Multi-user UAV Relayed Half-Duplex Uplink Cellular Networks with Direct Links and Control and Back-Haul Links

Tong Zhang(✉), Gang Wang, and Yikun Zou

Harbin Institute of Technology, Harbin 150001, China
18B905025@stu.hit.edu.cn

Abstract. In this paper, we study a half-duplex multi-user unmanned aerial vehicle (UAV) aided communication system, with constraints of control and back-haul data rates. The UAV is connected to the cellular networks, and because of its line of sight channel, it also works as a relay to receive and transmit the information from the ground users to the base station. The users, categorized in non-orthogonal multiple access (NOMA) groups, have direct links to base stations. In the meantime, to economize spectrum resources, the UAV's control and back-haul link is also multiplexed with users. In this paper, we design the communication scheme and resource allocation strategy to achieve higher spectrum efficiency. The numerical results show the convergence of the proposed scheme and show that the proposed scheme has better performance than OMA schemes.

Keywords: Spectrum efficiency · NOMA · UAV cellular networks · Multi-user

1 Introduction

In recent years, the application of unmanned aerial vehicles (UAV) on communication networks has attracted widespread attention. The potential of UAV relays has already been mentioned in release 15. At present, relevant researches focus on UAV-assisted emergency communication and temporary communication. In release 17, the requirement for cellular networks to enable UAVs' connection has been mentioned. Benefit from their high mobility, UAVs connected to cellular networks have broad prospects as cooperative relays to enhance communication performance.

Recent studies of UAV systems are usually about the design of trajectory and the power allocation [2,4,6,9], where the UAVs are dedicated relays or base-stations [11]. The UAV's control and backhaul relay is usually not considered. With the tension of spectrum resource, UAVs in cellular networks usually have limited time and frequency resources, while the control and back-haul links of UAVs should have guaranteed data rates so as to keep the safety of UAVs'

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operation. However, how to multiplex the UAV's control and backhaul relay when the UAV joins a cellular network is still not widely studied.

There are some researches about NOMA techniques for UAV's connection to cellular networks. In [5], the authors studied the interference of base stations (BSs) to UAVs, and designed a cooperative NOMA scheme for BSs and the UAV. But the research did not consider other ground users, which is usually not ignorable. In [7], a cooperative NOMA scheme for a multi-user UAV enabled communication system is studied. The UAV works as a macro cell BS, but the UAV's control link is not considered. In [10], the authors studied a downlink full-duplex UAV relaying system, the UAV works as a relay between the base station and the users. Differently, we study an uplink communication system consisting of direct links between the base station and the UAV, and the base station and the users. The control and back haul link between the UAV and the base station is also considered to guarantee the UAV's control and relaying mission's.

2 System Illustration

2.1 System Model

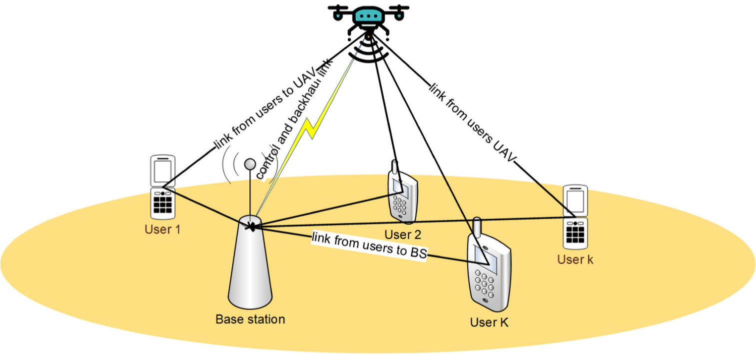

Fig. 1. The system model.

