Backhaul transmission scheme for UAV based on improved Nash equilibrium strategy

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Abstract

As a new alternative communication scheme in 5G, unmanned aerial vehicle (UAV) is used as a relay in the remote base station (BS) for assistant communication. In order to ameliorate the quality of the backhaul link, a UAV backhaul transmission scheme based on improved Nash equilibrium (NE) strategy is proposed. First, the capacity of air-to-ground (A2G) channel by the link preprocess is maximized. Then, the maximum utility function of each UAV is used as the basis of obtaining NE point according to the backhaul channel and the backhaul congestion. Finally, the improved NE strategy is applied in multiple iterations until maximum utility functions of all the UAVs are reached, and the UAVs which are rejected by air-to-air (A2A) link during the process would participate in the source recovery process to construct a multi-hop backhaul network. Simulation results show that average effective backhaul rate, minimum effective backhaul rate increases by 10%, 28.5% respectively in ideal A2G channel, and 11.8%, 42.3% respectively in fading channel, comparing to pure NE strategy. And the average number of iterations is decreased by 5%.

Keywords: UAV relay, Multi-hop backhaul network, NE strategy, Resource recovery, Link preprocess

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1. Introduction

At present, mobile communication technology is about to fully enter 5G, extremely high transmission rate, low delay and rich communication ecology will be applied in our lives. Meanwhile, the requirement of huge data traffic business will bring about difficulties to the existing terrestrial cellular network in coping with some special service scenarios, such as high-load communication in hotspot areas [1], emergency communication in disaster areas [2], etc. The development of unmanned aerial vehicle (UAV)-assisted communication provides an effective solution to this problem [3]. The low cost, easy deployment, high agility, ability to establish line-of-sight (LoS) connections, and strong linkage [4] allow UAVs to operate in areas that are densely crowded or difficult to be directly covered by a ground base station (BS) to assist in performing communication services, thereby effectively expand coverage and improve information transmission efficiency.

Therefore, recently, many researchers have engaged in researches on the application of UAV in various scenarios. Hsu et al. proposed a UAV collision avoidance algorithm based on reinforcement learning, and abstracted the IoT device data collection problem into a traveling salesman problem which is no-returned, thereby obtaining a vintage backward path to serve the heterogeneous ground IoT devices efficiently [5]. Liu et al. proposed a real-time IoT model for multi-UAV and ground vehicle communication by dividing the global problem into three sub-problems: scheduling optimization, power allocation optimization and trajectory optimization [6]. Wang et al. proposed a hybrid deployment motion algorithm based on centralized and distributed. First, the minimum number of UAVs required to be invested and the sub-optimal coverage position are obtained through the centralized search algorithm. Then the local optimal position was optimized through the distributed motion algorithm, which based on the virtual force model, ultimately obtain efficient coverage [7]. Phung et al. designed a cost function under the constraints of the optimality, safety and feasibility of the UAV moving in a complex environment, and proposed a particle-swarm-optimization algorithm based on spherical vector to obtain an efficient path planning scheme [8]. Yang et al. proposed a UAV edge computing model with block-coordinate-descent method based on half duplex and smart reflector assistance [9]. Lai et al. considered the deployment of UAV as a problem which like knapsack, and proposed an algorithm which can sense density to cover users on demand, thereby improving coverage and reducing power consumption under the constraint of ensuring the minimum data rate [10]. Yao et al. studied the vintage ratio of BSs with energy source and BSs without energy source in a heterogeneous cellular network composed of small cells and macro cells, aiming to improve the energy efficiency without reducing network performance [11]. Luan et al. considered both the load balancing problem and the data rate balancing problem of the ground users served during UAV deployment, and proposed a UAV proliferation deployment algorithm based on a virtual force field. The algorithm makes global and local distributed adjustments to the system through two different forces according to special performance metrics to achieve global equilibrium [12]. Zhang et al. considered a UAV service model based on the FSO backhaul framework, and divided the whole network optimization problem into UAV placement part and resource allocation part. They proposed a loop iterative algorithm to solve these two parts and maximize the network throughput [13]. Tang et al. considered how UAV, as a node of federated edge learning in the IoT system, can reasonably balance its idle and working states by adjusting the CPU frequency under limited battery constraints, and proposed an optimization algorithm to effectively reduce the system delay and energy consumption based on deep deterministic policy gradient [14]. In these studies, optimizing the throughput of users in the UAV service area is an important research direction. However, most of the studies in the above literature focus on UAV deployment and resource allocation of bandwidth or power, while ignore the support of the backhaul link required by the UAV access link service. Although currently UAV can be directly connected to the core network as an air base station, but due to the high power consumption, a more reliable solution is for the UAV to assist by acting as a BS relay to provide long-distance communication services [15]. On this basis, how to form an efficient backhaul link to help the UAV maximize the throughput of users in the service area has become an urgent and meaningful problem.

At present, game theory provides possibility for the formation of an efficient backhaul channel. In order to obtain the excellent capacity brought by the dense deployment of small base stations, the literature [16] formulated a utility function to make the UAVs play a network game so that balance the air-to-ground (A2G) channel and the air-to-air (A2A) channel, aiming to make a structure of an efficient multi-hop backhaul network to improve the transmission effect from the core network to the small base station. To go a step further, the literature [17] proposed a pure Nash equilibrium (NE) strategy and a mixed NE strategy, aiming to avoid UAV falling into a loop in the process of NE game, so as to form a reliable and stable multi-hop backhaul network. However, because its research object is still the backhaul network between the core gateway and BS, and there is currently a lack of researches related to the backhaul link among BS, UAVs and users. Although some studies have also considered backhaul limitations in UAV deployment and resource allocation [18][19], most of them cooperate with the optimization of the forward link, and lacks specific in-depth optimization of the backhaul link after the deployment is completed.

This paper proposes a multi-hop backhaul transmission scheme based on improved NE strategy. Compared with the pure NE strategy, this solution is more perfect for the layout of the backhaul link when solving the UAV backhaul problem. On the one hand, considering the problem that the utility function in the pure NE strategy may reduce the useful A2G channel, a link preprocessing process is introduced to divide the UAVs into resident UAV and non-resident UAV, where the resident UAV will not participate in the NE process to change its backhaul channel. On the other hand, since some UAVs may be rejected by the A2A link when participating in the NE process in the case of poor backhaul environment, a resource recovery process is introduced to improve the link quality of these UAVs. At the level of the NE algorithm, the random game strategy in the pure NE strategy is adjusted to an equilibrium game strategy with a priority order. UAVs which are far away from the BS are preferentially involved in the NE process to minimize the link loss of the UAVs rejected by the link, so as to ensure UAV access balance as much as possible, and achieve both internal and external equilibrium of NE and access equilibrium. In general, the contributions of this paper are as follows:

1) We consider the maximum demand rate of the UAV based on the actual situation, and this demand rate can be collected after the deployment of the forward link. In practical applications, we can obtain the best backhaul link through the proposed scheme according to the current maximum demand rate of the UAV swarm to ensure the quality of the forward link as much as possible.

2) We improve the application of NE strategy on the backhaul link side by introducing priority access equalization to achieve inner and outer two-layer equilibrium. The simulation results show that the overall backhaul performance is slightly improved, and the local minimum backhaul performance can be greatly improved, whatever with or without extra

channel fading. At the same time, the number of iterations of the algorithm can be reduced to a certain extent.

3) We propose resource recovery process based on the NE strategy. We prove the non-zero or one characteristic of UAV participation in the NE process, thereby making full use of the backhaul transmission margin in resident UAVs. At the same time, a greedy layer-by-layer traversal algorithm with the base station as the root node is proposed to perform link optimization access matching for the UAVs that are excluded by the A2A link in the NE process.

2. System Model

This paper first considers that there is only one BS denoted as BS_0. The sum of UAVs is N. The UAV numbered i is represented by UAV_i. In a rectangular area with a range of 4 km × 4 km, multiple UAVs have found their optimal service locations. At this time, it is necessary to connect with the remote BS through a certain topology to form a multi-hop backhaul network, which is shown in **Fig. 1**, where C_i represents the maximum demand rate required by UAV_i, so as to efficiently transmit data traffic to the ground users.

