Resource Management for Heterogeneous Aerial Networks with Backhaul Constraints

Daosen Zhai*, Qiqi Shi*, Haotong Cao†, Sahil Garg‡, Xi Chen§, Rongxing Lu¶
*Northwestern Polytechnical University, Xi'an, Shaanxi, 710072, China
†The Hong Kong Polytechnic University, Hong Kong SAR, China
‡Resilient Machine Learning Institute (ReMI), Montreal, QC H3C 1K3, Canada
§School Of Computer Science, McGill University, Montréal, QC H3A 2A7, Canada
¶Faculty of Computer Science, University of New Brunswick, Canada E3B 5A3
(e-mail: zhaidaosen@nwpu.edu.cn, shiqiqi@mail.nwpu.edu.cn, haotong.cao@polyu.edu.hk, garg.sahil1990@gmail.com, xi.chen11@mcgill.ca, rlu1@unb.ca)

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***Abstract*—In this paper, we study the coverage maximization problem in the aerial networks. Specifically, we propose a heterogeneous aerial network (HetAN) consisting of a high-altitude base station (HBS) acting as a hub to provide wireless backhaul and multiple low-altitude BSs (LBSs) acting as access points to provide on-demand wireless coverage. Besides, we adopt the non-orthogonal multiple access (NOMA) technique for the uplink transmissions of the terrestrial users so as to support massive connections. Then, we formulate a joint power control, channel assignment, and rate control problem with the objective to maximize user connectivity and network throughput. Based on the graph methods and theoretical analysis, we propose an efficient iterative algorithm to solve the formulated problem. Simulation results demonstrate that our algorithm outperforms the other schemes in terms of connectivity and throughput.**

***Index Terms*—Aerial networks, resource management, non-orthogonal multiple access, wireless backhaul.**

I. Introduction

The Internet of Everything (IoE) is becoming a reality thanks to the rapid development of communication technologies in the era of 5G. The IoE connects people, machines, and things together, enabling them to interact with each other and carry out complex activities in an intelligent and autonomous way. In the previous mobile communication systems, increasing the base station (BS) density and reducing the coverage area of the cell are mainly adopted to enhance the network coverage performance [1]. However, in the future B5G/6G, continuing to increase the BS density will incur some severe problems, such as strong inter-cell interference, frequent handover, high deployment cost, etc [2]. To enable the IoE everywhere, we need to explore new networking techniques to further upgrade the network coverage capability, such as user connectivity and network throughput.

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Unmanned aerial vehicle (UAV) based communication is considered as a promising way to realize the vision of everywhere IoE. Owing to its high maneuverability [3], the UAV equipped with BS can be easily and quickly deployed to provide on-demand communication services in emergency or temporary scenarios [4]. Furthermore, it is challenging for the UAV-based networks to support the massive amount of connections in the IoE. To tackle this challenge, we apply the non-orthogonal multiple access (NOMA) technique which is a key technology for supporting the massive connectivity in the IoE [5]. Another challenge lies in the limited capacity of the wireless backhaul links. Millimeter-wave (mmWave) frequency bands with much wider bandwidth from 30 GHz to 300 GHz is a promising solution to cope with this challenge [6]. Owing to its huge spectrum bandwidth and beam-based directional transmission, employing mmWave for wireless backhaul link has attracted widespread interest.

Recently, a large number of research efforts have been dedicated to the use of NOMA or mmWave technologies for UAV-based networks. For NOMA, Qin et al. in [7] proposed a heterogeneous network consisting of a high altitude platform station. In [8] and [9], the weighted max-min fairness problem for UAV-assisted NOMA-based cellular networks was studied by jointly optimizing the user clustering and power allocation. In [10], the spectrum and energy efficiency problem for UAV-aided cellular networks was investigated. To minimize the total power of the system, a scheduling problem was formulated and effective optimization algorithms were proposed to deal with it. For mmWave, Cao et al. in [11] focused on the UAV-aided maritime communication systems, where mmWave integrated with the multi-antenna beamforming technique is used to achieve the maximization of the backhaul capacity. Tafintsev et al. in [12] evaluated the system performance of the UAV-based integrated access and backhaul mmWave network. Furthermore, Kumar et al. in [13] optimized the resource allocation to maximize the total data rate while guaranteeing the rate requirement of each user.

However, there are few works combining NOMA and mmWave with the heterogeneous aerial networks (HetANs).