We consider a half-duplex uplink communication system, consisting of a basestation, a UAV and multiple ground nodes. The UAV flies at a given altitude and works as a decoding and forward relay. Since the UAV is connected to cellular networks as a special user, its position is given because of requirements of mission. Suppose there are K users sharing the same spectrum resource. The power transmitted from the ground nodes at time slot t is denoted as $p_{u,k,t}$. The power from the UAV to the BS is denoted as p_U. The control and backhaul power from the BS for the UAV is denoted as p_B. The noise power spectral density is N_0, and the bandwidth is B.

Denote the channel between the UAV and user k as $h_{u2U,k}$, the channel between the BS and the user k as $h_{u2B,k}$, and the channel between the BS and the UAV as h_{U2B}. Since there are line of sight links in the air-to-ground (A2G) channel, we consider $h_{u2U,k}$ and h_{U2B} as Rician channel, and the direct link between the BS and users $h_{u2B,k}$ as Rayleigh channel. Then we have

$$h_{u2U,k} = h_{u2U,k}^{large} h_{u2U,k}^{small}, \tag{1}$$

$$h_{U2B} = h_{U2B}^{large} h_{U2B}^{small}, \tag{2}$$

and

$$h_{u2B,k} = h_{u2B,k}^{large} h_{u2B,k}^{small}. \tag{3}$$

where h^{large} denotes large scale fading, which is influence by the distance and frequency. h^{small} is the small scale fading. $h_{u2U,k}^{small}$ and h_{U2B}^{small} are with Rician distribution, and $h_{u2B,k}^{small}$ is with Rayleigh distribution.

2.2 Proposed NOMA Scheme

The half duplex communication procedure is divided into two time slots. The proposed NOMA scheme is:

- In the first time slot, the UAV receives information from the users in a NOMA group, which is decided in advance according to NOMA grouping schemes [1, 3]. The BS transmits control information to the UAV. All the NOMA users and the BS share the same spectrum resource.
- In the second time slot, the user transmits information to the BS directly, since the channels between users and BS are usually not blocked completely. The users share the same spectrum resource. In the meantime, the UAV transmits back-haul information to the BS, using the same spectrum.

Since the control and backhaul channel and the users' channel share the same spectrum resource, the decoding procedure at the UAV node is designed according to the channel with the users and the BS. Firstly, we sort the channel gain by descending order as

$$|h_{u2U,a_1}|^2 \geq \cdots \geq |h_{U2B,a_j}|^2 \geq \cdots \geq |h_{u2U,a_{K+1}}|^2. \tag{4}$$

Similarly, as for the second time slot, the BS should first sort the channel gain as

$$|h_{u2B,b_1}|^2 \geq \cdots \geq |h_{U2B,b_j}|^2 \geq \cdots \geq |h_{u2B,b_{K+1}}|^2, \tag{5}$$

where a_j and b_j denotes the number of users, i.e., $a_j = k$. And we have $a_j = 0$ and $b_j = 0$ for the channel between the UAV and the BS. The indexes for the user's order is necessary, because the order of a user's channel to UAV and the order of the same user's channel to BS is usually different. But the UAV and the BS both needs to decode the information according the decrease order of the channel gains. After the decoding procedure at the second time slot, the BS will need to pair the received information of a user from the relay and the information of the user from the direct link. In fact, in the simulation procedure, we found that this sorting procedure can be finished by multiplying a matrix, which will be not increase much complexity. Note that the channel gains $|h_{U2B,a_k}|^2$ and $|h_{U2B,b_k}|^2$ are possibly listed at the head of the list because the UAV-to-BS links usually have better channels when the UAV is closer to the BS.

Table 1. Tables of parameters in the proposed NOMA scheme.