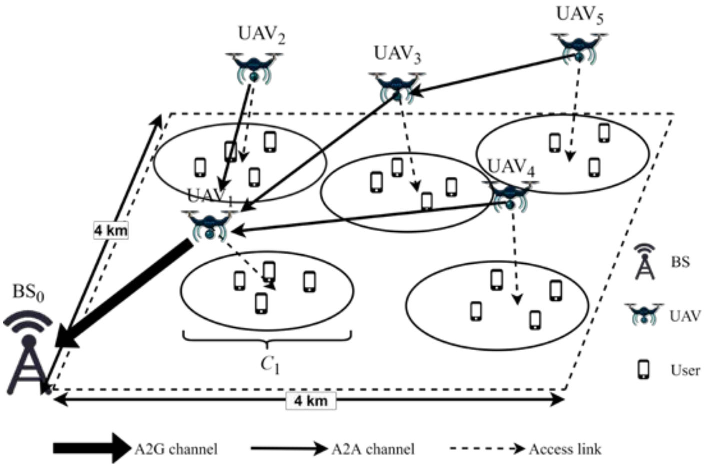


Fig. 1. UAV network service model

It is assumed that the UAV's default flight height h=100 m [7], and the frequency bands occupied by channels between different UAVs and between UAVs and BSs are orthogonal to each other. At the same time, the horizontal position coordinates of each UAV and the total maximum demand rate of the users it serves can be dynamically received.

2.1. System channel model

For each UAV, in the case of end-to-end single link (the UAV is directly connected to the BS), their transmission channel is the A2G channel. In the case of a multi-hop link, the UAV sends the backhaul signal to other UAVs, which then relay the signal or send it to the BS. The channel model between different UAVs is the A2A channel, until the last relay UAV transmits the signal to the BS and becomes the A2G channel. The A2G channel adopts the mixed probability transmission model of Los and none-Los (NLos), which can be respectively expressed as:

$$P^{Los}(\theta_{i,0}) = \frac{1}{1+\alpha\exp(-\beta(\theta_{i,0}-\alpha))}, \quad (1)$$

$$P^{Nlos}(\theta_{i,0}) = 1 - P^{Los}(\theta_{i,0}), \tag{2}$$

where α and β represent two constants depended on the environment around users (such as rural, urban, and densely populated, etc.). $\theta_{i,0}$ is the elevation angle between BS_0 and UAV_i, and can be expressed as:

$$\theta_{i,0} = \tan^{-1}(\frac{h}{l_{i,0}}), \tag{3}$$

where $l_{i,0}$ represents the horizontal distance between UAV_i and BS_0.

After (1) and (2) are determined, the link loss function of the A2G channel can be obtained, and can be expressed as:

$$g_{i,0} = P^{Los}(\theta_{i,0})L_{i,0}^{Los} + (1 - P^{Los}(\theta_{i,0}))L_{i,0}^{NLos}, \tag{4}$$

where $L_{i,0}^{Los}$ is the Los link loss and $L_{i,0}^{NLos}$ is the NLos link loss, which can be expressed as:

$$L_{i,0}^{Los} = 20\lg(\frac{4\pi f d_{i,0}}{c}) + \mu^{Los}, \tag{5}$$

$$L_{i,0}^{NLos} = 20\lg(\frac{4\pi f d_{i,0}}{c}) + \mu^{NLos}, \tag{6}$$

where f denotes the carrier frequency, $d_{i,0}$ denotes the 3D distance between UAV_i and BS_0 in three-dimensional space, c denotes the light speed, and μ^{Los} and μ^{Nlos} denote the general extra losses in Los and NLos transmission states, respectively.

Since UAVs fly at the same altitude and are all Los transmissions, the link loss between different UAVs can be directly expressed as:

$$g_{i,j} = 20\lg(\frac{4\pi f l_{i,j}}{c}) + \mu^{Los}, \tag{7}$$

where $g_{i,j}$ is the link loss between UAV_i and UAV_j, $l_{i,j}$ denotes the horizontal distance between UAV_i and UAV_j.

Since the backhaul link channels of each UAV are orthogonal to each other, the signal-to-noise ratio of the channel between UAV_i and BS_0 and UAV_j can be expressed as:

$$r_{i,0} = \frac{p10^{\frac{-g_{i,0}}{10}}}{\sigma^2}, \tag{8}$$

$$r_{i,j} = \frac{p10^{\frac{-g_{i,j}}{10}}}{\sigma^2}, \tag{9}$$

where p represents the signal transmit power of the UAV, σ^2 represents the average noise power. According to Shannon's formula, the maximum transmission rate of the channel between UAV_i and BS_0 and UAV_j can be expressed as:

$$R_{i,0} = B\log_2(1 + r_{i,0}), \tag{10}$$

$$R_{i,j} = B\log_2(1 + r_{i,j}), \tag{11}$$

where B represents the transmission bandwidth of UAV.

To sum up, a complete channel model that can be used for analysis and calculation is able to be obtained, and the validity of the proposed scheme can be verified according to the channel. For ease of calculation, we will use this channel as the basis for our analysis of the backhaul. In addition, in order to verify the performance of the proposed scheme under complex channel models, we further add an additional fading model to the A2G channel, which additionally includes shadow fading and multipath fading. According to a mean value model of multipath and shadow fading [20], the A2G channel loss in the channel fading model can be expressed as:

$$g_{i,0}^{\dagger} = g_{i,0} + EP_b(\theta_{i,0} - EP_c), \tag{12}$$

where EP_b and EP_c are two empirical constants, which are used to adjust the relationship between elevation angle and path loss, and the effect of elevation angle on path loss respectively. Under this model, the default altitude of the UAV is set to 2.5 km [20], the side length of the rectangular active area of UAV is set to 12 km. We present additional simulation results at the end of Section 4 for this fading model under this condition.

2.2. Problem formulation

Let $G(v, s)$ denote a backhaul network directed graph to represent the formed backhaul network**,** where v denotes the location information of the UAV in the area. Let $v_i=(x_i, y_i)$ represent the horizontal two-dimensional coordinates of the UAV$_i$, s represents the connection information of UAV. Let $s_i = \{ j \text{ or } 0 \mid 1 \le j \le N \}$ represent the connection object of UAV$_i$, where j represents UAV$_j$, and 0 represents BS$_0$. Then the backhaul path of UAV$_i$ can be obtained in a recursive way and expressed as:

$$\mathbf{q}_i = \left[i,\ s_i,\ s_{s_i},\ \ldots,\ q_i^{-1} \right], \tag{13}$$

where i represents the UAV$_i$ itself, with location information v_i and connection information s_i, q_i^{-1} represents the UAV or BS that cannot continue recursion in the UAV$_i$ backhaul path, and let the length of $\mathbf{q}_i$ be K.

This paper researches the problem of maximizing the effective backhaul rate and the constraint is the maximum UAV demand rate, which can be expressed as:

$$\mathbf{P1}:\ \max \sum_{i=1}^{N} R_i^*, \tag{14}$$

where R_i^* represents the effective backhaul transmission rate of UAV$_i$. Through the equivalence relationship of R_i^*, the above formula can be expressed as:

$$\max \sum_{i=1}^{N} \min\left(\min_{k=1,2,\ldots,K-1} R_{i_k, i_{k+1}},\ C_i \right), \tag{15}$$

where i_k represents the k-th UAV in the backhaul path $\mathbf{q}_i$ of UAV$_i$, K is the length of $\mathbf{q}_i$, and $R_{i_k, i_{k+1}}$ denotes the maximum transmission rate between the k-th UAV and the k+1-th UAV (or BS) in $\mathbf{q}_i$. C_i represents the maximum demand rate of UAV$_i$, that is, the sum of the maximum demand rates of all users who are served by UAV$_i$, which means that when the data transmission rate exceeds this rate, the part is invalid. To highlight the point, this paper directly replaces this summation process with C_i. The restrictions are:

$$s_i \ne \varnothing,\ 1 \le i \le N, \tag{16}$$

$$q_i^{-1} = 0,\ 1 \le i \le N, \tag{17}$$

$$i \notin \mathbf{q}_j,\ \forall j (j \ne i) \in \mathbf{q}_i,\ 1 \le i \le N, \tag{18}$$

$$C_i = \Lambda,\ 1 \le i \le N, \tag{19}$$

$$\sum_{i \in \{i | s_i = 0\}} R_{i,0} \ge \sum_{j \in \{j | s_j \ne 0\}} R_j^* + \sum_{i \in \{i | s_i = 0\}} R_i^*, \tag{20}$$

where formula (16) ensures that each UAV can have a connection object. Formula (17) guarantees that the data can finally reach the BS. Formula (18) avoids the formation of circular links between different UAVs. Λ in formula (19) is an artificially set constant, and the value of the maximum demand rate of the service area can be changed by adjusting Λ. Formula (20) ensures that all data transmitted by the A2A channel ultimately originates from the A2G channel.