The HetANs working as a team have more advantages including scalability, survivability, and robustness [14], making it a promising method to achieve wide-area and high-capacity wireless coverage. Thus, we investigate the coverage maximization problem for the NOMA-based HetANs with mmWave backhaul links. Specifically, we put forward a new HetAN architecture composed of a high-altitude BS (HBS) and multiple low-altitude BSs (LBSs). The HBS using the mmWave acts as a hub to provide wireless backhaul for the LBSs, and the LBSs provide on-demand wireless coverage for the terrestrial users (TUs). To maximize the user connectivity and network throughput, we first propose the joint power-and-channel control algorithms based on theory analysis and graph methods, and then devise the rate control algorithm to satisfy the backhaul constraints. Finally, we conduct simulations to evaluate the performance of our proposed algorithms.

II. System Model and Problem Formulation

A. System Model

We consider a double-layer network consisting of a HBS, N LBSs, and M TUs, as shown in Fig. 1. The LBSs and TUs are denoted by $\mathcal{N}$ and $\mathcal{M}$ respectively. The HBS acts as a hub to provide wireless backhaul for the LBSs by using the mmWave frequency bands. Compared with the dynamic LEO, the HBS is more reliable. The bandwidth of the backhaul link from the HBS to the ground station (GS) is B_1, and that from each LBS to the HBS is B_2. There is no mutual interference through spectrum planning. Besides, we adopt the uplink NOMA for the TUs on the sub-6GHz to support massive connectivity. Each LBS has K orthogonal channels denoted by $\mathcal{K}$, and the frequencies among different LBSs are also orthogonal. The bandwidth of each channel in the LBSs is B_3, which can be reused by at most $\mathit{\Delta}$ TUs (i.e., each LBS can support at most $K\mathit{\Delta}$ TUs.) constrained by the SIC decoding capability.

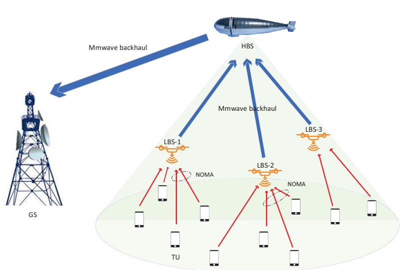


Fig. 1. A NOMA enhanced heterogeneous aerial network.

The TUs associate with the LBSs by the criteria of the maximum received signal strength indicator (RSSI). The set of the TUs associated with LBS n is denoted by $\mathcal{M}_n$. The channel power gain (CPG) from TU m to LBS n is defined as g_m^n. Since there are almost no obstacles between the HBS and the LBSs, we adopt the free space model, given by

$$PL_{LoS} = 32.44 + 20\log_{10}(d) + 20\log_{10}(f_c), \tag{1}$$

where d is the distance between the transmitter and the receiver (meters), and f_c is the carrier frequency (GHz).

For the channels between the LBSs and the TUs, we use the probability model as in [15], where The NLoS model is

$$PL_{NLoS} = 32.4 + 30\log_{10}(d) + 20\log_{10}(f_c). \tag{2}$$

Let $\mathbf{S} = \left\{ s_{m,k}^n \right\}$ denote the channel assignment indicators, where $s_{m,k}^n = 1$ represents that TU m occupies channel k of LBS n, otherwise $s_{m,k}^n = 0$. Let $\mathbf{P} = \{p_m^n\}$ denote the power control variables, where p_m^n denotes the transmission (TX) power of TU m in $\mathcal{M}_n$. Given the control policy $\{\mathbf{S}, \mathbf{P}\}$, the signal-to-interference-plus-noise ratio (SINR) of TU m in $\mathcal{M}_n$ on channel k can be expressed as

$$\gamma_{m,k}^n = \frac{s_{m,k}^n p_m^n g_m^n}{\sum_{i \in \left\{ \mathcal{M}_n | g_i^n < g_m^n \right\}} s_{i,k}^n p_i^n g_i^n + B_3 N_0}, \tag{3}$$

where N_0 represents the noise power spectral density (NPSD). So, the SINR of TU m in the network is $\gamma_m^n = \sum_{k \in \mathcal{K}} \gamma_{m,k}^n$.