Time slot Num/item		BS	UAV	Users
Time slot 1	Power	p_B	–	$p_{u2U,k,1}$
	Channel	$h_{U2B,1}$	$h_{u2B,1}$	$h_{u2U,k,1}$
Time slot 2	Power	–	p_U	$p_{u2B,k,2}$
	Channel	$h_{U2B,2}$	$h_{u2B,2}$	$h_{u2B,k,2}$

The parameters for the proposed NOMA scheme is given in Table 1. At time slot 1, the UAV receives information from the ground users and the BS. The ground users and the BS shares the same spectrum resource. According Shannon theory, the spectrum efficiency between the user k and the UAV at time slot t are denoted as $R_{U,k,t}$, and is given by

$$R_{u2U,k,1} = \log_2\left(1 + \frac{p_{u,k,1}|h_{u2U,k,1}|^2}{I_{u2U,k,1} + N_0 B}\right). \tag{6}$$

The spectrum efficiency from the BS to the UAV $R_{U2B,t}$, and from the UAV to the BS $R_{U2B,t}$ are both

$$R_{U2B,t} = \log_2\left(1 + \frac{p_U|h_B|^2}{I_{U2B,k,t} + N_0 B}\right). \tag{7}$$

Note that as for (7), the interference at time slot 1 and time slot 2 are different, because at time slot 1, $R_{U2B,1}$ is the control data rate to the UAV, the interference consists of the users' information to the UAV; as for time slot 2, $R_{U2B,2}$ is the back-haul link from the UAV to BS, the interference of which consists of the data of the direct link from the users to the BS. The spectrum efficiency from the users to the BS is given by

$$R_{u2B,k,2} = \log_2\left(1 + \frac{p_{u,k,2}|h_{u2B,k,2}|^2}{I_{u2B,k,2} + N_0 B}\right). \tag{8}$$

Then at time slot 1, at the UAV relaying node, the interference is the received information from the users with lower channel gain than the user k in (4).

$$I_{u2U,k,1} = \sum_{j=a_{k+1}}^{a_{K+1}} \widetilde{p}_{j,1}|\widetilde{h}_{j,1}|^2, \tag{9}$$

similarly, at time slot 2, at the BS, the interference is

$$I_{u2B,k,2} \text{ or } I_{U2B,k,2} = \sum_{j=b_{k+1}}^{b_{K+1}} \widetilde{p}_{j,2} |\widetilde{h}_{j,2}|^2. \tag{10}$$

Note that in (9), $\widetilde{p}_{j,1}$ and $\widetilde{h}_{j,1}$ represent p_B or $p_{u2U,j,1}$ and $h_{u2U,j}$ or $h_{U2B,j}$ in (4). And in (10), $\widetilde{p}_{j,2}$ and $\widetilde{h}_{j,2}$ represent p_U or $p_{u2B,j,2}$ and $h_{u2B,j}$ or $h_{U2B,j}$ in (5).

3 Mathematical Problem Formulation

Considering the communication quality for each users, we maximize the minimum achievable rate per Hz of the users, under the constraints of the available power of users, the UAV and the BS. In addition, we also guarantee the quality of the UAV's control and back-haul data rates. The problem is formulated as

$$\max_{p_{u,k,t}, p_U, p_B} \min \frac{R_{u2U,k,1} + R_{u2B,k,2}}{2}, k = 1, \cdots, K \tag{P1}$$

$$\text{s.t. } R_{U2B,1} \geq R_{Backhaul}, \tag{11}$$

$$R_{U2B,2} \geq \sum_{k=1}^{K} R_{u2U} + R_{Backhaul}, \tag{12}$$

$$\sum_{t=1}^{2} p_{u,k,t} \leq P_{u,k}, k = 1, \cdots, K, \tag{13}$$

$$p_U \leq P_U, \tag{14}$$

$$p_B \leq P_B, \tag{15}$$

where (11) is the channel capacity constraint of the control link from the BS to the UAV. (12) is to guarantee the users' data all transmitted to the BS through the UAV relay, as well as ensuring the back-haul data of the UAV transmitted to the BS with required data rates. (13), (14) and (15) are the constraints of power consumption. The problem (P1) is a non-convex problem because of the objective function, (11) and (12), which is hard to be solved. In the next section, we propose the suboptimal solution to design the power allocation scheme of the users, the UAV and BS iteratively.