For formula (14), the ordinary traversal method cannot solve the large-scale UAV group problem (because its time complexity can reach $O(n^n)$ and there are a large number of links that cannot satisfy formula (16), (17) and (18)), so this paper proposes a UAV backhaul transmission scheme based on an improved NE strategy to solve this problem.

3. Backhaul Transmission Scheme

Due to the non-zero or one property of the congestion function in the traditional NE strategy, it is difficult to improve with a centralized scheme. Therefore, in order to solve P1, this paper decouples the entire optimization process into three steps (link preprocessing, NE process and resource recovery) and two problems (centralized optimization problem and local optimization problem).

3.1. Link preprocessing

Since the utility function acts on the backhaul network formation is sub-optimal, for example, in the service model of Fig. 1, when UAV_2 gradually approaches BS_0 until $R_{2,0} > C_2$, there may still be $s_2 = 1$ (expect that UAV_2 and BS_0 form a link at this time). Obviously this will decrease the left part of the formula (19), further because of:

$$\sum_{i=1}^{N} R_i^* = \sum_{j\in\{j|s_j\neq 0\}} R_j^* + \sum_{i\in\{i|s_i=0\}} R_i^* , \tag{21}$$

the upper limit of formula (12) will be caused to decrease. therefore, in this paper, UAVs are divided into resident UAVs and non-resident UAVs, which can be expressed as:

$$U^R = \{i \mid R_{i,0} \le \Lambda,\ 1 \le i \le N\} , \tag{22}$$

$$U^{NR} = \mathrm{U} - U^R , \tag{23}$$

where U^R and U^{NR} denote resident UAVs and non-resident UAVs respectively.

3.2. Backhaul network formation algorithm based on improved NE strategy

According to the description of NE in game theory [21], in a game formation process, NE represents a strategic profile when all individuals execute on the strategy, which means that when all individuals are satisfied that no more appropriate changes can be made when the environment remains unchanged, the whole system reaches NE. Therefore, before finding this strategy, it is necessary to figure out a utility function to judge whether the NE point is reached. The utility function [17] is denoted as:

$$u_i(G) = \frac{\sqrt{\min\limits_{k=1,2,\ldots,K-1} R_{i_k,i_{k+1}}}}{\tau_{i,\mathbf{q}_i}(G)^{0.3}} , \tag{24}$$

where G is simplified representation form of $G(v, s)$, $\tau_{i,\mathbf{q}_i}(G)$ represents the congestion level of the UAV_i backhaul path $\mathbf{q}_i$, which can be denoted as:

$$\tau_{i,\mathbf{q}_i}(G) = \sum_{k=1,2,\ldots,K-1} \left(\frac{\varphi_{i_k} + 2(R_{i_k,i_{k+1}} - \varphi_{i_k})}{2R_{i_k,i_{k+1}}(R_{i_k,i_{k+1}} - \varphi_{i_k})}\right) , \tag{25}$$

where φ_{i_k} represents the total data rate (including the rate that UAV_{i_k} itself needs to be transmitted) received by the k-th UAV in the backhaul path $\mathbf{q}_i$ of UAV_i and needs to be transmitted, and $R_{i_k,i_{k+1}}$ denotes the maximum transfer rate between the k-th UAV and the k+1-th UAV in $\mathbf{q}_i$. Note that if $R_{i_k,i_{k+1}}$ is less than φ_{i_k} for any $(i_k, i_{k+1}) \in \mathbf{q}_i$ in $\tau_{i,\mathbf{q}_i}(G)$, $\tau_{i,\mathbf{q}_i}(G)$ will be assigned with -1 to indicate that the result is invalid.

Definition 1: The connection object s_i of UAV_i can be regarded as the current strategy of the UAV_i . So for UAV_i, an overall strategy with local NE can be expressed as $s = (s_i^{NE}, s_{-i})$.

It represents a state, that is, under the condition that other UAVs' strategies s_{-i} remain unchanged, UAV$_i$ will not change the current strategy s_i, but the strategies s_{-i} of other UAVs may change in the same environment, so practically the overall strategies s do not reach the NE state. Further, the overall NE strategy is represented as $s^{NE}=(s_1^{NE},\ s_2^{NE},\ \ldots,\ s_N^{NE})=(s_i^{NE},\ s_{-i}^{NE})$, which also represents a state, that is, each UAV$_i$ will not change its strategy s_i when other UAV's strategies s_{-i} remain unchanged, and at the same time other UAVs' strategies s_{-i} are also unable to make changes in the current environment.

Then, the strategy can be linked with the NE through the utility function, and the strategy corresponding to the maximum value of each UAV's own utility function (24) can be used as the strategy goal of each UAV to find its own NE point. Since only non-resident UAVs participate in the NE process, the process is expressed as:

$$s_{i\in U^{NR}}^{NE}=\begin{cases}\arg\max u_i(G) & \text{if } \exists u_i(G)\geq 0\\ s_i & \text{else}\end{cases}. \tag{26}$$

In the process of finding the NE point, the UAV will virtually connect to each other in turn (the link formed by the connection is called a virtual link) until the above formula is satisfied. So according to definition 1 and the above formula, when a certain UAV$_i$ finds the NE point, there is $(s_i,\ s_{-i})\Rightarrow(s_i^{NE},\ s_{-i})$, where $s_i^{NE}=\{\arg\max u_i(G)\text{ or }s_i\}$. It can be clearly seen that in any case, s_i^{NE} will not change if other UAVs do not change their own strategies s_{-i}. And further, when the condition of all UAVs reach NE, which implies that the last UAV$_i$ finds the NE point, all UAVs still keep NE, that is, $s=(s_i,\ s_{-i}^{NE})\Rightarrow s^{NE}=(s_i^{NE},\ s_{-i}^{NE})$, where for any $i\in U^{NR}$, there is $s_i^{NE}=\{\arg\max u_i(G)\text{ or }s_i\}$, and the system reaches a stable state.

Since the NE of each UAV needs to meet the characteristics of the invariant environment, only one UAV can participate in the NE process at the same time (each time a s_i finds its own s_i^{NE}), so it can be defined as follows.

Definition 2: Use $s^t=(s_1^t,\ s_2^t,\ \ldots,\ s_N^t)=(s_i^t,\ s_{-i}^t)$ to represent the global strategy at time t, then for any time t+1, there is only one non-resident UAV$_i$ participates in the NE process $s^t=(s_{i\in U^{NR}}^t,\ s_{-i}^t)\Rightarrow s^{t+1}=(s_{i\in U^{NR}}^{NE},\ s_{-i}^{t+1})$, where $s_{-i}^{t+1}=s_{-i}^t$ and $s_{j\in U^R}^{NE}\subseteq s_{-i}^t,\forall t\in ¡$ exist at the same time.

