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Spectrum Allocation for Sum Rate Maximization in UAV-to-UAV Communication Underlaid Cellular Networks

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This paper explores the sum rate performance by optimizing spectrum allocation in an unmanned aerial vehicle (UAV)-to-UAV communication underlaid cellular network consisting of a BS and a UAV swarm. Each transmitting UAV selects to communicate with the BS or its nearest UAV according to a received signal strength (RSS)-based mode selection scheme. With the mode selection scheme, if the RSS at the BS is greater than a threshold θ, it will select cellular communication mode with the BS; otherwise, it will select UAV-to-UAV communication mode with its nearest UAV. Our mode selection scheme is general in the sense that it can cover the following networks as special cases: cellular networks when $\theta = 0$, and ad hoc networks when $\theta = +\infty$. We utilize the coalition formation game theory to model the sum rate maximization problem. To this end, we first formulate the sum rate maximization as a non-linear and non-convex optimization problem, which is generally difficult to solve. Then, we propose a coalition formation algorithm to solve the optimization problem by optimizing the spectrum allocation among UAV-to-UAV links. The algorithm is further proved to converge to a Nash-stable equilibrium. Finally, simulation results are provided to indicate the impact of critical system parameters on the sum rate performance.

Keywords: UAV-to-UAV communication, cellular networks, sum rate, spectrum allocation, coalition formation algorithm

1. INTRODUCTION

Recently, unmanned aerial vehicle (UAV) communications have been recognized as an appealing technology in various military and civilian applications, such as traffic control, industrial inspection, surveillance, search and rescue, precision agriculture, *etc*. [1–4], due to their swift deployment, high mobility and low cost. Traditional UAVs mainly perform simple point-to-point communications over the unlicensed spectrum (*e.g.*, 2.4 GHZ), which leads to a low data rate, unreliable and limited communication range. To support a wide range of applications, it is of great importance to require new wireless

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technologies to significantly improve the UAV communication performance. A promising approach is to combine the cellular networks and UAV-to-UAV communications. It is notable that UAVs utilize cellular networks to realize remote and reliable communications at almost every corner of the world using the licensed spectrum. Moreover, UAV-to-UAV communications enable the nearby UAVs to directly communicate with each other bypassing base stations (BS), which can offload the cellular traffic data, especially in urban area with dense traffic demands and in disaster circumstances without the support of infrastructure (*e.g.*, BSs). In the emerging UAV-to-UAV communication underlaid cellular networks, the sum rate performance is a critical metric for guaranteeing the optimal design and deployment of such networks. However, it has not been explored in the networks by now.

The existing works on the rate performance mainly focus on the two types of communication scenarios with/without cellular networks [5–14]. In the scenario without cellular networks, UAVs act as aerial BSs to serve the ground users. For the scenario, a maximum rate from a source to its destination can be obtained by jointly optimizing power allocation and UAV trajectory in a single UAV network where the UAV serves as a relay of the source [5]. In a UAV network with a directional antenna equipped at a UAV, a maximum sum rate is determined by a joint optimization of the antenna beamwidth and UAV altitude, wherein the UAV communicates with multiple ground users [6]. The work in [7] further investigates the problem of sum rate maximization by a joint optimization of the power allocation and trajectory of UAVs in a network consisting of multiple UAVs. The max-min rate, *i.e.*, the maximum value of minimum rate, is obtained by a joint optimization of power allocation, UAV trajectory and bandwidth, wherein a UAV is deployed to serve multiple ground users [8]. In a network with a UAV and multiple ground users, the work in [9] aims to maximize the minimum rate by a joint optimization of bandwidth and power allocations, antenna beamwidth and UAV altitude. Consider a network with multiple UAVs and ground users, the max-min rate is obtained by optimizing these parameters like transmission scheduling and association, power allocation, and UAV trajectory [10].

Regarding the scenario with cellular networks, the maximum rate from BS to UAV is determined by a joint optimization of beamforming and power allocation at BSs, wherein there exist multiple ground BSs serving as multiple UAVs and ground UEs in a downlink transmission [11]. The objective of [12] is to optimize the power allocation and cell association of a UAV for maximizing the weighted sum rate of uplink transmission in a network including multiple BSs, ground users and a UAV. The work in [13] aims to maximize the sum rate by a joint optimization of power allocation and location of UAV in a two-hop relay network, where a UAV serves as a relay to forward message from the transmissions between multiple BSs and ground users. Recently, the work in [14] is to maximize the sum rate by a joint optimization of spectrum allocation and flying speed of UAVs in an uplink transmission network with multiple UAVs, users and a BS.