4 Solution Approach

Since the problem (P1) is a non-convex problem, we iteratively solve it referring to difference of convex functions (DC) programming [8]. According to DC programming, the minimization of the difference of two convex functions

$\mathbf{q}(x) = \mathbf{f}(x) - \mathbf{g}(x)$ can be approached iteratively by solving its convex upper bound $\mathbf{q}(x) = \mathbf{f}(x) - \mathbf{g}^{(l)}(x) - \nabla\mathbf{g}(x^{(l)})^T(x - x^{(l)})$. After using slake parameter $R_{u,min}$, the problem (P1) is given by

$$\max_{p_{u,k,t}, p_U, p_B} R_{u,min} \tag{P2}$$

$$\text{s.t. } (13), (14), (15) \tag{16}$$

$$R_{u,min} + \frac{1}{2}(-R_{u2U,k,1})^{ub} + \frac{1}{2}(-R_{u2B,k,2})^{ub} \leq 0, k = 1, \cdots, K, \tag{17}$$

$$R_{backhaul} + (-R_{U2B,1})^{ub} \leq 0, \tag{18}$$

$$R_{backhaul} + \sum_{k=1}^{K} R_{u2U,k,1}^{ub} + (-R_{U2B,2})^{ub} \leq 0, \tag{19}$$

where $[\cdot]^{ub}$ is the upper bound according to DC programming. For example,let

$$\mathbf{f}(p_{u,k,1}) = -\log_2\left(\sum_{j=a_k}^{a_K+1} \widetilde{p}_{j,1}|\widetilde{h}_{j,1}|^2 + N_0B\right), \tag{20}$$

$$\mathbf{g}(p_{u,k,1}) = \left[-\log_2\left(\sum_{j=a_{k+1}}^{a_K+1} \widetilde{p}_{j,1}|\widetilde{h}_{j,1}|^2 + N_0B\right)\right], \tag{21}$$

then the derivative of $\mathbf{g}(p_{u,k,1})$ is

$$\nabla\mathbf{g}(p_{u,k,1}^{(l)}) = -\frac{[|\widetilde{h}_{a_{k+1},1}|^2, \cdots, |\widetilde{h}_{a_K,1}|^2]^T}{\ln 2\left(\sum_{j=a_{k+1}}^{a_K+1} \widetilde{p}_{j,1}^{(l)}|\widetilde{h}_{j,1}|^2 + N_0B\right)}, \tag{22}$$

where l is the iterative index. Then the upper bound of $-R_{u2U,k,1}$ is

$$(-R_{u2U,k,1})^{up} = \mathbf{f}(p_{u,k,1}) - \mathbf{g}(p_{u,k,1}^{(l)}) - \nabla\mathbf{g}(p_{u,k,1}^{(l)})(p_{u,k,1} - p_{u,k,1}^{(l)}) \tag{23}$$

Similarly, as for the upper bound of $R_{u2B,k,2}$, let

$$\mathbf{f}(p_{u,k,2}) = -\log_2\left(\sum_{j=b_k}^{b_K+1} \widetilde{p}_{j,2}|\widetilde{h}_{j,2}|^2 + N_0B\right), \tag{24}$$

$$\mathbf{g}(p_{u,k,2}) = \left[-\log_2\left(\sum_{j=b_{k+1}}^{b_K+1} \widetilde{p}_{j,2}|\widetilde{h}_{j,2}|^2 + N_0B\right)\right], \tag{25}$$

then the derivative of $\mathbf{g}(p_{u,k,2})$ is

$$\nabla\mathbf{g}(p_{u,k,2}^{(l)}) = -\frac{[|\widetilde{h}_{b_{k+1},2}|^2, \cdots, |\widetilde{h}_{b_K,2}|^2]^T}{\ln 2\left(\sum_{j=b_{k+1}}^{b_K+1} \widetilde{p}_{j,2}|\widetilde{h}_{j,2}|^2 + N_0B\right)}. \tag{26}$$