According to definition 1 and definition 2, it can be obtained that there exists $t = t^*$ in the time-varying game to make the system reach the NE state, and the global strategy is expressed as $s^{t^*}=(s_1^{t^*},\ s_2^{t^*},\ \ldots,\ s_N^{t^*})=s^{NE}=(s_1^{NE},\ s_2^{NE},\ \ldots,\ s_N^{NE})=(s_i^{NE},\ s_{-i}^{NE})$ at this time. Before this, when the last UAV$_i$ finds the NE point, the other UAVs keep their strategies unchanged, that is, $s^{t^*-1}=(s_i,\ s_{-i}^{NE})\Rightarrow s^{t^*}=(s_i^{NE},\ s_{-i}^{NE})=s^{NE}$. And after that, from the previous analysis, for any $i\in U^{NR}$, there is $s_i^{NE}=\{\arg\max u_i(G)\text{ or }s_i\}$, and the system reaches a stable state, that is, $s^{t^*}=(s_i^{NE},\ s_{-i}^{NE})=s^{NE}\Rightarrow s^{t^*+1}=(s_i^{NE},\ s_{-i}^{NE})=s^{NE}$.

Lemma 1: For any moment, in the process of finding the NE point of the non-resident UAV$_i$, if there is $u_i(G)\geq 0$, there must be $R_i^*=\Lambda$, otherwise, there must be $R_i^*<\Lambda$.

Proof: When $u_i(G)\geq 0$, according to the explanation of formula (24), in the congestion function $\tau_{i,\mathbf{q}_i}(G)$, for any $(i_k,\ i_{k+1})\in\mathbf{q}_i$, $R_{i_k,i_{k+1}}$ is greater than φ_{i_k}, and for any φ_{i_k}, there is $\varphi_{i_k}\geq\Lambda$, so when k takes $k^*=\arg\min_k R_{i_k,i_{k+1}}$, there is:

$$R_{i_{k^*},i_{k^*+1}}=\min_{k=1,2,\ldots,K-1}R_{i_k,i_{k+1}}\geq\varphi_{i_{k^*}}\geq\Lambda. \tag{27}$$

So we can get $R_i^* = \min(\min_{k=1,2,...,K-1} R_{i_k,i_{k+1}}, \Lambda) = \Lambda$. When $u_i(G) < 0$, for any $(i_k, i_{k+1}) \in \mathbf{q}_i$, $R_{i_k,i_{k+1}}$ is less than φ_{i_k}, take $k^* = \arg\min_k \varphi_{i_k}$, at this time $k^* = 1$, there is $\varphi_{i_{k^*}} = \Lambda$, and $R_{i_{k^*},i_{k^*+1}} < \varphi_{i_{k^*}}$, obviously $R_{i_{k^*},i_{k^*+1}} \geq \min_{k=1,2,...,K-1} R_{i_k,i_{k+1}}$, so there is:

$$\Lambda = \varphi_{i_{k^*}} \geq R_{i_{k^*},i_{k^*+1}} > \min_{k=1,2,...,K-1} R_{i_k,i_{k+1}}. \tag{28}$$

So $R_i^* = \min(\min_{k=1,2,...,K-1} R_{i_k,i_{k+1}}, \Lambda) < \Lambda$. Certificate completed.

This lemma proves that in the NE process which UAV participates, once the A2A link can be accessed, there must be at least one virtual link so that the maximum backhaul data transmission rate is not less than the maximum demand rate. Otherwise, all virtual links cannot meet the maximum demand rate.

In the NE process, from time *t* to time *t*+1, there is $s^t = (s^t_{i\in U^{NR}}, s^t_{-i}) \Rightarrow s^{t+1} = (s^{NE}_{i\in U^{NR}}, s^{t+1}_{-i})$, and UAV$_i$ reaches the NE point. However, when $s^{t+1} = (s^{t+1}_{j\in U^{NR}}, s^{t+1}_{-j}) \Rightarrow s^{t+2} = (s^{NE}_{j\in U^{NR}}, s^{t+2}_{-j})$ from time *t*+1 to time *t*+2, due to $s^t_j \in s^t_{-i} \Rightarrow s^{NE}_j \in s^{t+1}_{-i}$, the environment changes, and there may be $s_i^{t+1} \neq s_i^{NE}$ at this time, so the equalization fails, and the UAV needs to participate in the NE process again. To solve this problem, the sum of the participation of each non-resident UAV in one NE process is regarded as one iteration and the backhaul network after the iteration is denoted as $G^n(v, s)$, where *n* represents the *n*-th iteration. The game relationship for each iteration is given below.

Since only one UAV can participate in the NE process at each time *t* increases, this paper adopts a probability density method in a hybrid NE strategy [21] to control the orderly participation of all UAVs in the NE process. Besides, since each non-resident UAV can only participate in the NE process once in each iteration, the following definition is given.

Definition 3: Use $\chi(t)$ to represent all UAV sequences waiting to participate in the NE process at time *t* in each iteration, and there is $\chi(t) = \chi(t-1) - i$ after each UAV$_i$ participates in the NE process, and $\chi(0) = U^{NR}$ is initialized after each iteration. Let $\psi(s_i^t)$ denotes the probability that UAV$_i$ participates in the NE process when time *t* increases.

According to the probabilistic and statistical properties in Definition 3, a restriction will obviously be added:

$$\sum_{i=1}^{N} \psi(s_i^t) = 1. \tag{29}$$

In addition, according to Lemma 1, it can be known that the A2A link can be accessed only when the maximum demand rate of the UAV is fully satisfied in the NE process. On the contrary, even if there is an A2A link that can meet most of the maximum demand rates, it cannot be accessed and will be rejected by the link. This UAV is denoted as U^J, and the UAV that can access the A2A link is denoted as U^{NJ}. In the NE process, it is obviously only possible that U^{NJ} will have a positive effect on optimization (15). Therefore, in the process of solving $\max_{G(v,s)} \sum_{i\in U^{NJ}} R_i^*$, combined with the constraints, it can be further written as:

$$\textbf{P1-a}: \max_{G(v,s)} \sum_{i\in U^{NJ}} \Lambda, \tag{30}$$

$$\textbf{s.t.}\ (15),(16),(17),(18),(19),(28).$$

Since U^{NJ} is obtained after $G^n(v, s)$ is determined, and Λ is a constant. This problem can be equivalent to finding the maximization of the length of U^{NJ}. Specifically, in the process of each iteration, when time *t* increases, the non-resident UAV participating in the NE process satisfies the following probability allocation strategy:

$$\begin{cases} \psi(s^t_{i^*}) = 1, i^* = \arg\max_i \{\|v_i - (x_0,\ y_0)\| \mid i \in \chi(t)\} \\ \psi(s^t_{-i^*}) = 0 \end{cases} \tag{31}$$

where v_i and (x_0, y_0) represent the horizontal two-dimensional coordinates of UAV_i and BS_0, respectively. This strategy means that the UAV with the farthest distance from the BS preferentially participates in the NE process.

Through the probability allocation strategy (31), the sequence of the non-resident UAV participating in the NE process in each iteration can be obtained. According to this sequence, the strategy of each UAV participating in the NE process is updated through (26), until $\chi(t) = \varnothing$. Then, this iteration ends and the next iteration begins until the formed backhaul network is the same as the previously formed backhaul network. The whole algorithm process (including the preprocessing process) is summarized as the algorithm 1.

The algorithm maximizes the effective backhaul transmission rate of UAVs by maximizing the U^{NJ} length, and prioritizes non-resident UAVs with poor A2G channels during the NE process, which reduces the link loss for UAVs in A2G channels that are rejected by the A2A link.

Overall, since all UAVs are taken into account in the algorithm, the process can act as a centralized optimization for the formation of the entire backhaul network. However, due to the link exclusion phenomenon in the NE process, some non-resident UAVs cannot obtain efficient A2A transmission channels, so these UAVs will be optimized locally.

Algorithm 1 Backhaul network formation algorithm based on improved NE strategy.

1. Initialize $G^{n=0}(v,\ s)$, where $s_i = 0, i \in U$.
2. UAV is divided into U^R and U^{NR} by (22)(23).
3. **do**
4. Initialize $\chi(t=0) = U^{NR}$.
5. **While** $\chi(t) \neq \varnothing$ **do**
6. Obtain *i** participating in the NE process through (31);
7. Obtain the corresponding strategy after *i** reaches NE through (26);
8. update strategy $s^t = (s^t_{i^*},\ s^t_{-i^*}) \Rightarrow s^{t+1} = (s^{NE}_{i^*},\ s^{t+1}_{-i^*})$;
9. *t*++;
10. $\chi(t) = \chi(t-1) - i^*$;
11. **end while**
12. *n*++;
13. Save the backhaul network $G^n(v,\ s)$ formed by this iteration;
14. **until** $\exists n^* < n$, $G^n(v,\ s) = G^{n^*}(v,\ s)$.
15. Output $G(v,\ s)$ at the *n*-th iteration and U^J.