Let $\mathbf{R} = \{R_m^n\}$ denote the rate set, where R_m^n is the achievable data rate of TU m in LBS n, i.e.,

$$R_m^n = B_3 \log_2 (1 + \gamma_m^n). \tag{4}$$

Then, the network throughput is

$$R_{\text{tot}} = \sum_{n \in \mathcal{N}} R_n = \sum_{n \in \mathcal{N}} \sum_{m \in \mathcal{M}_n} R_m^n. \tag{5}$$

The channel capacity of the backhaul from LBS n to the HBS is denoted by C_n, and that from the HBS to the GS is denoted by C_0. Owing to the backhaul constraints, $R_n \le C_n$ and $R_{\text{tot}} \le C_0$ must be satisfied. Define θ as the decoding threshold (affects the coverage radius) and $\overline{R}$ as the minimum rate requirement, then the number of connections is

$$Q_{\text{tot}} = \sum_{n \in \mathcal{N}} \sum_{m \in \mathcal{M}_n} \sum_{k \in \mathcal{K}} I\left(\gamma_m^n \ge \theta\right) s_{m,k}^n. \tag{6}$$

B. Problem Formulation

This paper focuses on the multi-objective optimization problem, where the primary objective is to maximize the user connectivity Q_{tot}, and the secondary objective is to maximize the network throughput R_{tot}. To distinguish the priority of Q_{tot} and R_{tot}, we set a weight coefficient λ in the objective function. As explained earlier, we know that $R_{\text{tot}} \le C_0$, such that when $\lambda < \frac{1}{C_0}$, the dominator in the objective function $Q_{\text{tot}} + \lambda R_{\text{tot}}$ is Q_{tot}. To maximize $Q_{\text{tot}} + \lambda R_{\text{tot}}$, we jointly optimize $\mathbf{P}$, $\mathbf{S}$, and $\mathbf{R}$, which is formulated as

$$\begin{aligned} \max_{\mathbf{P},\mathbf{S},\mathbf{R}} \; & Q_{\text{tot}} + \lambda R_{\text{tot}} \\ \text{s.t.} \quad & \text{C1}: R_n \le C_n, \forall n \\ & \text{C2}: R_{\text{tot}} \le C_0 \\ & \text{C3}: 0 \le p_m^n \le P_m^{\max}, \forall m \\ & \text{C4}: \sum_{k \in \mathcal{K}} s_{m,k}^n \le 1, \forall m, n \\ & \text{C5}: \sum_{m \in \mathcal{M}_n} s_{m,k}^n \le \mathit{\Delta}, \forall k, n \\ & \text{C6}: s_{m,k}^n \in \{0, 1\}, \forall k, n, m. \end{aligned} \tag{7}$$

III. Description of the Proposed Algorithms

To solve the joint problem in (7), we first calculate the optimal power of the TUs under all possible channel assignment schemes. Then, we solve the channel assignment problem by recasting it as a K-MWIS problem in graph theory. Noted that these transformations are equivalent to the original joint power-and-channel optimization problem. Finally, we adjust the data rate of the TUs to satisfy the backhaul constraints.

A. Power Control

Define $\mathcal{C}$ as a TU cluster $(1,2,...,t)\,(t \leq \Delta)$, which represents that the TUs $1,2,...,t$ in the same LBS n share the same channel k by NOMA (i.e., $s_{m,k}^n = 1,\ \forall m \in \mathcal{C}$), and their CPGs satisfy $g_1^n > g_2^n > ... > g_t^n$. Then, the power control subproblem in cluster $\mathcal{C}$ is given by

$$\begin{aligned} &\max_{\mathbf{P}_\mathcal{C}} \sum_{m\in\mathcal{C}} R_m^n \\ &\text{s.t. C1}: \gamma_m^n \geq \theta, \forall m \in \mathcal{C} \\ &\quad\ \ \text{C2}: 0 \leq p_m^n \leq P_m^{\max}, \forall m \in \mathcal{C}. \end{aligned} \tag{8}$$

For (8), we need to judge whether it is feasible. If it is feasible, it means that the corresponding channel assignment scheme is a potential solution. Then, we calculate the optimal transmission power of the TUs. Otherwise, it means that the corresponding channel assignment scheme is infeasible, which will not be considered in the following operation.