All above works have devoted to the studies of the rate performance for the UAV communications with/without cellular networks, which contribute to the design and deployment of such networks. However, the sum rate performance still keeps unknown by now in UAV-to-UAV communication underlaid cellular networks. To address this issue, this paper investigates the sum rate performance by optimizing spectrum allocation among UAV-to-UAV links. Specially, spectrum allocation is paramount to reduce the interference between cellular and UAV-to-UAV links while improving the sum rate performance in such networks. The main contributions of this paper are summarized as follows.

- We utilize the coalition formation game theory to model the sum rate maximization problem in a UAV-to-UAV communication underlaid cellular network. In this network, each transmitting UAV selects to communicate with the BS or its nearest UAV based on a mode selection scheme. Under the mode selection scheme, if the RSS at the BS is greater than a threshold θ, it will select cellular communication mode with the BS. Otherwise, it will select UAV-to-UAV communication mode with its nearest UAV.
- The sum rate maximization is formulated as a non-linear and non-convex optimization problem, which is to maximize the sum rate by optimizing spectrum allocation among UAV-UAV links. We further propose a coalition formation algorithm to solve the optimization problem. The algorithm is further proved to converge to a Nash-stable equilibrium.
- Finally, simulation results are provided to indicate the impact of some critical system parameters on the sum rate performance.

The rest of the paper is organized as follows. Section 2 introduces the system models and problem formulation. Section 3 presents coalition formation game. Simulation results are provided in Sections 4. Finally, Section 5 concludes the paper.

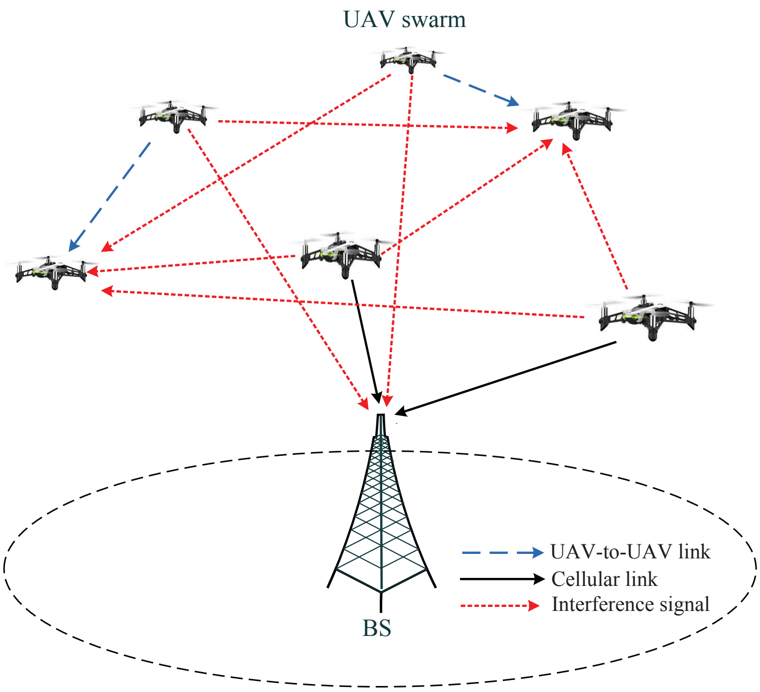

Fig. 1. Network model consisting of a BS and a UAV swarm.

2. SYSTEM MODELS AND PROBLEM FORMULATION

2.1 Network Model

We consider an uplink cellular network with one BS and a UAV swarm, as shown in Fig. 1. The transmitting UAVs and the receiving UAVs follow independent homogeneous Poisson point processes (PPPs) Φ_{Tu} and Φ_{Ru} of densities λ_{Tu} and λ_{Ru}, respectively. Similar to previous work [15], each UAV flies over a fixed altitude H_u.

According to a RSS-based mode selection scheme, each transmitting UAV selects one of cellular and UAV-to-UAV communication modes, wherein the former mode represents the UAV transmits message to the BS, while the latter mode represents it transmits message to its nearest receiving UAV. Under the mode selection scheme, if the RSS at the BS is greater than a threshold θ, it will select cellular communication mode; otherwise, it will select UAV-to-UAV communication mode with its nearest UAV. Our mode selection scheme is general in the sense that it can cover the following networks as special cases: cellular networks when $\theta = 0$, and ad hoc networks when $\theta = +\infty$. In this paper, the UAVs selecting cellular mode are termed as cellular UAVs. On the other hand, they are termed as U2U UAVs to select UAV-to-UAV communication mode.

