the best of our knowledge, the resource allocation in NOMA-based fog UAV wireless networks has not been well studied yet. In this article, we are devoted to solving the problem through subchannel assignment and the allocation of power resource. The main contributions of this article are as follows.

- We propose a novel UAV system architecture where FRAN and NOMA coexist. In the presented UAV wireless networks, this paper considers NOMA-based UAV to relieve limited spectrum resources, and introduces fog-based caching technology to release link and traffic burden. Accordingly, these together form a network with a high energy efficiency.
- The allocation of subchannel is converted into a two-sided matching process based on matching theory. A two-sided matching and swapping algorithm is proposed to optimize the energy efficiency of UAV wireless networks. Additionally, the algorithm is described in detail to verify the superiority of this algorithm, including analysis of complexity and simulations.
- The proposed power allocation problem is non-convex, we solve it through transforming it into a convex optimization one with the difference of convex (DC) programming. Then, this problem can be solved and a suboptimal power allocation method is obtained iteratively with convex optimization knowledge. Finally, simulation results show the superior of the method given in this article.

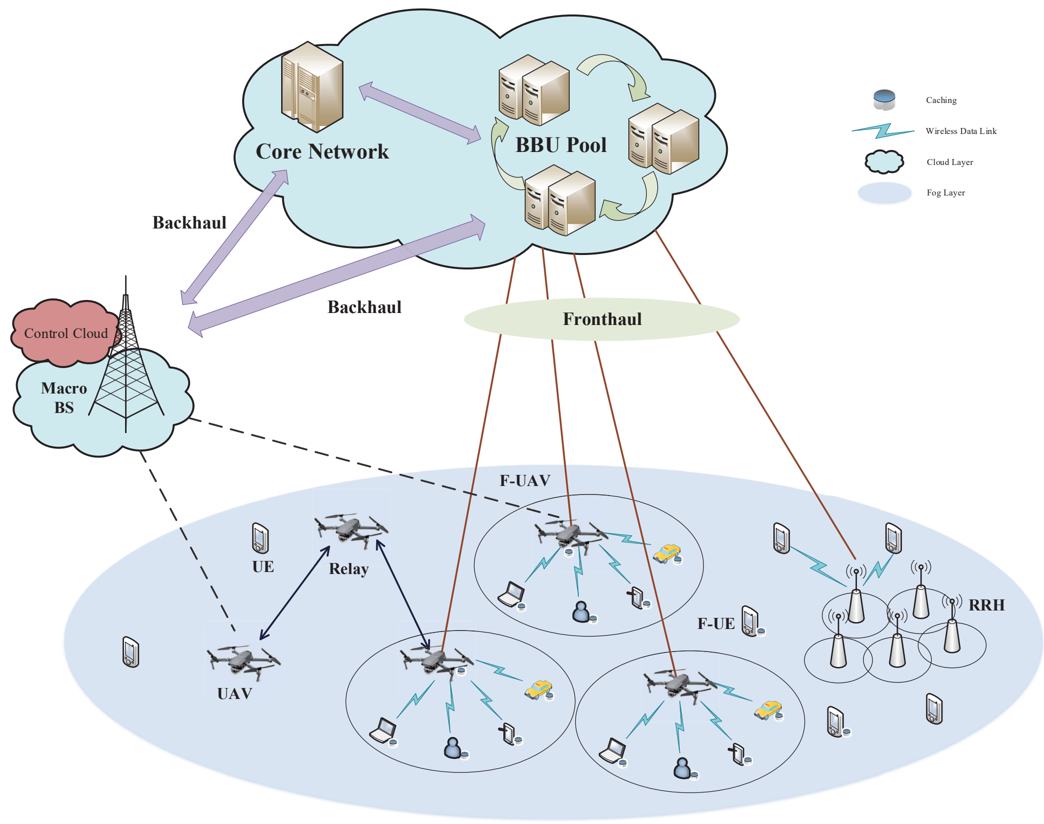

Fig. 1. The network architecture in NOMA-based fog UAV wireless network.