Let $x_i = p_i^n g_i^n$ represent the received power of TU i. Then, the sum rate of the TUs in $\mathcal{C}$ can be expressed as

$$\sum_{m\in\mathcal{C}} R_m^n = B_3\log_2\left(\sum_{i=1}^{t} x_i + B_3N_0\right) - B_3\log_2(B_3N_0). \tag{9}$$

According to (9), we can get that for a cluster $\mathcal{C}$, the larger the sum of received power, the larger the sum data rate. Based on this conclusion, we first set $p_1^n = p_2^n = ... = p_t^n = P_m^{\max}$. If the decoding threshold of all TUs is satisfied, the optimal transmission power of each TU is $P_m^{\max}$. Otherwise, we need to adjust the transmission power of some TUs. For the optimal order, we have the following lemma.

Lemma 1. *To maximize (9), the optimal power adjustment order should be in the ascending order of the CPGs.*

Proof: Without loss of generality, we assume that TU i can not satisfy its decoding threshold while the TUs with smaller serial number meet the requirements, i.e., $\gamma_i < \theta_i$, $\gamma_j \geq \theta_j, \forall j \in [1, i-1]$. According to the principle of the uplink NOMA, the TUs with larger CPG will not cause interference to the TUs with smaller CPG. As such, the transmission power of TUs $1, \cdots, i-1$ has no influence on the other TUs, and we can set $p_1^n = p_2^n = ... = p_{i-1}^n = P_m^{\max}$.

For TU i, the decrement of p_i^n will reduce γ_i, so its power can only be the maximum value, i.e., $p_i^n = P_m^{\max}$. In order to reduce the interference to TU i, we must decrease the power of TUs $i+1, \cdots, t$. Substituting (3) into the constraint C1 in (8) and rearranging them, we can get

$$x_k \geq \left(\sum_{j=k+1}^{t} x_j + B_3N_0\right)\theta,\ k = i, \cdots, t. \tag{10}$$

As shown in (10), the inequalities are closely coupled. According to (9), subtracting the same value of different TUs from their received power has the same effect on the sum rate, however, the TUs with smaller CPGs will cause interference to more TUs. Thus, for getting the value range of x_i, we need to first determine the values from x_t to x_{i+1}. In other words, the received power of each TU determined in the ascending order of their CPGs is optimal. ■

Based on Lemma 1, to avoid repeated operations on the same user, we stipulate that only when the power of one TU has already been decreased to the minimum which satisfies its decoding threshold, the power of the next TU will be adjusted. More specifically, we suppose that the power of TUs $k+1, k+2, ..., t\,(k > i)$ has been adjusted to meet their decoding threshold, denoted by $p_{k+1}^{n*}, p_{k+2}^{n*}, ..., p_t^{n*}$ respectively, but there are still some TUs not satisfied. In sequence, we next optimize the power of TUs k, which subjects to

$$\gamma_i \geq \theta, \gamma_{i+1} \geq \theta, ..., \gamma_k \geq \theta. \tag{11}$$

It is worth noting that TU $k-1$ can only achieve the decoding threshold by adjusting the interference of TU k to it, while TUs $k-2$ to i can also perform subsequent operations to meet the conditions. Therefore, if the constraints $\gamma_{k-1} \geq \theta$ and $\gamma_k \geq \theta$ are satisfied, we can conclude that the power control for TU k is completed.

Rearranging (11), we can acquire

$$\begin{cases} x_k \leq \frac{x_a}{\theta} - \sum\limits_{j=a+1}^{k-1} x_j - \sum\limits_{j=k+1}^{t} x_j - B_3N_0, (a \in [i, k-1]) \\ x_k \geq \left(\sum\limits_{j=k+1}^{t} x_j + B_3N_0\right)\theta. \end{cases} \tag{12}$$

For convenience of description, we simplify (12) as

$$\begin{cases} x_k & \leq x_k^c\left(a\right), (a \in [i, k-1]) \\ x_k & \geq x_k^{min} \end{cases}, \tag{13}$$

where $x_k^c(a)$ represents the upper bound of x_k derived from the constraint $\gamma_a \geq \theta$. $x_k^{\min}$ denotes the minimum transmission power for TU k to satisfy the decoding threshold. The specific expressions of $x_k^c(a)$ and $x_k^{\min}$ are respectively given by

$$x_k^c\left(a\right) = \frac{x_a}{\theta} - \sum_{j=a+1}^{k-1} x_j - \sum_{j=k+1}^{t} x_j - B_3N_0. \tag{14}$$

$$x_k^{\min} = \left(\sum_{j=k+1}^{u} x_j + B_3N_0\right)\theta. \tag{15}$$

For (13), there are three possible cases:

1) All constraints in (13) can be met, i.e., $x_k^{\min} \leq \min\left(x_k^c\right)$, then $x_k = \min\left(x_k^c\right)$ and $p_k^{n*} = x_k/g_k^n$, $p_1^{n*} = \ldots = p_{k-1}^{n*} = P_m^{\max}$. The optimal power has been obtained.
2) Constraints $\gamma_k \geq \theta$ and $\gamma_{k-1} \geq \theta$ are satisfied simultaneously, i.e., $x_k^{\min} \leq x_k^c\left(k-1\right)$, then $x_k = x_k^{\min}$ and $p_k^{n*} = x_k/g_k^n$. In this case, we will continue to adjust the power of TU $k-1$.
3) Constraints $\gamma_k \geq \theta$ and $\gamma_{k-1} \geq \theta$ can not be satisfied simultaneously, i.e., $x_k^{\min} > x_k^c\left(k-1\right)$, it means that the channel assignment scheme is infeasible.

Algorithm 1 Power Control Algorithm

Initialization: $p_m^n = P_m^{\max}$, $x_m = p_m^n g_m^n$, $\forall m \in \mathcal{C}$ and $a = 0$.
Calculate the SINR of TUs in descending order of CPG until the TU does not meet the decoding threshold, and assign its serial number to a, let $p_m^{n*} = P_m^{\max}, m = 1, \cdots, a$.
for $b = t : -1 : a+1$ **do**
    Calculate $x_b^{\min} = \left(\sum\limits_{j=b+1}^{t} x_j + B_3 N_0\right)\theta$.
    for $d = a : b-1$ **do**
        Set $dd = d - a + 1$.
        $x\left(dd\right) = \frac{x_d}{\theta} - \sum\limits_{j=d+1}^{b-1} x_j - \left(\sum\limits_{j=b+1}^{t} x_j + B_3 N_0\right)$.
    end for
    if $x_b^{\min} < \min\left(x\right)$ **then**
        Set $x_b = \min\left(x\right)$ and $p_b^{n*} = x_b/g_b^n$.
        Set $p_m^{n*} = P_m^{\max}, m = 1, \cdots, b-1$.
        break.
    else if $x_b^{\min} < x\left(dd\right)$ **then**
        Set $x_b = x\left(dd\right)$ and $p_b^{n*} = x_b^n/g_b^n$.
    else
        Set $p_m^{n*} = 0, m = 1, \cdots, t$.
        break.
    end if
end for
Output: The power control policy $\mathbf{P}$.

Based on the the above analysis, we propose the power control algorithm, which is summarized in Algorithm 1.

B. Channel Assignment

Given $\mathbf{P}$, the channel assignment problem can be divided into N subproblems, each of which corresponds to a LBS and is expressed as (16), where $\mathbf{S}_n = \left\{s_{m,k}^n | m \in \mathcal{M}_n\right\}$.

$$\begin{aligned} \max_{\mathbf{S}_n} & \sum_{m\in\mathcal{M}_n}\sum_{k\in\mathcal{K}} I\left(\gamma_m^n \geq \theta\right)\left(s_{m,k}^n + \lambda R_m^n\right) \\ \text{s.t.} \quad & \mathrm{C1}: \sum_{k\in\mathcal{K}} s_{m,k}^n \leq 1, \forall m \in \mathcal{M}_n \\ & \mathrm{C2}: \sum_{m\in\mathcal{M}_n} s_{m,k}^n \leq \Delta, \forall k \in \mathcal{K} \\ & \mathrm{C3}: s_{m,k}^n \in \{0,1\}, \forall k \in \mathcal{K}, m \in \mathcal{M}_n. \end{aligned} \tag{16}$$

To solve the above problem, we recast it as a maximum weighted independent set problem in graph theory. Define $G = (V, E, W)$ as an undirected weighted graph, where V represents the vertex set in the weighted graph G, E denotes the edge set, and W is the weight of each vertex. Specially, the vertice v in V correspond to a cluster $\mathcal{C}$ as described above. If the vertex v_i and v_j contain the same TUs or channel, there is an edge $\left(v_i, v_j\right)$ between these two vertices. Furthermore, the weight W_v of vertice v is defined as

$$W_v = \sum_{m\in\mathcal{C}_k} I\left(\gamma_m^n \geq \theta\right)\left(1 + \lambda R_m^n\right). \tag{17}$$