3.3. Resource recovery

In this section, this scheme is further optimized locally for UAVs which are rejected by A2A links during the NE process. According to Lemma 1, it can be seen that the NE process has a non-zero or one characteristic for the conditions of UAV access to the A2A link, so the backhaul capability of most UAVs has not reached saturation. Therefore, an optimal access matching process can be performed on the U^J by calculating their backhaul transmission margins, thereby further improving the overall effective backhaul transmission rate of the system.

In the backhaul path $\mathbf{q}_i$ of UAV$_i$, data flows from i_k to i_{k+1}, and then from i_{k+1} to i_{k+2}, until it finally flows to the BS. Therefore, the backhaul transmission margin of UAV$_i$ depends on the minimum value of the transmission margin of the backhaul channel in the backhaul path $\mathbf{q}_i$, which can be denoted as:

$$R_{i,\mathbf{q}_i}^{rest} = \min\{R_{i_k,i_{k+1}} - \varphi_{i_k} \mid k = 1, 2, \ \dots \ , K\}, \tag{32}$$

where $R_{i_k,i_{k+1}} - \varphi_{i_k}$ represents the backhaul transmission margin of the channel between the k-th UAV and the k+1-th UAV in the backhaul path $\mathbf{q}_i$.

In the NE process, since each UAV can meet the data transmission rate requirements from other UAVs in parallel, there is no transmission queuing problem, so the maximum effective backhaul transmission rate can be expressed by equation (15). In this section, when the data rate overflows the backhaul transmission margin after UAV$_i$ is connected to an A2A link, there will be a transmission queuing problem. Therefore, the UAV$_i$ effective backhaul transmission rate involved in the resource recovery process in this section can be equivalently expressed as:

$$R_i^* = \min\{R_{s_i,\mathbf{q}_i}^{rest}, \ R_{i,s_i}\}, i \in U^J, \tag{33}$$

where $R_{s_i,\mathbf{q}_i}^{rest}$ represents the backhaul transmission margin of the object (UAV or BS) to which the UAV$_i$ is connected, and R_{i,s_i} represents the maximum transmission rate of the channel between the UAV$_i$ and the connected object. Since BS does not have the problem of backhaul saturation, when $s_i = 0$, there is $R_{0,\mathbf{q}_0}^{rest} = \infty$.

After obtaining the effective backhaul transmission rate of U^J, the local optimization problem in this section can be expressed as:

$$\textbf{P1-b}: \max_{G(v,s)} \sum_{i \in U^J} \min\{R_{s_i,\mathbf{q}_i}^{rest}, \ R_{i,s_i}\}, \tag{34}$$

$$\textbf{s.t.} \ (16),(17),(18),(19),(20).$$

According to (30), it can be easily deduced that in a tree-like backhaul network formed by all UAVs that has a backhaul relationship with a non-resident UAV as the root, the closer the UAV to the BS is, the more the backhaul transmission margin is. At the same time, when the backhaul transmission margin of any UAV in this type of tree-like backhaul network decreases, the upper limit of the backhaul transmission margin of the entire network will also decrease. Therefore, for the U^J, the UAV in the backhaul path will be preferentially selected as the A2A channel access object to maximize $R_{s_i,\mathbf{q}_i}^{rest}$. However, the effective backhaul transmission rate takes $\min\{R_{s_i,\mathbf{q}_i}^{rest}, \ R_{i,s_i}\}$, so when $R_{s_i,\mathbf{q}_i}^{rest} > R_{i,s_i}$, the access object will be extended to the previous access object (the extension direction is the opposite direction along the backhaul path) until $R_{s_i,\mathbf{q}_i}^{rest} \le R_{i,s_i}$. **Fig. 2** shows the entire optimized access matching process.

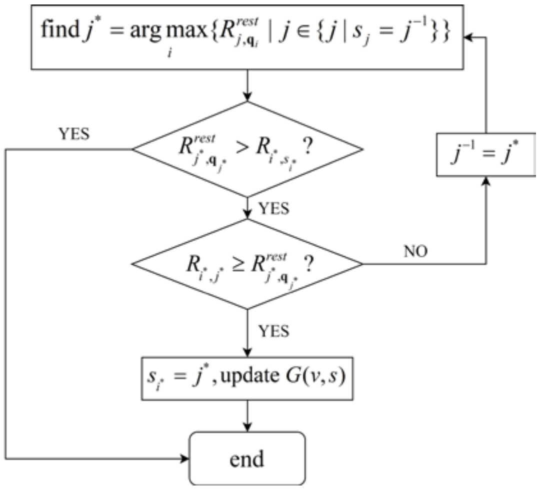


Fig. 2. Optimized access matching process

where j^{-1} represents the previous access object, and the initial value of j^{-1} is 0, which means BS_0.

Similar to (31), in U^J, i* which is far away from BS is also preferentially selected for resource recovery process. The greedy algorithm is used to optimize the access matching process for i*, and the non-resident UAV with the largest backhaul transmission margin is preferentially selected for A2A link access. Use χ^J to represent the UAV initialization sequence that is rejected by the link, so the whole process can be summarized as the following algorithm 2.

Algorithm 2 Resource recovery
1. Get $G(v,s)$, U^J by solving **P1-a.**
2. Initialize $\chi^J = U^J$
3. **While** $\chi^J \neq \varnothing$ **do**
4. Find $i^* = \arg\max_i \{\lVert v_i - (x_0, y_0)\rVert \mid i \in \chi^J\}$;
5. Perform the access matching process as shown in **Fig. 2** on i^*;
6. Remove i^* from χ^J;
7. **end while**
8. Output current $G(v,s)$

4. Results and Analysis

In this section, we first compare the effects of different schemes on the system backhaul performance without additional channel fading and conduct a detailed analysis. Then, we further give a comparison of the performance of different schemes under the condition of additional channel fading, so as to verify the effectiveness and generality of the algorithm in more complex channels. The algorithm is tested in Windows 11 system, Python platform, and all the simulations are performed on a laptop with a AMD Ryzen 7 5800H with Radeon Graphics (3.20 GHz) CPU.

The performance indicators contain three aspects: the average effective backhaul transmission rate R^*_{av} of the system, the minimum effective backhaul transmission rate R^*_{min}

and the number of iterations. Among them, R_{av}^{*} represents the overall common performance improvement of the system, and R_{min}^{*} represents the balanced performance improvement of the system. The possible influencing factors include the signal transmit power p of the UAV, the maximum demand rate Λ of the UAV, and the number N of UAVs in the service area.

We consider that UAV obeys a random distribution in the active area of 4 km × 4 km. At this time, the UAV and the remote BS need to establish a specific backhaul topology structure so as to supply the communication services for terrestrial users. **Table 1** shows the relevant simulation parameters under the default conditions.

Table 1. Simulation parameters

Parameters	Value
h	100 m
α	9.6
β	0.28
f	2 GHz
B	40 MHz
μ^{Los}	1 dB
μ^{NLos}	20 dB
σ^2	-90 dBm
EP_b	-1.85
EP_c	1.41

In addition, in order to ensure the reliability of the data, the simulation results are all from the average value of 100 random distributions. At the same time, when there is no additional description, we set the number of UAVs to 15, the maximum demand rate to 8 Mbps, and the transmit power of UAVs to 20 dBm as the default simulation parameters.