II. System Architecture

The architecture of fog UAV wireless networks is depicted in Fig. 1, where multiple UAVs provide service support for ground users. A UAV relay can be applied to forward the data information which comes from the signal source. For simplicity, assuming that UAVs placement is optimized and will not exceed a specific range. All signal processing units work centrally in the baseband unit (BBU) pool where they can share the signaling, data, and channel status information (CSI) of the entire network. The macro BS assumes the functions of the control platform to transmit control signaling and reference signals for fog user equipments (F-UEs) [14]. UAVs and macro BS can be treated as the edge communication entities. In addition, the macro BS can provide wide coverage for F-UEs with high mobility, thereby reducing unnecessary handovers and mitigating synchronization restrictions.

In Fig. 1, UAVs are used as mobile BSs to process and transmit the data received from others. Multiple adjacent UAVs can interact to form various kinds of topologies. UAVs are connected to BBU pool which processes the signal transmitted by fronthaul links which can use millimeter wave technology, while backhaul links are used to connect the macro BS and BBU pool. Meanwhile, BBU pool is located in cloud layer. CRAN always has a long delay during transmission and heavy traffic on fronthaul. Unlike CRAN, remote radio heads (RRHs) are put there to share the signals waiting for processing in BBU pool, thus the burden on fronthaul will be greatly reduced.

UAVs are treated as simple RRHs which deliver data sent from users to BBU pool to maximize the gains of collaboration radio signal processing (CRSP) and cooperative radio resource management (CRRM). Moreover, certain functions of CRSP and CRRM in FRAN are shifted to UAVs and F-UEs, which obviously weaken the constraints of fronthaul in CRAN. In addition, the distributed CRSP and CRRM can reduce the interference between adjacent UAVs. Also, to keep away from the burden that the data and traffic may be offloaded from the cloud server directly, some of them can be transmitted from near RRHs like UAVs.

Normally, contents with high popularity are storaged at the edge of the network preferentially and users do not need to obtain them from traditional remote data centers, which can reduce data traffic and network burden of backhaul and fronthaul links. It is noted that what contents users choose to cache is not random, the caching strategy like first-in and first-out can be very beneficial in improving overall network capacity considering the limited cache space of edge devices. If some users cache content which is highly similar to other users, it is not necessary for all users to upload individually, and the caching utilization in this way can save time, cache space, and traffic while providing easy access for all users. Also, if the cache of F-UEs of fog UAV reaches the upper limit, task service can offload from edge equipments instead of centralized caching cloud. Meanwhile, in order not to let the traffic be offloaded directly from the centralized caching cloud, a little data traffic can be transmitted from F-UEs, which can also save spectrum and reduce delay.

III. Resource Allocation in NOMA-based Fog UAV Wireless Network

The emergence of UAVs provides new ideas for the solution to alleviate the transmission pressure brought by the popularity of wireless applications. Indeed, many researchers begin to pay more attention to the development of UAV communication, mainly in terms of coverage or path optimization. However, in UAV wireless networks, what should be considered are more than a wider coverage or a higher spectrum efficiency, but also includes a more efficient way to allocate the limited resource with the increasing attention to the resource utilization and power constraints. Therefore, this article mainly focuses on the optimization of power allocation to have a higher energy efficiency in fog UAV wireless networks. Meanwhile, considering the constraints of transmission power and the data rate, the energy efficiency can be formulated. The procedure of subchannel and power resource allocation is shown in Fig. 2. On the basis of traditional two-sided matching procedure, a swapping procedure is proposed to achieve a better result. It is noted that the flying UAV can have a bad influence on the UAV-ground channel. Therefore, this paper studies the resource allocation after the position of UAV is optimized. That means when the user’ s position is fixed and known by UAV, an optimal UAV placement which can provide maximum coverage and better communication quality can be obtained. The search for this placement depends on the coverage and outage probability in simulation scenario.