2.2 Channel Model

The UAV-to-UAV links are modeled as line-of-sight (LoS) channels, and the cellular links from UAVs to the BS are modeled as LoS channels or non-line-of-sight (NLoS) channels. Similar to [16], the small scale fading is omitted for both the UAV-to-UAV and cellular links, due to the reason that the probability of appearing the LoS and NLoS channels is much higher than that of appearing the multipath fading links. The path loss under the NLoS channels is higher than that under the LoS channels thanks to the negative impact of the shadowing and signal reflection from obstacles for NLoS channels. As a result, an additional attenuation is associated with the NLoS channels compared to the LoS channels. We use L_{ub} to denote the path loss from a transmitting UAV u to the BS b. Based on the [17], we have

$$L_{ub} = \begin{cases} |d_{ub}|^{-\alpha_u}, & \text{LoS channel} \\ \rho |d_{ub}|^{-\alpha_u}, & \text{NLoS channel} \end{cases} \tag{1}$$

where d_{ub} denotes the distance between u and b, α_u denotes the path loss exponent and ρ is the additional attenuation factor of the NLoS channel.

We denote P_L and P_N as the probabilities of LoS channel and NLoS channel, respectively. Here, $P_N = 1 - P_L$. Based on [18], we have

$$P_L = \frac{1}{1 + A\exp(-B(\phi - A))}, \tag{2}$$

where the two constants A and B rely on different environments (*e.g.*, suburban, dense urban, rural and others). ϕ denotes the elevation angle of the BS, and

$$\phi = \frac{180}{\pi} \sin^{-1}\left(\frac{H_u}{|d_{ub}|}\right). \tag{3}$$

We use P_{ub} to denote the received signal power at the BS, and then we have

$$P_{ub} = P_u P_L |d_{ub}|^{-\alpha_u} + P_u P_N \rho |d_{ub}|^{-\alpha_u}, \tag{4}$$

where P_u denotes the transmit power of UAVs.

For a UAV-to-UAV link, the received signal power at a receiving UAV is calculated as

$$P_{uu} = P_u |d_{uu}|^{-\alpha_u}, \tag{5}$$

where P_{uu} and d_{uu} denote the received signal power and the distance between a pair of UAVs, respectively. Notice that Eq. (5) represents that the received signal power from a UAV transmitter to its UAV receiver regardless of interference from other UAV transmitters reusing the same spectrum block. The expression of the signal-to- interference-plus-noise ratio in Eq. (9) consider the impact of interference.

2.3 Spectrum Sharing Model

We divide the total system spectrum into K equal-sized orthogonal spectrum blocks represented by a set $SB = \{SB_1, SB_2, ..., SB_K\}$, wherein SB_i denotes the i-th spectrum block. If these exist cellular UAVs, K is equal to the number of cellular UAVs; otherwise we set K as a fixed value. These K orthogonal spectrum blocks are assigned to K different cellular UAVs, each of which uses one spectrum block. Each U2U UAV reuses only one spectrum block with one cellular UAV, and an identical spectrum block can be assigned to multiple U2U UAVs. Therefore, there does not exist interference among these cellular UAVs. However, the interference can be incurred by these U2U UAVs and the celluar UAV sharing an identical spectrum block. We assume that the bandwidth of each spectrum block is W GHZ.

2.4 Signal-to-Interference-Plus-Noise Ratio and Rate

Regarding the transmitting UAVs using the spectrum block SB_k, we denote Φ^k_{u2u} and $|\Phi^k_{u2u}|$ as the set of the U2U UAVs and their number, respectively.

- For a cellular link from a UAV u_c to the BS b operating over the SB_k, the signal-to-interference-plus-noise ratio (SINR) of the cellular link is expressed as

$$\mathrm{SINR}^k_{u_c b} = \frac{P_u P_L |d_{u_c b}|^{-\alpha_u} + P_u P_N \rho |d_{u_c b}|^{-\alpha_u}}{I^k_{u2u} + \sigma^2}, \tag{6}$$

where $\mathrm{SINR}^k_{u_c b}$ denotes the SINR of the cellular link, and I^k_{u2u} denotes the interference from the U2U transmitters reusing the SB_k, and $|d_{u_c b}|$ denotes the distance between u_c and b. I^k_{u2u} is determined as

$$I^k_{u2u} = \sum_{u \in \Phi^k_{u2u}} \left(P_u P_L |d_{ub}|^{-\alpha_u} + P_u P_N \rho |d_{ub}|^{-\alpha_u} \right). \tag{7}$$