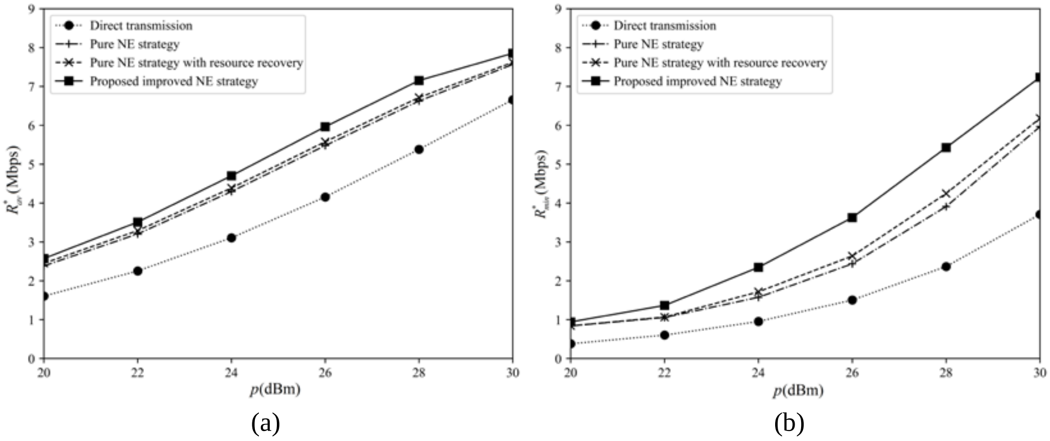


Fig. 3. The relationship between UAV transmission power and the average effective backhaul rate and the minimum effective backhaul rate under different schemes.

Fig. 3 shows the influence of p on R_{av}^{*} and R_{min}^{*}, respectively. Obviously, the increase of p will significantly improve the backhaul capability of UAV, which stems from more resident UAVs and more accessible A2A links and backhaul transmission margin. **Fig. 3 (a)** shows that compared with the direct connection base station scheme and the pure NE strategy, the proposed improved NE strategy has an average improvement of 37% and 7.4% in the indicator R_{av}^{*} (only from p = 20 dBm to p = 30 dBm). Among them, the maximum increases are 59.9% (p = 20 dBm), 9.5% (p = 22 dBm), and the minimum are 17.9% (p = 30 dBm) and 3.8% (p =

30 dBm). Besides, the growth rate of the proposed scheme in the pure NE strategy shows a climate which is first increasing and then decreasing. This is because when the link conditions have not yet reached the maximum demand rate for all UAVs to pass through the A2G link, as p increases, there will be more and more resident UAVs. Non-resident UAVs whose A2G link cannot reach the maximum demand rate can have an efficient backhaul transmission channel, by forming a multi-hop backhaul network with the resident UAV as the root. Therefore, within a certain range of p growth, the performance improvement is more obvious. And when p reaches a certain level, there will be fewer and fewer non-resident UAVs. As a result, the effect of channel optimization targeting the effective backhaul rate will become less prominent under the condition that the maximum demand rate remains unchanged, and the room for improvement will become smaller and smaller. There is obviously a similar feature effect in **Fig. 3 (b)**, but unlike **Fig. 3 (a)**, the performance improvement of the proposed scheme on R^*_{min} is significantly better than R^*_{av}. **Fig. 3 (b)** shows that, compared with the direct connection base station scheme and the pure NE strategy, the proposed improved NE strategy has an average improvement of 119.9% and 32.6% in the indicator R^*_{min}, respectively. Among them, the largest increases are 146.9% (p = 20 dBm) and 48.8% (p = 24 dBm), and the smallest are increased by 95.1% (p = 30 dBm) and 12.1% (p = 20 dBm). In addition, compared with the pure NE strategy, the optimization effect of resource recovery is increased by an average of 1.6% for R^*_{av} and an average of 5.7% for R^*_{min}. In general, the proposed scheme has different degrees of performance improvement under different conditions, more consideration of the balance of the system, and a more obvious improvement in the index of the minimum UAV effective backhaul rate in the system.

In addition, what is worth noting is that since most of the backhaul environments formed under random distribution are poor, neither the pure NE strategy nor the improved NE strategy can form an efficient backhaul network. This thus neutralizes the significant improvement brought by the improved NE strategy in the case of a favorable backhaul environment. Simulations show that in 100 independent experiments with random distribution, compared with the direct connection to the base station and the pure NE strategy, the proposed scheme can achieve a maximum improvement of 360.6% and 53.6% in total effective backhaul data rate, respectively.

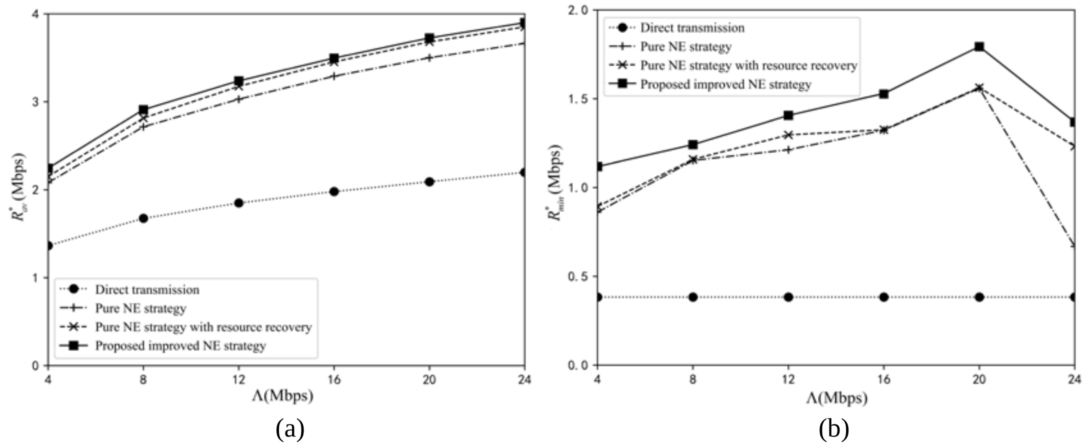
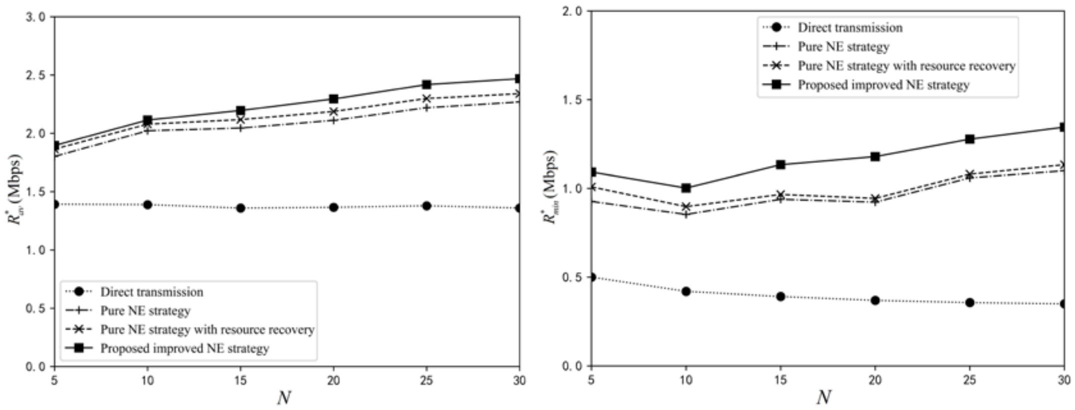


Fig. 4. The relationship between the maximum demand rate and the average effective return rate and the minimum effective return rate under different scenarios.