A. NOMA Technology based UAV Wireless Networks

Unlike OFDMA technology, a subchannel can be shared by many users using non-orthogonal spectrum [15]. The user signal can be extracted successfully through the received signals by using SIC technology. Assuming that there are four users in one subchannel in the downlink wireless network of NOMA-based UAV communication system. Through uplink, the UAV receives X which consists of signals of all users and extra noise. In this scene, the channel response normalized by noise (CRNN) order of user equipments in the same subchannel can be treated in an ascending order as UE_1^{CRNN} , UE_2^{CRNN}, UE_3^{CRNN}, UE_4^{CRNN}. According to channel conditions, users who have a better channel condition can eliminate the interference from users who have the poor channel condition. Thus, the signal of User1 will be detected and decoded first for its minimal CRNN. When it is the turn of User2, system will first eliminate User1 and then the signal of User2 can be decoded. Similarly, the signal of User3 can be also decoded. At last, when the first three users are decoded in order by SIC technology, the last one can be decoded easily. However, users assigned to each subchannel are often limited because the design

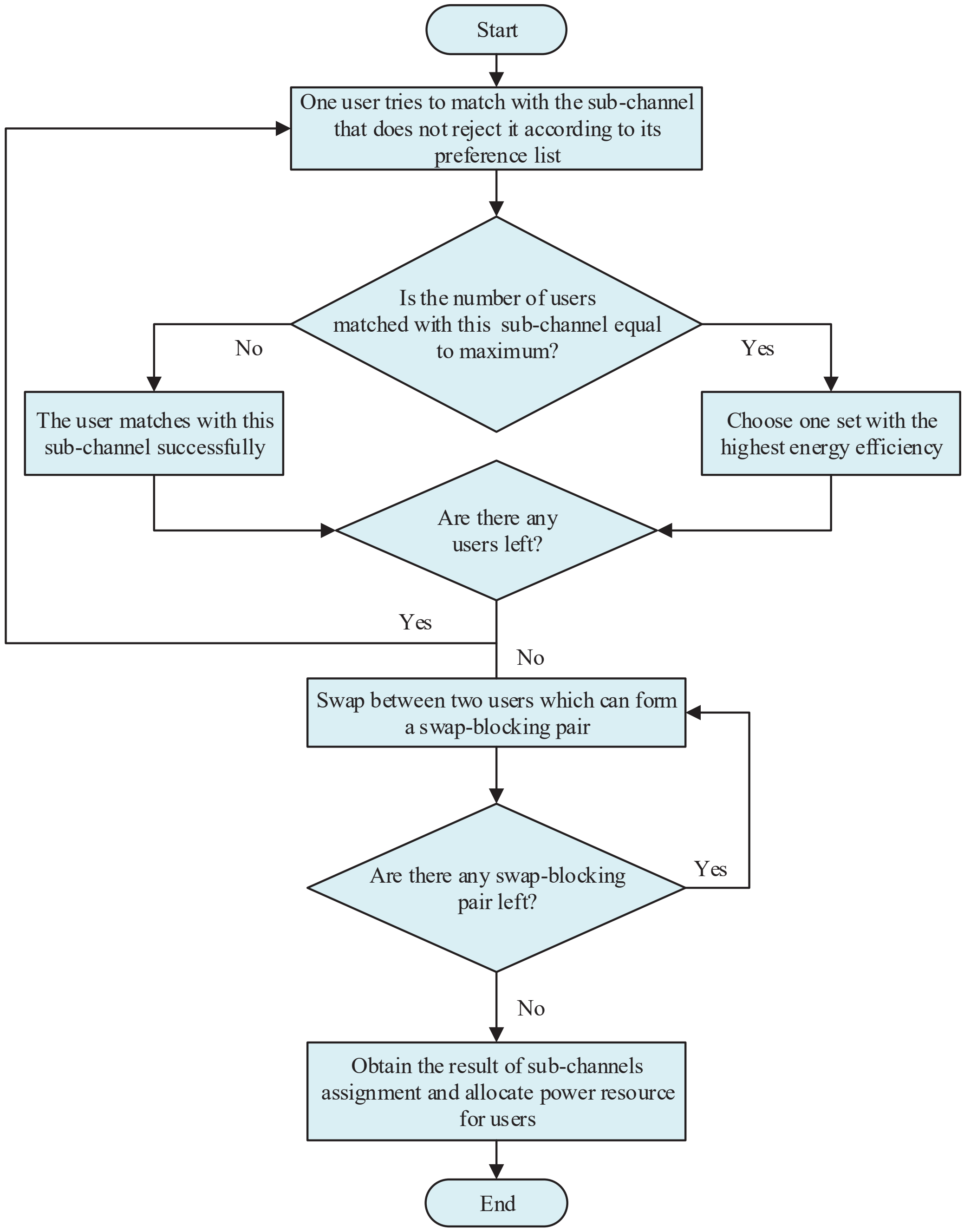

Fig. 2. The energy-efficient resource optimization procedure.

requirements of SIC receiver for multiple users are complex to achieve.

B. Subchannel Assignment in UAV Wireless Networks

The assignment of subchannel can be considered a two-sided matching procedure according to the preference lists of both subchannels and users. To describe the relationships between users and subchannel easily, it can be supposed that each one of them has its own preference list. Assuming that there are M users and N subchannels in the downlink network of a UAV wireless network, where the UAV knows every aspect of the CSI. It is noted that each subchannel could be matched with multiple users but only one subchannel that one user can match. In order to get a low-complexity matching procedure, each subchannel can not have more than $\alpha_{\max}$ users at most.

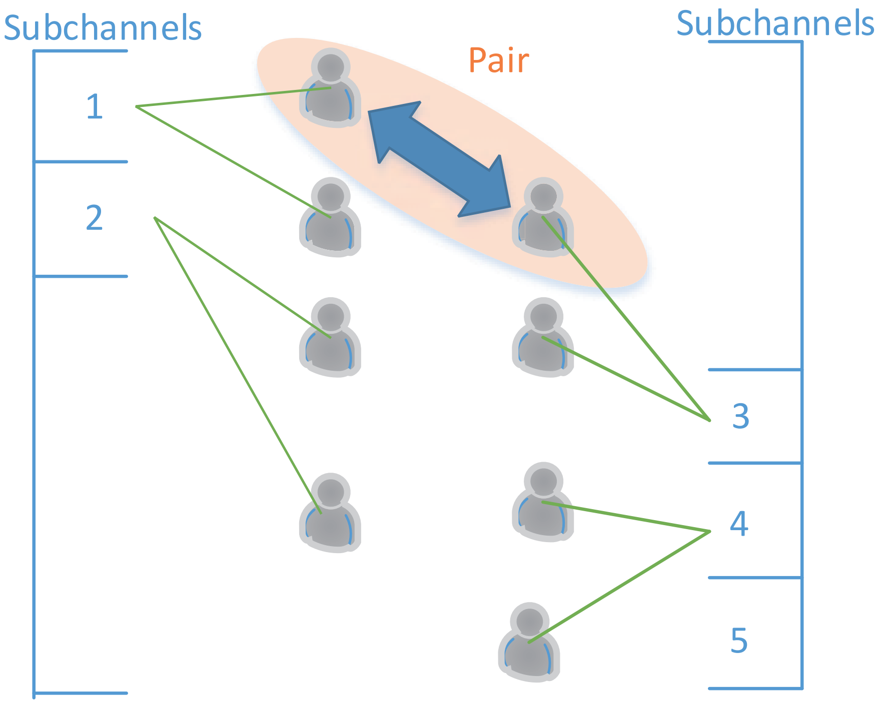

Fig. 3. The process of swapping.