We use $R^k_{u_c b}$ to denote the rate of the cellular link from u_c to b, and then we have

$$R^k_{u_c b} = W \log_2 (1 + \mathrm{SINR}^k_{u_c b}). \tag{8}$$

- For a UAV-to-UAV link, we use $\mathrm{SINR}^k_{u_t u_r}$ to denote the SINR of the UAV-to-UAV link from a transmitting UAV u_t to its receiving UAV u_r over the SB_k. Then, we have

$$\mathrm{SINR}^k_{u_t u_r} = \frac{P_u |d_{u_t u_r}|^{-\alpha_u}}{I^k_{u_c b} + I^k_{u_t^* u_r^*} + \sigma^2}, \tag{9}$$

where u_t^* and u_r^* denote any transmitting U2U UAV (except u_t) and its receiving UAV (except u_r), respectively. $I^k_{u_c b}$ denotes the interference from the cellular UAV using the SB_k, and $I^k_{u_t^* u_r^*}$ denotes the interference from other transmitting U2U UAV (except u_t).

$I^k_{u_c b}$ can be determined as

$$I^k_{u_c b} = P_u |d_{u_c u_r}|^{-\alpha_u}, \tag{10}$$

and $I^k_{u_t^* u_r^*}$ can be determined as

$$I^k_{u_t^* u_r^*} = \sum_{u_t^* \in \Phi^k_{u2u} \setminus \{u_t\}} P_u |d_{u_t^* u_r}|^{-\alpha_u}. \tag{11}$$

We use $R^k_{u_t u_r}$ to denote the rate of the UAV-to-UAV link over the RB_k, and then we have

$$R^k_{u_t u_r} = W \log_2(1 + \mathrm{SINR}^k_{u_t u_r}). \tag{12}$$

2.5 Problem Formulation of Sum Rate Maximization

We use R_{sum} to denote the network sum rate, and then we have

$$R_{sum} = \sum_{k \in SB} \left(\sum_{u_c \in \Phi_{ub}} \beta_{ku_c} R^k_{u_c b} + \sum_{u_t \in \Phi^k_{u2u}} \omega_{ku_t} R^k_{u_t u_r} \right), \tag{13}$$

where β_{ku_c} and $\omega_{ku_t} \in \{0,1\}$ are two binary variables. $\beta_{ku_c} = 1$ and $\omega_{ku_t} = 1$ indicate that the SB_k is assigned to a cellular link and a UAV-to-UAV link, respectively. $\beta_{ku_c} = 0$ and $\omega_{ku_t} = 0$, otherwise.

We formulate the sum rate maximization as the following optimization problem, which aims to optimize the spectrum allocation for maximizing the network sum rate.

$$\max_{\beta_{ku_c}, \omega_{ku_t}} \quad R_{sum}, \tag{14a}$$

$$s.t. \quad \beta_{ku_c} \in \{0,1\}, \tag{14b}$$

$$\omega_{ku_t} \in \{0,1\}, \tag{14c}$$

$$\sum_{u_c \in \Phi_{ub}} \beta_{ku_c} = 1, \tag{14d}$$

$$\sum_{k \in SB} \omega_{ku_t} = 1, \tag{14e}$$

where Eq. (14d) ensures that each spectrum block (*e.g.*, SB_k) is assigned to only one cellular link, Eq. (14e) ensures that each UAV-to-UAV link reuses one spectrum block, and Φ_{ub} represents the set of the transmitters of cellular links.

This is a non-linear integer programming problem, and the objective function in Eq. (14) is not monotonic or concave, and thus the optimization problem is non-linear and non-concave. It is NP-hard and generally difficult to solve. In the next section, a coalition formation algorithm is proposed to solve it based on game theory.

3. COALITION GAME FRAMEWORK

This section first presents coalition game formulation based on game theory, and then a coalition formation algorithm is proposed to optimize the spectrum allocation for maximizing the sum rate.

3.1 Coalition Game Formulation

The objective of the coalition game is to let transmitting UAVs form different coalitions to maximize the sum rate of the network. The U2U UAVs, which reuse the same spectrum block, are in an identical coalition. Obviously, a large number of U2U UAVs in a coalition could lead to severe interference among these UAV-to-UAV links and the cellular link using the same spectrum block. As a result, this will degrade the sum rate performance. Thus, all the U2U UAVs have no incentive to form a grand coalition. To mitigate the negative effect of interference, these U2U UAVs will choose spectrum blocks to form different coalitions for maximizing the sum rate of the network.

In the network, each U2U UAV reuses only one spectrum block with a cellular UAV, wherein each cellular UAV is allocated to an orthogonal spectrum block. Different U2U UAVs can also reuse an identical spectrum block. Thus, these UAVs will form at most K coalitions. The coalition formation process can be modeled as the following coalition game.