Fig. 4 (a) and **Fig. 4 (b)** show the effect of Λ on R^*_{av} and R^*_{min}, respectively. What can be found from **Fig. 4 (a)** is that although the improvement of Λ improves R^*_{av} on the surface, it actually reduces the quality of service (the ratio of R^*_{av} to Λ). This is because with Λ improving, the sum of resident UAVs and their channel transmission margins are constantly decreasing, which leads to a large number of UAVs rejected by A2A links in the NE process and resource shortage in the resource recovery process. These UAVs are thus forced to transmit data directly to the BS through inefficient A2G channels. Therefore, in the scenario where the service area requires high throughput and the UAVs are deployed far away from the BS, it is difficult to come into being a good multi-hop backhaul network, the absolute optimization effect brought by the proposed scheme is very limited. For example, when Λ is 4 Mbps in **Fig. 4 (a)**, on average, each UAV can satisfy more than 50% of Λ, but when Λ is 24 Mbps, the average proportion of Λ satisfied by each UAV is less than 17%. At present, it is difficult to find a useful method to solve this problem without changing the position of the UAV after deployment. In addition to the above conclusions, also what can be found from **Fig. 4 (a)** is that with the Λ improving, the backhaul scheme with the resource recovery process increases the average backhaul rate of the system more and more and gradually coincides with the improved NE strategy scheme. This is because resource recovery is the continuous utilization of channel resources, and the NE is a process of determining whether to access the channel by judging whether the Λ of the UAV is fully satisfied, and its access requirements are non-zero or one. The increase of Λ will continuously reduce the available backhaul channel transmission margin, thereby reduce the probability of UAV finding the NE point in the process of participating in the NE, and increasing the fragmented backhaul transmission margin. Therefore, the main optimization effect is changed from improving the NE strategy to the resource recovery process. What can be seen from the **Fig. 4 (b)** is that except the minimum backhaul rate of the directly connected BS remains unchanged with the increase of Λ, the minimum backhaul rates of the other three optimization schemes both show a climate of first increasing and then decreasing. This is because when Λ is not enough high, the number of resident UAVs is large, and the backhaul transmission margin is also larger than that of Λ, so the factor limiting the minimum backhaul rate in UAV is mainly Λ. With the further increase of Λ, the resident UAV will continue to decrease, so it cannot provide enough channel transmission resources for the UAV that is far away from the BS to use, resulting in a sharp drop in the minimum backhaul rate of the system. Furthermore, it is more obvious that there is a maximum value when Λ is equal to 20 Mbps. This feature is actually related to the quality of the UAVs' backhaul environment. If the UAVs' backhaul environment is better (e.g., the channel interference is smaller or the channel distance is shorter), $\exists \Lambda^* > \Lambda,\ R^*_{min}(\Lambda^*) > \Lambda$, increasing Λ may increase R^*_{min}. At this time, the Λ corresponding to the maximum value of R^*_{min} will also increase.



(a) (b)

Fig. 5. The relationship between the sum of UAVs and the average effective backhaul rate and the minimum effective backhaul rate under different schemes.

Fig. 5 (a) and **Fig. 5 (b)** show the influence of N on R_{av}^* and R_{min}^*, respectively (here the maximum demand rate Λ is set to 4 Mbps). What can be seen from the **Fig. 5 (a)** is that R_{av}^* shows an increasing climate with the increase of N. This is because the increase of R_{av}^* brought by the increase of resident UAV in the proposed scheme is greater than the decrease of this indicator caused by non-resident UAV. Specifically, although the increase of N increases the resident UAV and the non-resident UAV in the same proportion as before, the effect of the former on the improvement of the backhaul performance is greater than the effect of the latter on the decrease of the backhaul capacity, so that the curve shows an upward climate. In terms of performance improvement, compared with the direct connection to the base station scheme and the pure strategy NE scheme, the proposed scheme has an average improvement of 62.3% and 7.4% in the index R_{av}^* (only from N = 5 to N = 30). Among them, the largest increase are 81.5% (N = 30 at this time), 8.9% (N = 25 at this time), and the smallest increase are 36.2% (N = 5) and 4.5% (N = 10). What can be seen from the **Fig. 5 (b)** is that there are different variation characteristics under different backhaul schemes. Under the direct connection base station scheme, the minimum backhaul rate reduces gradually with the N heighten. The change of the minimum backhaul rate is not stable under the pure NE strategy scheme and the pure NE strategy scheme with resource recovery process. While the proposed improved NE strategy maintains a relatively high minimum backhaul rate index, the index is also relatively stable. Compared with the direct connection base station and pure NE strategy, the proposed scheme has an average improvement of 194.5% and 21.2% in the index R_{min}^*, respectively. Among them, the largest increase was 284.6% (N = 30), 27.8% (N = 20), and the smallest was 118.4% (N = 5) and 17.4% (N = 10). This is because the improved equalization system preferentially selects UAVs with poor channels to access the A2A link, and determines the NE conditions and performs the NE process for them, so as to achieve two equalizations of access equalization and transmission equalization. By ensuring the access rationality of the two link types, including A2A and A2G, the performance balance of the UAV backhaul link is improved.

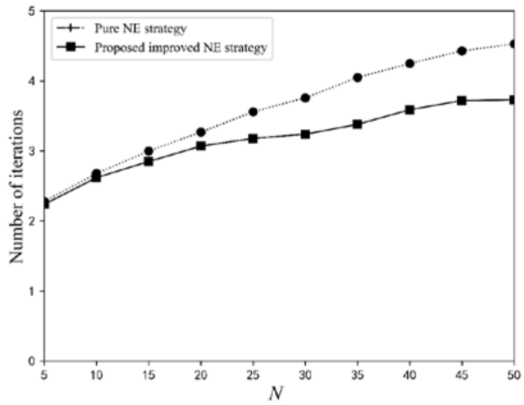


Fig. 6. The relationship between the sum of UAVs and the number of iterations

Fig. 6 shows the influence of N on the number of algorithm iterations under different schemes (in order to allow more UAVs to participate in the NE process, the maximum demand rate Λ is set to 1 Mbps here). Compared with the pure NE strategy, the improved NE strategy reduces the number of iterations by 11.7% on average (only from $N = 5$ to $N = 50$). Among them, the highest decrease is 17.6% ($N = 50$), and the lowest is 1.7% ($N = 5$). Therefore, what can be found is that the larger the N, the more iterations of the two NE strategies, and the greater the decrease in the number of iterations of the proposed improved NE strategy, compared to that of the pure NE strategy. On the one hand, because the link preprocessing process cuts back the number of UAVs participating in the NE process, the whole iterative system becomes simpler. On the other hand, it may be because the proposed strategy is more in line with the control mode of the utility function for the UAV, that is to say, the action of finding the NE point of the selected UAV in the process of participating in the NE correspond the expected maximum value of the utility function to a higher degree. This reduces the probability that the UAV iterates further to find better NE points and thus has the effect of reducing the number of iterations. It is worth noting that the NE convergence conditions in the proposed scheme are not the same as the traditional convergence conditions. The latter compares the backhaul network formed by the current iteration with the previous iteration to determine whether the NE has converged. In this paper, once the backhaul network formed is the same as the backhaul network formed by any previous iteration, the iteration is stopped, so as to complete the rapid convergence of NE. However, in our actual simulation, it is found that most of the NE processes still conform to the traditional convergence mode, and a small number of NE processes fall into a loop. However, considering that improving this situation is not ideal for strengthening the performance of the backhaul system, from the perspective of the problem solved in this paper, it is more appropriate to use the former convergence condition.