Then the upper bound of $-R_{u2B,k,2}$ is

$$(-R_{u2B,k,2})^{up} = \mathbf{f}(p_{u,k,2}) - \mathbf{g}(p_{u,k,2}^{(l)}) - \nabla\mathbf{g}(p_{u,k,2}^{(l)})(p_{u,k,2} - p_{u,k,2}^{(l)}). \quad (27)$$

Since the function of spectrum efficiency form can be expressed as the difference between two log functions, other upper bounds can be derived similarly. Note that the upper bounds of the functions are all convex. Accordingly, the problem (P2) is a convex optimization problem, which can be solved efficiently using CVX tools or interior methods in Matlab. Then the power allocation algorithm is proposed is Algorithm 1

Algorithm 1. Design of power allocation for UAV NOMA communication system

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1: Initialize the iteration number $l = 0$, and the initial values of $p_{u,k,t}, p_U, p_B$.
2: repeat
3:     Solve the convex optimization problem (P2), the solutions of the variables are used to update $p_{u,k,t}^{(l+1)}, p_U^{(l+1)}$, and $p_B^{(l+1)}$;
4:     Update the iteration number $l = l + 1$.
5: until The value of the objective function reaches a convergence
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5 Numerical Results and Discussion

In this section, we show the numerical results of the proposed algorithms. In the system, we consider a square place with length 1000 m and width 1000 m. At the studied time slots, the UAV's position is given as (400 m, 200 m, 100 m). The base-station is fixed at (0 m, 500 m, 0 m). The number of users is 4. Their positions are given randomly in the area of (500 m, 1000 m) for x, (0 m, 1000 m) for y, and $z = 0$ m. The communication system works at 5 GHz with the bandwidth of 20 MHz. Thus the parameter of large-scale path-loss factor at reference distance is -46 dB, the path-loss exponent is set to be 2. The noise spectrum density is -150 dBm/Hz.

We consider OMA scheme as a comparison. As for the OMA scheme, in the first time slot, the UAV also receives information from the ground users and receives control data from the base station. But all the users requires separate spectrum resources. As for the second time slot, the UAV transmits received information as well as control and back-haul data to the BS. And the users transmit data with their separate spectrum resources. For both of the two schemes, we optimize the power of users, BS and UAV to maximize the minimum spectrum efficiency of users. The channels of users to UAV and UAV to BS are Rician channel, with the Rician factor of 5. The channel between users and BS at the second time slot is Rayleigh channel.

Figure 2 shows the convergence of the proposed algorithms.

Figure 3 shows the influence of the available power of the ground nodes. The minimum back-haul data rate per Hz of the base-station is set to be 0.02 bps/Hz, the maximum transmitted power from the base-station for the control and back-haul information to the UAV is 0.02 Watt. The maximum communication power consumption for the UAV is 0.02 Watt. As can be seen from the Fig. 3, with more power available, the minimum spectrum efficiency of the users increases. Also, the results show that the proposed NOMA scheme outperforms the OMA shceme.

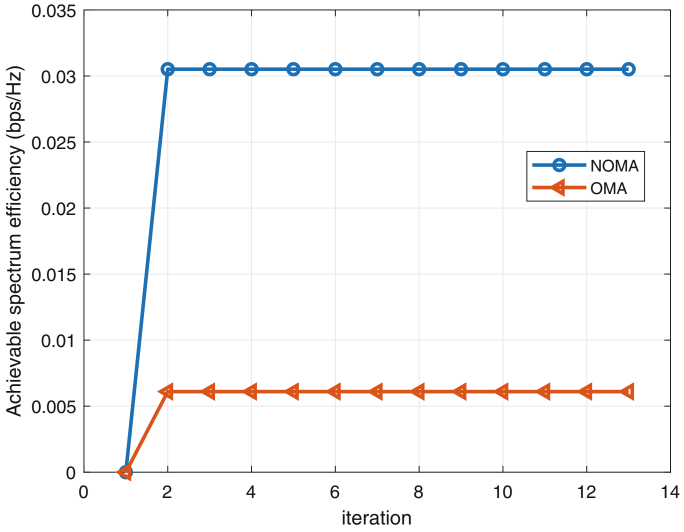

Fig. 2. The convergence of the proposed algorithm.