Definition 1 (Coalition game): We use a triple (Φ_U, C, T) to define the coalition game, and then this game is formulated as follows.

- *Players*. Each player represents a U2U UAV. All U2U UAVs form a set of players denoted by Φ_U.
- *Coalition Partition*. The coalition partition is defined as a set $C = \{C_1, C_2, ..., C_K\}$, where each element C_k represents a coalition consisting of the players reusing an identical spectrum block SB_k with at most a cellular UAV. In the coalition partition, any two coalitions are disjoint, *i.e.*, $C_k \cap C_{k'} = \varnothing$ for any $k \neq k'$, an $\cup_{k=1}^{K} C_k = \Phi_U$.
- *Utility*. $T(C_k)$ denotes the utility (*i.e.*, sum rate) of a coalition C_k. Each U2U UAV makes a decision to leave or join a coalition according to the utility of coalition where it resides, the utility of the residing coalition (except itself) and the new coalition.

For a coalition C_k operating over the SB_k, the utility $T(C_k)$ of the coalition is determined as

$$T(C_k) = flag * R^k_{u_c b} + \sum_{u_t \in C_k} R^k_{u_t u_r}, \tag{15}$$

where a binary variable $flag = 1$ denotes there exist cellular UAVs, and $flag = 0$ otherwise.

3.2 Coalition Formation Algorithm

The important issue in coalition partition formation is to design a scheme that each player joins or leaves a coalition while guaranteeing the improvement of sum rate performance. To do so, we define a preference relation as follows.

Definition 2 (Preference relation): For a preference relation $\succ_i$ with any U2U UAV i, $C_k \succ_i C_{k'}$ means that the sum rate of the coalitions C_k and $C_{k'}$ when $i \in C_k$ and $i \notin C_{k'}$ is more than their sum rate when $i \notin C_k$ and $i \in C_{k'}$. For the U2U UAV i ($i \in C_k, C_{k'}$), the preference can be defined as

$$C_k \succ_i C_{k'} \Leftrightarrow T(C_k) + T(C_{k'} \backslash i) \;>\; T(C_k \backslash i) + T(C_{k'}). \tag{16}$$

The preference in Eq. (16) implies that the network sum rate increases when the U2U UAV i is a member of coalition C_k rather than $C_{k'}$.

According to the preference relation, we define the following switch operation, with the help of which a new coalition partition is formed.

Definition 3 (Switch operation): For a coalition partition set $C = \{C_1, C_2, ..., C_K\}$ and any two elements $C_k \cap C_{k'} = \varnothing$, when a U2U UAV i conducts a switch operation that i moves from its current coalition $C_{k'}$ to the coalition C_k, C is updated into a new coalition partition $C' = \{C \backslash \{C_k, C_{k'}\}\} \cup \{C_{k'} \backslash \{i\}, C_k \cup \{i\}\}$.

Consider a random coalition partition $C = \{C_1, C_2, ..., C_K\}$ and any U2U UAV i is in a coalition $C_{k'} \in C$. A coalition C_k is randomly chosen from C, wherein $C_k \in C$ and $C_k \neq C_{k'}$. If the preference relation $C_k \succ_i C_{k'}$ is true, the U2U UAV i performs the switch operation moving from $C_{k'}$ to C_k, and updates current coalition C_k into a new coalition partition C' based on Definition 3. Now, a coalition formation algorithm is proposed in Algorithm 1 to solve the sum rate maximization problem based on the above the preference relation and switch operation.

Algorithm 1 : Coalition Formation Algorithm

1. **Input:** Given a random coalition partition C;
   Define a sum rate variable $R_{sum} = 0$;
2. **Output:** R_{sum};
3. **repeat**
4. Randomly choose a U2U UAV i from C, and i is in a coalition $C_{k'} \in C$;
5. Randomly choose another coalition C_k from C, wherein $C_k \neq C_{k'}$;
6. Determine whether or not $C_k \succ_i C_{k'}$ is satisfied;
7. **if** satisfy the preference relation **then**

The following switch operation is performed:
i leaves its own coalition $C_{k'}$ and joins the coalition C_k;
Update $C = \{C \backslash \{C_k, C_{k'}\}\} \cup \{C_{k'} \backslash \{i\}, C_k \cup \{i\}\}$;
end if
until C converges to a Nash stable, wherein the switch operation is not performed.
Determine the sum rate R_{sum}.

For Algorithm 1, we generate a random coalition partition C and define a variable R_{sum} to store the network sum rate.