To achieve an optimal effect with a feasible matching procedure, a two-sided matching and swapping algorithm can be given as follows. In the two-sided matching algorithm, each user will initialize its own preference list based on the data rate and achieved channel gain. Once each user has a preference list, a matching request will be sent to subchannels, and then the user and preferred subchannel can form a matching pair. Because of the limited users on each subchannel, the subchannel can receive users up to $\alpha_{\max}$. If the number is less than $\alpha_{\max}$, the subchannel will receive the request and match with the user. Otherwise, it will choose $\alpha_{\max}$ users which can satisfy the maximum energy efficiency, then reject other requests. These rejected users are put into the list unmatched successfully and then start their new request to subchannels which do not reject them until the list has no user. The first part ends here and outputs a preliminary result of subchannel matching. It has to say that the result of the whole process above is sub-optimal, although it complies with the preference list of users with a certain limit.

The swapping process means exchanging two users which are matched in the first part. There are two points in the swapping process: 1) The swapping process happens only between two users on different channels at a time, while the state of other users and subchannels remain unchanged; 2) The purpose of this swapping is for better gains, so the energy efficiency of all participating players can not be reduced after each successful swapping. If two users can form a swapping pair, it means that the energy efficiency of at least one user in this pair will have a promotion and others can not have any decrease after every swapping. In swapping process, matched users search users on the other subchannels to form a swap-blocking pair if they can meet the above conditions as shown in Fig. 3. The number of swappings between two users can not exceed 2 to prevent unnecessary looping.

Considering the complexity of this algorithm, the value of $\alpha_{\max}$ can be equal to 2 to simplify the calculation, and an acceptable complexity can be obtained when the number of users is limited. It is noted there are two main differences in subchannel assignment from previous work [15]. The first is that this article adds a swapping process to get a better result on the basis of traditional two-sided matching. The second is the swapping process is based on the maximization of energy efficiency rather than the data rate. Thus, users can be assigned to the UAV through subchannels.

C. Power Allocation in UAV Wireless Networks

Applying NOMA technology to UAV wireless network has made progress in the utilization of limited spectrum resources. The addition of FRAN would improve the performance of overall network especially in the data rate and caching ability. As society' s attention to energy increases, the total energy eficiency is a problem that needs to be considered. Thus, we mainly pay attention to maximizing the total energy efficiency considering the limited transmitted power in this section.

- UAV placement. The changing location of UAVs and the presence of airborne obstacles all have an impact on the UAV-ground channel. In general, the proper placement or trajectory design based on the time-varying division is beneficial for resources management in UAV networks. For simplicity, this article assumes that the flight range is an optimized position where UAVs can achieve a maximum wireless coverage. So the impact on channel is ignored considering the limited range and small change, and this article mainly focus on subchannel assignment and power allocation.
- Caching model. The data and information stored in the edge of system networks can bring reward from the utilization of caching strategy. The caching strategy makes sense if the content is stored in UAVs or F-UEs with caching capabilities, especially for the improvement of data rate and the reduction of delivery latency. The gain brought by the caching is considered as part of the objective function here which can be denoted by $r_m g_{cache}$, where r_m denotes the rate of the requested content and g_{cache} denotes the revenue from caching contents.
- Energy efficiency. Directly, the maximum achievable energy efficiency of UAV wireless network is regarded as the optimization function. The traditional energy efficiency function can be expressed as the ratio of effective capacity to power consumed. Accordingly, we add the caching reward to the numerator mentioned in the previous paragraph. Since the above power optimization problem is a non-convex problem considering the upper limit of transmitted power of UAV, it could be converted to a convex one using convex optimization knowledge and solved iteratively through DC programming. DC programming is a way to solve the convex optimization problem by transforming the objective function into a subtraction form.

D. Simulation Results

In this subsection, we present the feasibility of the proposed resource allocation method by analyzing the data results from simulation experiments. The height of UAVs is fixed at 100m, and users are randomly located within a radius of 300m. The power spectral density of noise is set to be -110 dBm/Hz, and -60 dBm is the channel gain. Particularly, the UAV transmitted power is 8 Watt in Fig. 5 and the users number in Fig. 6 is 50. The distance between UAVs is set very far, so this paper ignores the interference between UAVs and focuses on the resource allocation strategy of a single UAV.