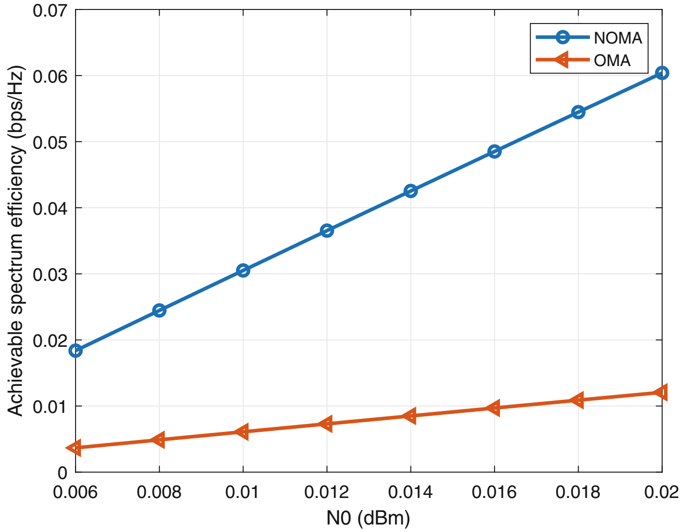

Fig. 3. The influence of the available power for ground users.

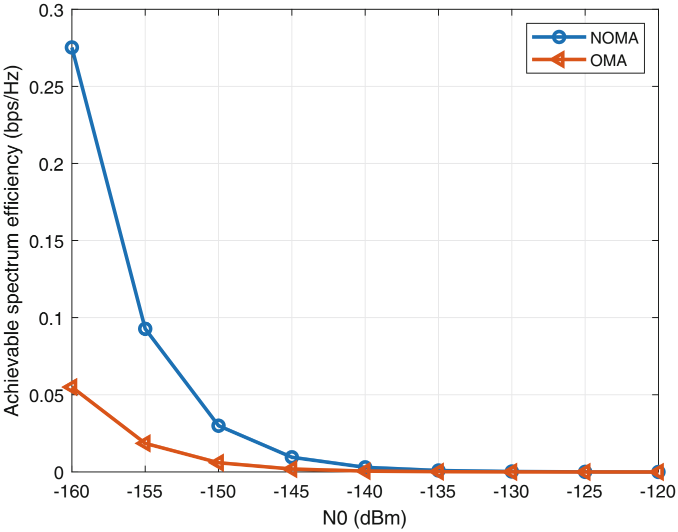

Fig. 4. The influence of noise power spectral density.

Figure 4 shows the influence of noise power. The maximum power from each user is set to be 0.01 Watt. The spectrum efficiency decreases with the increasing of noise power spectral density. It is observed that with the channel condition getting worse, the achievable spectrum efficiencies of NOMA and OMA schemes are both getting worse.

6 Conclusion

In this paper, we studied a cellular network with a UAV and multiple ground users. The UAV communicates with the BS to receive and transmit control and back-haul information as well as works as a relay to enhance the communication performance of ground users. To maximize the spectrum efficiency, we designed the power allocation scheme by solving the non-convex problem using DC programming. Numerical Results show the convergence of the proposed algorithm and prove that the cooperative NOMA scheme can achieve better spectrum efficiency than the OMA scheme. The future work will be extended to user grouping. Also, the influence of the UAV's dynamic trajectory will be studied in following work.

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