The following steps will be conducted repeatedly in the algorithm. Any U2U UAV decides whether it leaves its own coalition and joins a new coalition or not. Thus, the network randomly chooses a U2U UAV i, where i is in a coalition $C_{k'} \in C$. Another coalition C_k is also randomly chosen from C, where $C_k \neq C_{k'}$. To decide whether or not i needs to leave its own coalition C_k and join the coalition $C_{k'}$, we determine the preference relation $C_k \succ_i C_{k'}$. If the preference relation is satisfied, it is removed from $C_{k'}$ and insert it into C_k. Meanwhile, the coalition partition C needs to be updated. These operations will be stopped performing once C converges to a Nash stable. Finally, we obtain the network sum rate R_{sum}.

3.3 Convergence Property

We now prove the convergence property of Algorithm 1.

Theorem 1 *Starting from any initial coalition partition, Algorithm 1 always can experience a sequence of switch operations to converge to a final coalition partition.*

Proof 1 *Based on the preference relation of Eq. (16), we know that a new coalition partition will be generated after performing each switch operation. Since there are a limited number of coalition partitions, which is the Bell number determined in [19], the switch operations always can stop. Therefore, Algorithm 1 will converge to a final coalition partition after a finite number of switch operations.*

3.4 Stability Property

Before giving the stability property of Algorithm 1, we first define the Nash stable structure.

Definition 4 (Nash stable structure): For a coalition partition $C = \{C_1, C_2, ..., C_K\}$, if any U2U UAV i belonging to $C_k \in C$, there is always $C_k \succ_i C_{k'} \cup \{i\}$ for all $C_{k'} \in C \backslash C_k$. We say that the coalition partition C is a Nash stable structure.

This definition demonstrates that in a stable coalition partition, there does not exist any U2U UAV which wants to leave its own coalition and join others. That is to say, no U2U UAV believes that the network sum rate could increase if it moves to other coalition.

We now give the stability property in the following theorem.

Theorem 2 *The final coalition partition under Algorithm 1 is Nash stable.*

Proof 2 *If the final coalition partition under Algorithm 1 cannot converge to a Nash* *stable structure, we can choose a U2U UAV i in a coalition $C_{k'}$, and also find another coalition C_k such that $C_k \cup \{i\} \succ_i C_{k'}$. Then, the U2U UAV i can leave its own coalition $C_{k'}$ and join the coalition C_k after a switch operation. This implies that the partition is not the final one. Hence, the final partition under Algorithm 1 is a Nash stable structure.*

Table 1. Network parameters.

Parameters	Values
Network area	3.6×10^5 m^2
Total network bandwidth W	2 GHz
Location coordinates of BS	(0, 0, 0)
Density of transmitting UAVs λ_{T_u}	3×10^{-4} UAVs/m^2
Density of receiving UAVs λ_{R_u}	5×10^{-4} UAVs/m^2
Transmit power of UAVs P_u	1 W
Altitude of UAVs H_u	100 m
RSS threshold θ at BS	–60 dBm
Number of resource blocks K without cellular UEs	10
Path loss exponent of UAV-to-UAV link α_u	2
Additional attenuation factor for NLoS link ρ	0.01
Parameters for the probability of LoS link B and A	0.136, 11.95
Noise power σ^2	–90 dBm

4. NUMERICAL RESULTS

In this section, we will explore the impact of some important network parameters on the sum rate performance under our coalition game framework. The network parameters are set in Table 1, unless otherwise specified.

4.1 Impact of P_u On the Sum Rate

We investigate the impact of the transmit power of UAVs P_u on the sum rate performance. We summarize in Fig. 2 how the sum rate varies with P_u under the scenario of $H_u = \{100, 200, 300\}$ m. It can be observed from Fig. 2 that for each fixed H_u, the sum rate increases as P_u increases. This can be explained as follows. We know that the increasing of P_u leads to the increasing of the RSS at BS from any UAV. This means that more UAVs select the cellular communication mode according to the mode selection scheme. Note that in our study, the number of the orthogonal spectrum blocks K is equal to the number of the cellular UAVs if the cellular UAVs exist in the network. The increasing