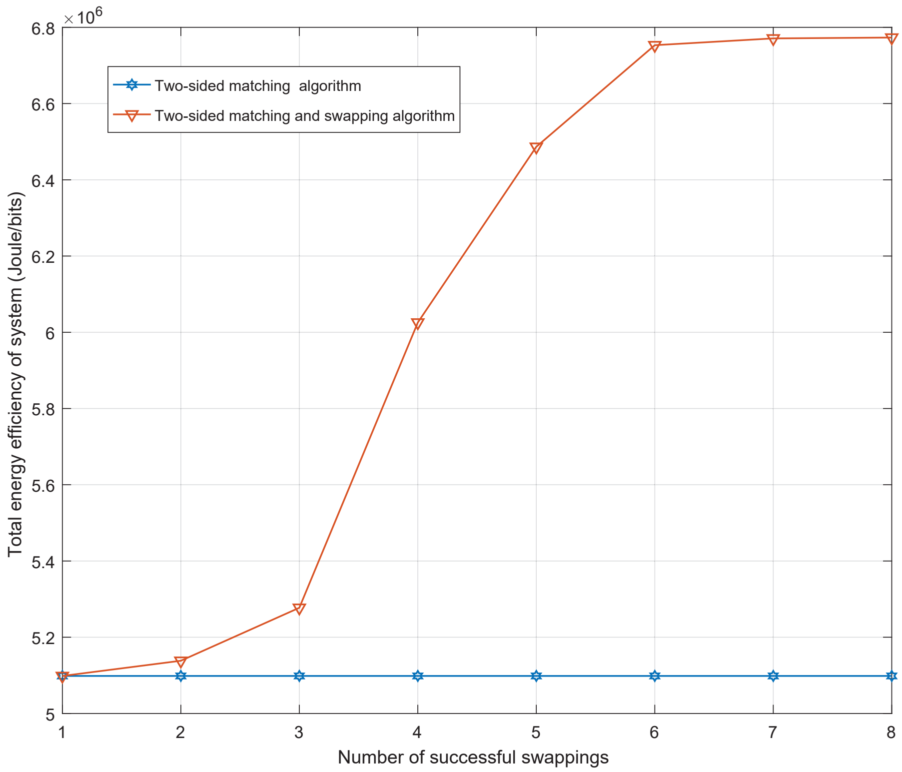

Fig. 4. The comparison between two algorithms.

From Fig. 4, it can be seen that the energy efficiency in the UAV wireless network is gradually increasing with the increase of the number of successful swappings. It shows that the two-sided matching and swapping algorithm can obtain a higher energy efficiency compared with the two-sided matching algorithm. In the end, there is a energy efficiency improvement of nearly 13%. It is noted that the swapping process in our proposed two-sided matching and swapping algorithm is on the basis of the result of two-sided matching algorithm. The two-sided matching algorithm has no swapping process, so the result remains unchanged, while the result of our proposed two-sided matching and swapping algorithm is getting better with the change of swapping times. The number of successful swappings is small because there are only bit swap-blocking pairs left.