Additionally, let $N_G\left(v\right)$ denote the neighborhood of v in G and $N_G^+\left(v\right) = N_G\left(v\right) \cup \{v\}$. Let $d_G\left(v\right)$ denote the degree of v in G, i.e., the number of neighbors. Classify all vertices in G according to the number of TUs corresponding to the vertices, we define V_i as the set of vertices with i TUs, E_i is the edge set of V_i, as such $G_i = \left(V_i, E_i, W_i\right)$ represents the weighted graph of vertices with i TUs, naturally, $G_i\left(V_i, E_i, W_i\right) \subseteq G\left(V, E, W\right)$.

Definition 1. (K Maximum Weighted Independent Set (K-MWIS)): K-MWIS is an independent set consisting of no more than K vertices, and the sum-weights of the vertices in it is the largest in graph G.

According to the above definitions, we can get that the channel assignment problem in (16) is equivalent to finding the K-MWIS U in the graph G. The main idea is to determine the priority of vertex selection based on the relationship between the number of TUs and channels. For instance, if the number of TUs is twice that of channels (assume $\Delta = 2$), we give preference to the vertices in V_2. In case there are no selectable vertices in V_2, we continue to select the vertices in V_1 until there are no vertices to choose or the number of selected vertices reaches the number of channels. In this way, all channels can be utilized while maximizing the sum-weight. The detailed algorithm is similar with that in [16]. So, we omit it for brevity.

C. Rate Control

In this system, the data rate of TUs in each LBS is limited by the LBS-HBS backhaul, and that of all TUs is limited by the HBS-GS backhaul. To meet the backhaul constraints, we must adjust the data rate of TUs. We first consider each LBS independently to make it meet the constraint C1 in (7). Take LBS n as an example. Given $\mathbf{S}_n$, we can acquire the number of connections in LBS n, which is expressed as

$$Q_n = \sum_{m\in\mathcal{M}_n}\sum_{k\in\mathcal{K}} s_{m,k}^n. \tag{18}$$

There are three conditions: (a) $R_n \leq C_n$, LBS n meets the backhaul constraint; (b) $R_n > C_n$ but $Q_n\overline{R} \leq C_n$, it shows that LBS n does not meet the backhaul constraint, but it's not necessary to change the channel assignment policy in $\mathbf{S}_n$; (c) $R_n > C_n$ and $Q_n\overline{R} > C_n$, it indicates that the accessed TUs have exceeded the service capability of LBS n. In this case, we have to eliminate one or more users to meet the backhaul constraint. The number of TUs that should be eliminated can be calculated by $de_n = \max\left\{Q_n - \left\lfloor C_n/\overline{R}\right\rfloor, 0\right\}$. Besides, the elimination order has a great influence on the performance. For the optimal order, we have the following conclusion.

Lemma 2. *For a cluster $\mathcal{C}$, the optimal user elimination order should be in the ascending order of the CPGs.*

Algorithm 2 Rate Control Algorithm

Initialization: Set $n = 0$.
while $n < N$ **do**
  Set $n = n + 1$ and calculate Q_n, C_n, and de_n.
  if $de_n > 0$ **then**
    Delete the de_n TUs with the lowest channel capacity and set their channel assignment variables to 0.
  end if
  Calculate the channel capacity of the remainder TUs RI and Q_n, then sum RI to get R_n.
  if $R_n > C_n$ **then**
    Look for TUs who need to be adjusted, set mean $= C_n/Q_n$, $A =$ find $(RI >$ mean$)$.
    Calculate the rate reduction of each TU, des $(A) = RI\,(A) -$ mean.
    Get the optimized TU rate $RI\,(A) = RI\,(A) -$ des (A) /sum (des (A)) $* (C_n - R_n)$.
    Set $R_n = C_n$.
  end if
end while
Calculate $R_{\text{tot}} = \sum\limits_n R_n$ and de.
if $de > 0$ **then**
  Delete the de TUs with the lowest channel capacity and set their channel allocation variables to 0.
  Calculate the channel capacity of the remainder TUs RI and Q_{tot}, then sum RI of all users to get R_{tot}.
  if $R_{\text{tot}} > C_0$ **then**
    mean $= C_0/Q_{\text{tot}}$, $A =$ find $(RI >$ mean$)$.
    $des\,(A) = RI\,(A) -$ mean, $RI\,(A) = RI\,(A) - des\,(A)$ /sum (des (A)) $* (C_0 - R_{\text{tot}})$.
    Set $R_{\text{tot}} = C_0$.
  end if
  Get the optimized TU rate $RI\,(A) = RI\,(A) -$ des (A) /sum (des (A)) $* (C_n - R_n)$.
  Set $R_n = C_n$.
end if
Output: The rate control policy $\mathbf{R}$.