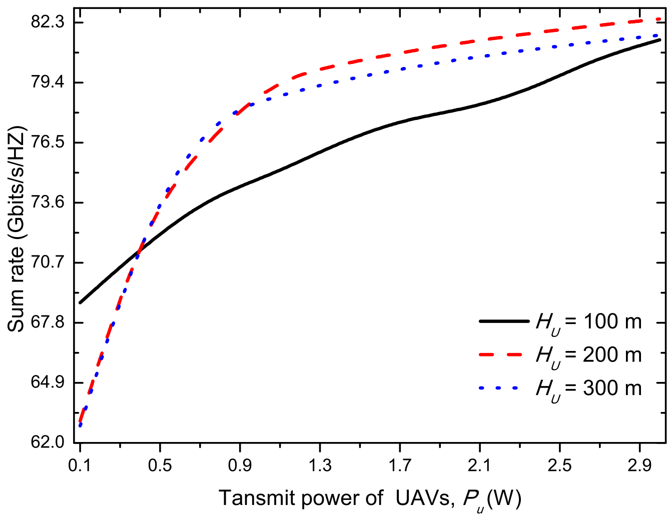

Fig. 2. Impact of P_u on the sum rate.

of spectrum blocks can reduce the interference caused by the sharing spectrum blocks between U2U UAVs and cellular UAVs. Moreover, the increasing of P_u can also lead to the increasing of the RSS at U2U receiver. Therefore, the sum rate increases with the increasing of the P_u, which leading to the increasing of sum rate.

Another careful observation from Fig. 2 reveals that as P_u increases, the black line at $H_u = 100$ m is higher at first but lower than the other two lines at $H_u = \{200, 300\}$ m at the last. This is due to the following reasons. As P_u is relative small, more UAVs at $H_u = 100$ m select the cellular communication mode compared to the UAVs at $H_u = \{200, 300\}$ m according to the mode selection scheme. Note that these cellular UAVs use the orthogonal spectrum blocks and thus there does not exist interference among them. Thus, the black line is higher than the other two lines. As P_u becomes relative big, more UAVs at $H_u = \{200, 300\}$ m select cellular communication mode, and the other UAVs selecting the UAV-to-UAV communication mode would generate less interference for the BS compared to the UAVs at $H_u = 100$ m, due to the fact that the distance between the former UAVs and the BS is longer than that between the latter UAVs and the BS. Thus, the black line is lower than the other two lines at the last.

4.2 Impact of H_u On the Sum Rate

We explore the impact of the altitude of UAVs H_u on the sum rate performance. Fig. 3 illustrates how the sum rate varies with H_u under the scenarios of $\theta = \{-63, -58, -54\}$ dBm. We can see from Fig. 3 that for each setting of H_u, the sum rate first increases and then decreases as H_u increases. The reason behind the phenomenon can be explained as follows. As H_u increases, the elevation angle of the BS ϕ increases according to Eq. (3). Thus, we further know that the probability of the LoS link from any UAV to the BS increases according to Eq. (2). Due to the low path loss under the LoS link, the RSS at the BS from any UAV increases as the probability of the LoS link increases, which results in the increasing of cellular UAVs and thus the decreasing of the interference caused by

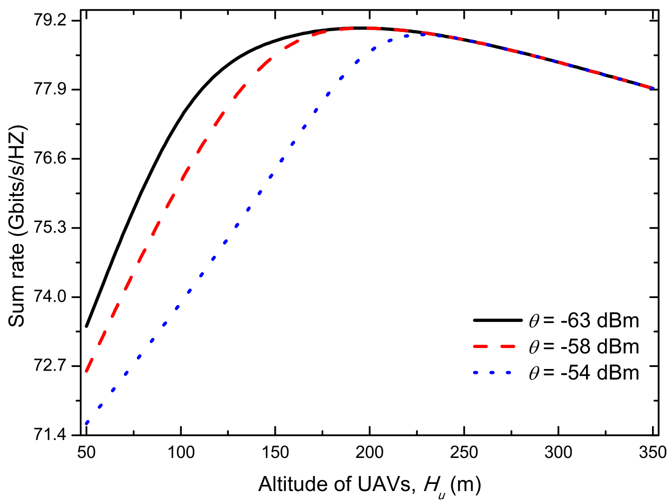

Fig. 3. Impact of H_u on the sum rate.

sharing the same spectrum blocks between U2U UAVs and cellular UAVs. As a result, the sum rate increases with the increasing of H_u. On the other hand, when all UAVs select the cellular communication mode, H_u continues to increase which leads to the increasing of the path loss. Thus, the sum rate decreases as H_u further increases.