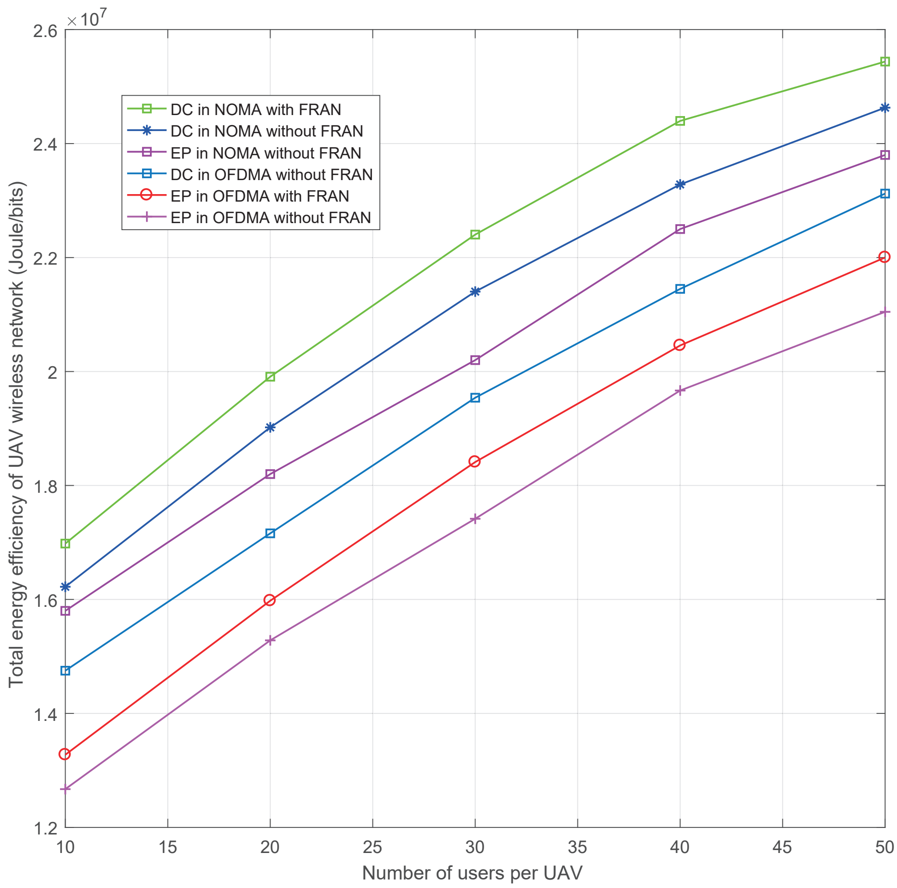

Fig. 5. Energy efficiency of UAV wireless network versus the number of users.

When users change from less to more, the performance of energy efficiency is shown in Fig. 5. From this figure, it could be found obviously the total energy efficiency is growing gradually with increasing users. When the number of users is 40, the caching technology brings 5.15% and 3.04% gain for energy efficiency in NOMA and OFDMA. This is because the caching of edge equipments not only saves the use of spectrum resources, but also increases network capacity which is a significant improvement in total energy efficiency. Meanwhile, the energy efficiency using proposed DC programming is higher than the equal allocation of power (EP) no matter