Proof: The total data rate of the TUs in a cluster can be expressed as (9). The transmission power is optimized in the ascending order of CPG. So, for TU i and $i+1$ ($i \in [1, t-1]$), we assume $g_i \geq g_{i+1}$. Then, there are three situations:

(a) Neither the rate of TU i nor $i+1$ is adjusted: $p_i = p_{i+1} = P^{\max}$, so $x_i \geq x_{i+1}$;

(b) Only adjust the rate of TU $i+1$: $p_i = P^{\max} > p_{i+1}$, so $x_i \geq x_{i+1}$;

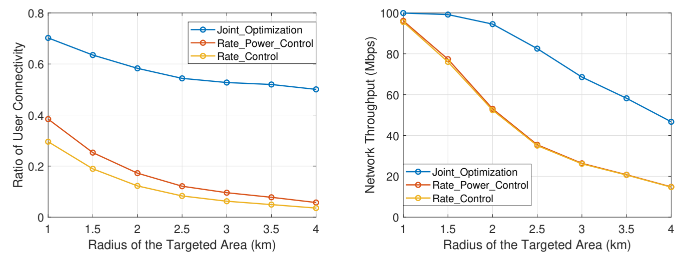
(c) Both the rates of TU i and $i+1$ are adjusted: $\gamma_{m_i} \geq \gamma_{m_{i+1}} = \theta$, we have ($N = N_0 B_3$)

$$\begin{aligned}
&\frac{x_i}{\sum\limits_{j=i+1}^{t} x_j + N} \geq \frac{x_{i+1}}{\sum\limits_{j=i+2}^{u} x_j + N} = \theta \\
&\Rightarrow x_i \left(\sum_{j=i+2}^{u} x_j + N \right) \geq x_{i+1} \left(\sum_{j=i+1}^{t} x_j + N \right) \\
&\Rightarrow x_i \left(\sum_{j=i+2}^{u} x_j + N \right) \geq x_{i+1} \left(\sum_{j=i+2}^{t} x_j + N \right) + x_{i+1}^2 \\
&\Rightarrow (x_i - x_{i+1}) \left(\sum_{j=i+2}^{u} x_j + N \right) \geq (x_{i+1})^2 > 0 \\
&\Rightarrow (x_i - x_{i+1}) \geq 0 \\
&\Rightarrow x_i \geq x_{i+1}.
\end{aligned} \tag{19}$$

Summarizing the three situations above, we can conclude that for a cluster $\mathcal{C}$ which satisfies $g_1 \geq g_2 \geq ... \geq g_t$, if all TUs can meet the rate requirement after power control, then $x_1 \geq x_2 \geq ... \geq x_t > 0$. So removing TU t has the least impact on the total data rate. Thus, Lemma 2 is proved. ■

TABLE I
PARAMETER SETTINGS

Height of the HBS	500 m
Environmental parameter, α	9.61
Environmental parameter, β	0.16
Low frequency/bandwidth	4.9 GHz
mmWave frequency/bandwidth	28 GHz
NPSD, N_0	-174 dbm/Hz
Max Tx power of the LBS	10 W
Max Tx power of the TUs, $P_m^{\max}$	1 W
Number of the LBSs, N	3
Channel number of each LBS, K	10
Number of TUs, M	60
Decoding threshold, θ	9 dB
Minimum rate requirement, $\overline{R}$	0.8 Mbps
Channel bandwidth[1], B_2/B_3	14.4/1.44 MHz
Simulation times	500



(a) User connectivity. (b) Network throughput.

Fig. 2. Network performance versus radius of the targeted area.