4.3 Impact of θ_u On the Sum Rate

We now examine the impact of the RSS threshold θ at the BS on the sum rate performance. We summarize in Fig. 4 how the sum rate with θ under the scenarios of $\lambda_{Tu} = \{10^{-3}, 2\times10^{-3}, 3\times10^{-3}\}$ UAVs/m^2. We observe from Fig. 4 that for each setting of λ_{Tu}, the sum rate decreases as θ increases. We can explain the phenomenon as follows. As θ increases, more UAVs select the UAV-to-UAV communication mode according to the mode selection scheme, which leads to the decreasing of the number of cellular UAVs and thus spectrum blocks. This could incur the severe interference among UAV-to-UAV links reusing the same spectrum block, and thus the sum rate decreases with the increasing of θ.

We can also see from Fig. 4 that the black line at $\lambda_{Tu} = 10^{-3}$ and red line at $\lambda_{Tu} = 2\times10^{-3}$ cross. This is because the impact of λ_{Tu} on the sum rate is complex which is illustrated in Fig. 5. The complex impact could lead to the crossing of the black and red lines.

4.4 Impact of λ_{Tu} On the Sum Rate

Finally, we investigate the impact of the density of transmitting UAVs on the sum rate performance. The results in Fig. 5 illustrate how the sum rate with λ_{Tu} under the scenarios of $P_u = \{0.1, 0.6, 1.1\}$W. We can see from Fig. 5 that for each setting of P_u, the change of the sum rate exhibits a non-monotonic feature as λ_{Tu} increases. This is mainly due to the complex impact of λ_{Tu} on the sum rate. The increasing of λ_{Tu} may increase the number of the cellular links and UAV-to-UAV links, which may lead to either the increasing or the decreasing of the interference among UAV-to-UAV links and cellular links. Meanwhile, it may lead to the increasing of RRS at any receiver. These result in the complex change of the sum rate.

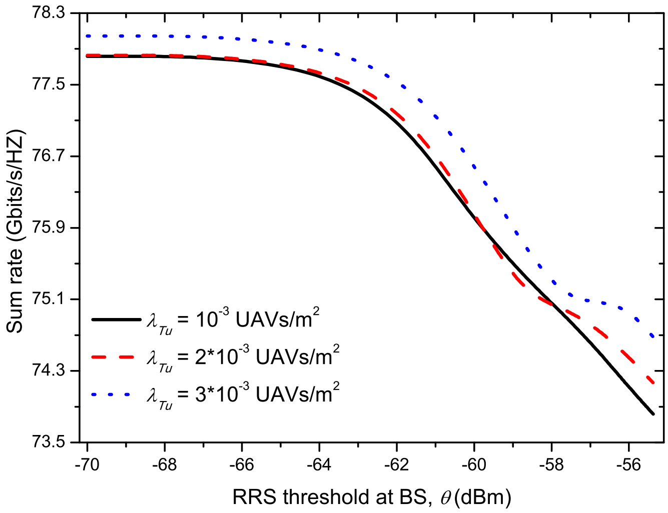

Fig. 4. Impact of θ on the sum rate.

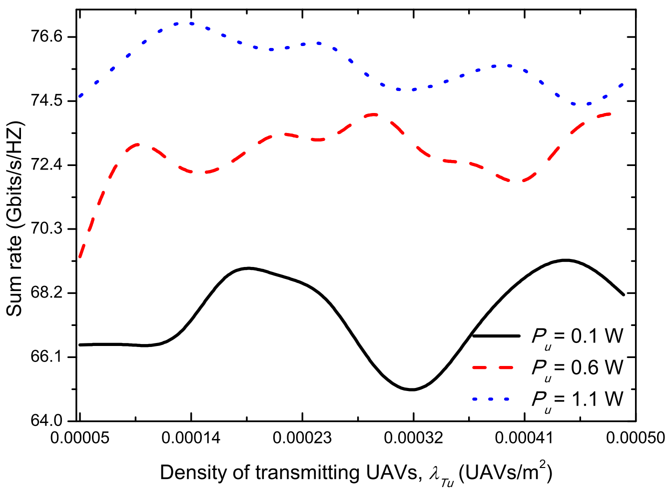

Fig. 5. Impact of λ_{Tu} on the sum rate.

5. CONCLUSION

In this paper, we investigated the maximum sum rate performance by optimizing spectrum allocation in a UAV-to-UAV communication underlaid cellular network. Specially, each transmitting UAV could select its communication mode according to a flexible mode selection scheme. We further developed a coalition formation game framework to explore the maximum sum rate. Simulation results indicate that the transmit power of UAVs can improve the maximum sum rate performance. Moreover, we can find an optimal altitude of UAVs for maximizing the sum rate.

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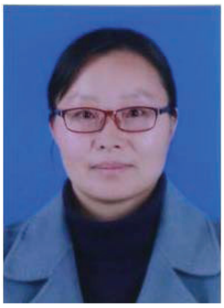

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