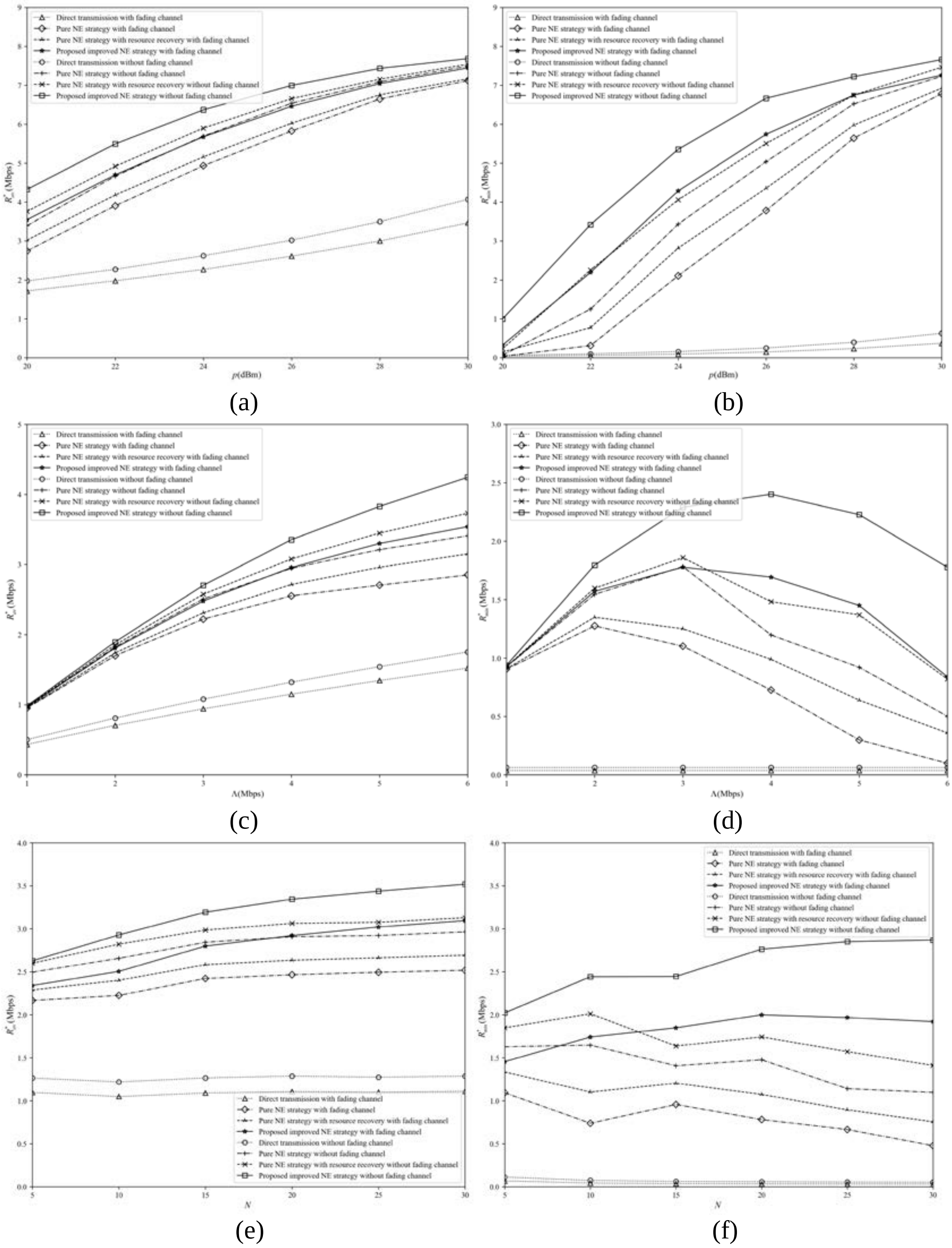


Fig. 7. Influence of different variables on system performance under different schemes and channel models

Fig. 7 shows the effects of different schemes on R_{av}^{*} and R_{min}^{*} when the UAV flight altitude is set to 2.5 km and the active area of UAV is set to 12 km (amplify the negative effects of channel fading), under two different channel models (with and without additional multipath and shadowing fading). This verifies the effectiveness and universality of the proposed algorithm under more complex channel models. The results of **Fig. 7 (a)** and **Fig. 7 (b)** show that in the presence of additional channel fading, the proposed improved NE strategy achieves an average improvement of 131.9% and 11.8% on the index R_{av}^*, respectively, comparing to the direct connection to the base station and the pure NE strategy. And the index R_{min}^* is much larger than the former, which is an average increase of 42.3%, comparing to the latter. Compared with no additional channel fading, the proposed scheme has an average reduction of 8.9% in the index R_{av}^* and an average of 15.2% in the index R_{min}^* under the condition of additional channel fading. It can be seen that although the fading leads to the decline of the performance of all aspects of the system, it does not affect the relative improvement brought by the improved NE strategy in the absolute environment, which verifies the generality of the algorithm. **Fig. 7 (c)** and **Fig. 7 (d)** show the effect of Λ on R_{av}^* and R_{min}^* in the two different channel models, respectively, and the overall analysis is similar to the previous one in **Fig. 4**. However, it is worth noting that in **Fig. 7 (d)**, the maximum value of R_{min}^* corresponds to different Λ in different channel environments. This is due to the additional channel fading that causes the link budget provided by the resident UAV to be insufficient to meet the link requirements of the non-resident UAV before the channel change. At this time, the UAV with the smallest effective backhaul rate will become more disadvantaged in the game due to the tightening of the link budget of other UAVs. At this time, if the effective backhaul rate of the UAV is less than a certain Λ^* (a certain value smaller than the current Λ), it is possible to achieve a larger effective backhaul rate in the Λ^*, so as to achieve the change effect in the figure. In addition, it can also be seen that the proposed scheme corresponds to a larger Λ when R_{min}^* reaches the maximum value. This means that although a small increase in Λ leads to a tightening of the backhaul link budget, due to the improved NE, the effective rate of the entire backhaul of the system is more reasonably amortized by UAVs in different backhaul environments. This makes the shrinkage of backhaul resources still within an acceptable range while R_{min}^* increases as Λ increases. **Fig. 7 (e)** and **Fig. 7 (f)** show the effect of N on R_{av}^* and R_{min}^* under two different channel environments, respectively. The effect shown by **Fig. 7 (e)** is basically similar to the previous one in **Fig. 5 (a)**, but the part of the curve shown by **Fig. 7 (f)** is slightly different from the previous one in **Fig. 5 (b)**. It can be seen that both the pure NE strategy and the pure NE strategy with the resource reuse process show a trend that R_{min}^* gradually decreases with the increase of N, no matter in the extra fading channel or the non-extra fading channel. Obviously, this is not the same as the previous trend of R_{min}^* increases as N increases in **Fig. 5 (b)**. This is due to the significant increase in the relative distance between the different UAVs that appear randomly when the active area changes from 4 km to 12 km. This results in a significant reduction in the capacity of the resulting A2G link and A2A link. Since the pure NE strategy does not consider the access priority, as N increases, on the one hand, UAVs that are farther away from the base station and have a worse backhaul environment may appear. On the other hand, more UAVs occupy limited link resources, and due to the probability relationship, it is difficult for newly emerged UAVs to be regarded as non-resident UAVs. These factors lead to a decreasing trend of R_{min}^* as N increases, although R_{av}^* shows an upward trend. And the proposed improved strategy, because the priority access mode of UAV is added in the NE process, the weak link resistance is stronger in the index R_{min}^*.

In general, the additional channel fading will have a negative impact on the link network formed by the NE strategy, but will not affect the relative improvement brought by the NE strategy and the improved NE strategy. At the same time, according to the comparison of the simulation results of the two channel environments, it can be seen that the influences of different parameters on each performance index are basically similar, although the channel environments are different. This verifies the relative effectiveness of the proposed scheme in a harsher channel environment.

5. Conclusion and Future Work

This paper studies how to form an efficient backhaul network to maximize the effective backhaul transmission rate, after UAV deployment is completed and limited by the maximum demand rate, and proposes a UAV backhaul transmission scheme based on an improved NE strategy. The simulation confirms the truth, which is that the proposed scheme has a significant backhaul capacity promotion compared with the directly connected base station. Under the default simulation conditions, compared with the pure NE strategy equalization scheme, the average effective backhaul performance is improved by about 10%, of which the maximum improvement can reach 42.2%, and the minimum improvement is 0%. The minimum effective backhaul performance is improved by an average of 28.5%, of which the maximum improvement can reach 668.8%, the minimum improvement is 0%, and the number of iterations is reduced by an average of 5%. And under A2G channel conditions with additional shadow and multipath fading, the effective backhaul performance is improved by an average of 11.8%, and the minimum effective backhaul performance is improved by an average of 42.3%. It is proved that under more complex channels, the relative improvement is still obvious, or even more.

Since some of the above test results are averages measured under random distribution of drones, the backhaul environment of drones is poor in most cases. This will offset the significant performance of the scheme in some good backhaul environments. Therefore, in the future, further research can be carried out on the relationship between position migration and backhaul of UAVs to explore how to create a good backhaul environment. From the data in the previous paragraph, it can be seen that in some cases, using the NE method to deal with the link problem can get a considerable performance improvement. However, when analyzing problems using NE at present, the utility function needs to be artificially designed. This means that on the one hand a lot of work is required to design the utility function, and on the other hand, the efficiency of the utility function cannot be guaranteed. Therefore, more in-depth research on the adaptive mode of utility function setting can be carried out in the future, which has far-reaching significance for the NE in analysis of problem.

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