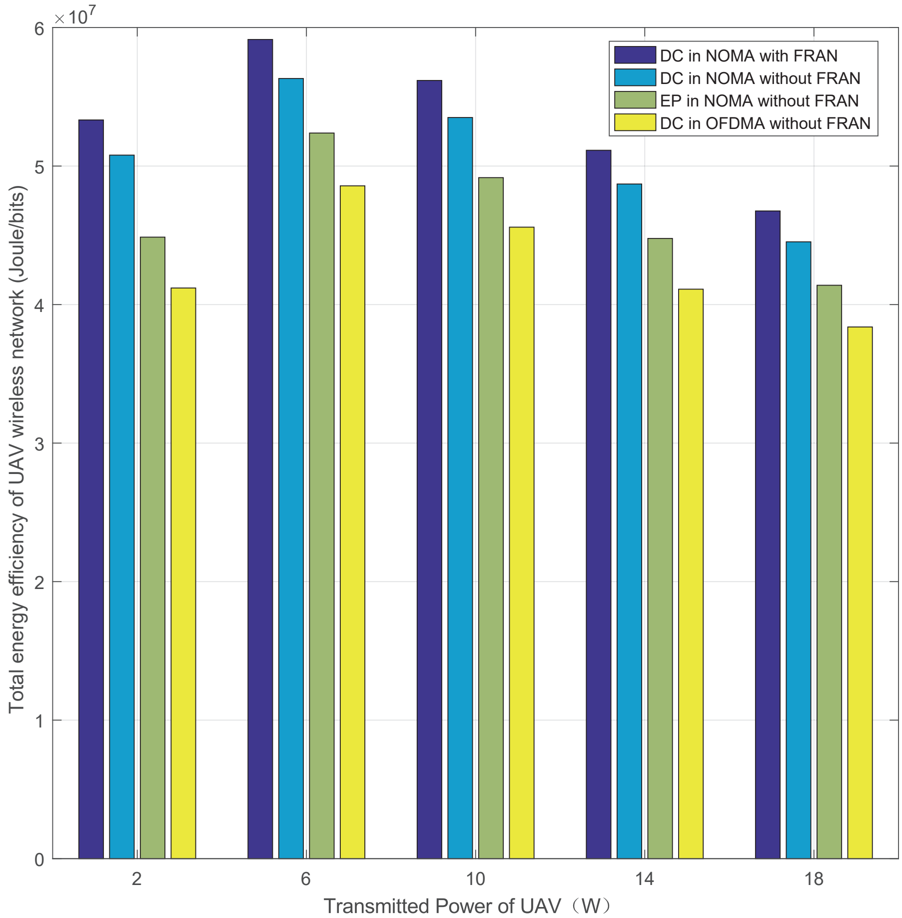

Fig. 6. Energy efficiency of UAV wireless network versus the power of UAV.

whether it is in NOMA and OFDMA. For example, the energy efficiency of proposed scheme (DC in NOMA without FRAN) is about 4% higher than that of existing scheme (EP in NOMA without FRAN) when the number of users is 40.

Fig. 6 reflects the relationship between the energy efficiency and the changing transmitted power of UAV with 50 users. When the transmitted power of UAV is small, the energy efficiency has a growth as the power increases. However, when the power increases to a critical point, the energy efficiency starts to gradually decrease because the power consumption on the denominator in the objective function is also increasing badly. Meanwhile, Fig. 6 shows that the energy efficiency in UAV wireless networks using DC programming performs better than that using EP. Similarly, the data traffic gain brought by caching technology has significantly improved the total energy efficiency.

IV. Open Issues and Challenges

Energy efficient resource allocation scheme can significantly promote the development of UAV communication towards a good direction. Although this article has achieved a better result than the existing work, there are still some inevitable issues and challenges waiting to be studied and solved in future research.

1) Unstable network topology. In UAV wireless networks, UAVs, as the carrier of mobile BS, together form a dynamic network topology. Due to the dynamic behavior of UAVs and the influence of radio waves, the UAV system topology would change irregularly and rapidly with time and location. Thus, there are many factors that need to be considered such as adverse effects on channel condition from flying BS and the height or the angle of the antenna.

2) The management of robustness. Unknown accidents may occur in the node location or wireless data transmission while UAVs are working. Moreover, the control packets may miss without any warnings. Therefore, the robustness management is vital in UAV wireless networks.

3) Complex application scenarios. UAVs are mostly used in complex and dynamic emergency environments where the change of work area or unexpected breakdown of UAVs may occur. Especially, the ability of responding to the emergency situations timely is important for UAVs. Therefore, what should be put on the agenda is the research about collaborative control of multiple UAVs based on complex and varied scenarios. Specially, complex scenes have higher requirements on the trajectory of UAVs. The combined researches between trajectory and resource allocation of UAV wireless networks should be a next direction worth studying.

V. Conclusion

The development of UAV wireless networks brings new ideas for the fast deployment of BSs. Based on the FRAN, we proposed a fog UAV wireless network architecture in this article. Meanwhile, we added NOMA technology into this architecture to alleviate the problem of limited spectrum resources and provided assistances for the sustainable development of UAVs. We proposed a two-sided matching and swapping algorithm to achieve subchannel assignment and a power allocation iteratively to maximize energy efficiency. Results shown that the energy efficiency of NOMA-based fog UAV wireless networks is higher than that of OFDMA scheme. The focus of the future work is about the impact of fronthaul link and trajectory design in UAV wireless networks.

Acknowledgment

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BIOGRAPHIES

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