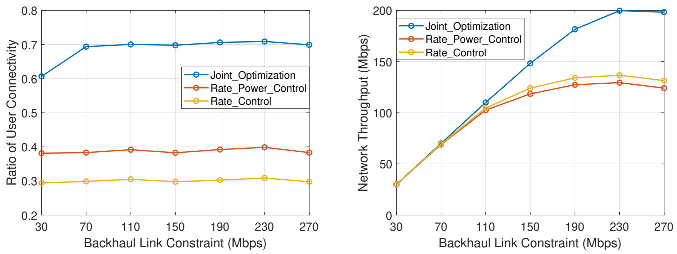
Based on Lemma 2, we can adjust the data rate of TUs in each LBS. After solving the rate control problem under the LBS-HBS backhaul constraint, the problem under the HBS-GS backhaul constraint is easily to handle by using the similar rule. The difference is that the number of deleted TUs is given by $de = \max\left(Q_n - \left\lfloor C_0/\overline{R} \right\rfloor, 0\right)$. The specific process is arranged in Algorithm 2.

IV. Simulation Analysis

We evaluate the performance of the proposed scheme (namely Joint_Optimization) via simulation. The common parameters are listed in Table 1 (a typical urban scenario), and the others are specified under each figure. In order to reveal the impact of each control variable on the network performance, we compare the Joint_Optimization with the other two schemes, namely Rate_Control and Rate_Power_Control.

Fig. 2 shows the network performance versus the region size, where the backhual capacity is set as $C_0 = 100$ Mbps. We can find that all of the control variables have effect on the network performance. Compared with the Rate_Control, the ratio of user connectivity increases by about 150% and the network throughput increases by about 120% by using the Joint_Optimization. From Fig. 2a, we can find that the gain of the channel assignment is the largest. This is because only when the TUs are appropriately clustered in a channel, the

[1]For the HBS-GS backhaul, we directly set the value of C_0. So, the bandwidth B_1 is not given.



(a) User connectivity. (b) Network throughput.

Fig. 3. Network performance versus HBS-GS backhaul capacity.

potential of NOMA in improving user connectivity can be fully exploited, and this phenomenon is more obvious with large region size. From Fig. 2b, we can observe that the network throughput of the Joint_Optimization is 100 Mbps when the region size is small. The reason is that the network throughput is limited by the HBS-GS backhaul capacity, and its value is 100 Mbps. Besides, it shows that the network throughput of the Rate_Power_Control is almost the same with that of the Rate_Control. This is because with the same channel assignment scheme, the power of TUs is adjusted to meet their decoding threshold, and thus the data rate is only equal to their minimum requirement with the Rate_Power_Control.

Fig. 3 illustrates the network performance versus the HBS-GS backhaul capacity, where the area radius is set as 1 km. The maximum number of connections is limited by the HBS-GS backhaul capacity. The upper bound is equal to $C_0/\overline{R}$. When $C_0 = 30$ Mbps, we can get the upper bound is 37, that is, the ratio is about 62%. In this case, the HBS-GS backhaul link has effect on user connectivity. However, when $C_0 = 70$ Mbps, the upper bound is 87, which is larger than the number of TUs. Then, the HBS-GS backhaul link is not the key factor and the others (for instance, the HBS-LBS backhaul links or the access links) become the bottleneck, and thus the ratio of user connectivity keeps the same value when $C_0 \geq 70$ Mbps. On the contrary, the network throughput of the Joint_Optimization always increases with the HBS-GS backhaul capacity. Although the user connectivity keeps unchanged, the network throughput can still be upgraded by improving the transmission power. The HBS-GS backhaul capacity is the key factor that limits the network throughput, especially when C_0 is small. As such, the network throughput increases linearly with C_0 in the initial stage, until C_0 is not the bottleneck. Compared with the other schemes, the Joint_Optimization can fully exploit the backhual capacity (i.e., C_0), which verifies the efficiency of our algorithms.

V. Conclusion

In this paper, we have investigated the network design and optimization problems for aerial networks. Specifically, we have proposed a two-layer aerial network consisting of a HBS acting as a wireless hub and multiple LBSs acting as access points to provide wide-area and on-demand coverage. To maximize the user connectivity and network throughput, we have jointly optimized the power, channel and rate of the TUs. To solve the joint optimization problem, we have analyzed the structure characteristic of each subproblem and adopted the K-MWIS method to devise an efficient iterative algorithm. Finally, we have compared the proposed algorithm with the other schemes to verify its effectiveness.

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