Bandwidth, Power, and Trajectory Optimization of Multi-UAV Base Stations with Backhaul Constraints (Postprint)

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Abstract

UAVs enable flexible deployment and high-rate transmission, and are expected to become a critical component of next-generation wireless networks. Consider a wireless communication system based on multi-UAV networking, where aerial base stations mounted on multiple UAVs provide services to multiple groups of users within the coverage area. In such networks, due to limited spectrum resources, the backhaul links of base stations share the same spectrum with the data links of users. To rationally utilize spectrum resources and improve communication performance for users, with the objective of maximizing the minimum average rate of all ground users, we jointly optimize the bandwidth and power of both backhaul and data links, as well as the flight trajectories of UAV base stations. This joint optimization is subject to constraints on UAV mobility, spectrum bandwidth, and transmission power. The resulting optimization problem is non-convex and difficult to solve optimally; therefore, we propose an efficient algorithm to obtain a high-performance suboptimal solution. Simulation results demonstrate that the minimum user rate achieved by the proposed joint optimization algorithm is significantly higher than that of benchmark schemes.

Full Text

Bandwidth, Power and Trajectory Optimization for Multiple UAV Base Stations with Backhaul Constraint

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Abstract: Unmanned aerial vehicles (UAVs) are envisioned to become an important part of new-generation wireless networks due to their advantages of flexible deployment and high-speed transmission. This paper considers a wireless communication system with multiple UAV-mounted aerial base stations serving multiple groups of users in a coverage area. In this network, due to limited spectrum resources, the backhaul links of the base stations and the data links of the users share the same spectrum. To utilize spectrum resources efficiently and improve user communication performance, this paper jointly optimizes the bandwidth and power of both backhaul and data links, as well as the flight trajectories of the UAV base stations, with the objective of maximizing the minimum average rate among all ground users. This joint optimization is subject to UAV mobility constraints, total spectrum bandwidth, and total transmit power. The resulting optimization problem is non-convex and difficult to solve optimally. Therefore, we propose an efficient algorithm to obtain a high-quality suboptimal solution. Simulation results demonstrate that the minimum user rate achieved by the proposed joint optimization algorithm is significantly higher than that of benchmark schemes.

Key words: multi-UAV; backhaul node; bandwidth; power; trajectory; optimization

0 Introduction

After decades of rapid development, unmanned aerial vehicles (UAVs) have been widely applied in military, transportation, agriculture, logistics, and other fields due to their high mobility, ease of deployment, and low cost, bringing convenience to people’ s lives. With the rise of fifth-generation (5G) wireless communications, UAVs assisting wireless networks in various application scenarios can help improve the communication performance of 5G networks. Compared with ground wireless networks where communication nodes are fixed on the ground, UAVs can flexibly design flight trajectories to establish line-of-sight links, thereby improving communication quality with counterparts and increasing communication coverage [1~3]. In UAV-assisted communication networks, UAVs can serve as aerial base stations or relay stations, which is particularly suitable for emergency situations such as traffic congestion or natural disasters [4,5].

Despite years of research, UAV-assisted communications still face several key technical challenges, and their potential advantages have not been fully exploited. For instance, references [6,7] considered UAVs as static base stations, reference [8] proposed an energy-efficient UAV relay scheme, and references [9,10] presented long-distance communication energy-saving strategies by optimizing UAV deployment positions. Additionally, UAVs can cooperate with ground vehicles to collect and grasp global network information or forward information as relays, thereby ensuring network connectivity and improving information transmission performance [11]. However, these works did not consider the high mobility performance of UAVs. In fact, in UAV communication networks, jointly optimizing communication resources and UAV trajectories according to network dynamics can greatly improve wireless communication performance, representing a very promising research direction.

Motivated by this, many researchers have investigated joint trajectory optimization and resource allocation schemes for UAV communication networks. Reference [12] considered a wireless network with a single UAV, jointly optimizing user scheduling and trajectory to maximize the minimum throughput among all users. References [13~15] studied joint power allocation and trajectory optimization for secure UAV communications under different scenarios. References [4] and [5] investigated joint resource allocation and UAV trajectory optimization in UAV relay systems. These works assumed fixed bandwidth for each data link, whereas performance can be further improved by adaptively adjusting the bandwidth of each data link according to channel and system dynamics. Reference [16] studied joint optimization of UAV deployment position, bandwidth, and beamwidth. Reference [17] investigated joint optimization of power and bandwidth for UAVs and base stations coexisting with device-to-device communication networks. Reference [18] studied joint bandwidth, power, and trajectory optimization for multi-hop UAV relaying systems, where end-to-end rate was maximized.

Previous works primarily focused on the bandwidth of access links connecting UAVs and users while ignoring the backhaul links connecting UAVs to the core network [19]. In practice, when backhaul link bandwidth is limited, the backhaul link may constrain the overall performance of the UAV network. Therefore, communication optimization in the network should consider backhaul link constraints. Reference [20] maximized the rate of UAV base station backhauls formed by multi-hop UAV relays. Reference [21] studied joint optimization of deployment and user association for static multi-UAV base station networks with backhaul constraints. As UAV missions become increasingly diverse, single-UAV models can no longer meet daily mission requirements, necessitating consideration of multi-UAV wireless communication networks. Reference [22] considered a multi-UAV wireless network, assuming sufficient backhaul link bandwidth, and optimized UAV user scheduling, power, and trajectory to maximize the minimum rate among all users. References [4] and [6] both studied multi-UAV multi-hop networks; the former only optimized power and trajectory without considering backhaul issues, while the latter considered backhaul issues but assumed static UAVs. To the best of our knowledge, the problem of jointly optimizing bandwidth, power, and trajectory for multi-UAV communications with backhaul constraints has not been studied.

As shown in [Figure 1: see original paper], this paper considers improving the communication performance of a multi-UAV network with backhaul constraints, where users are divided into multiple groups and each UAV serves one group. Due to spectrum scarcity, the network’ s backhaul and user data links share the same spectrum. The backhaul link constrains the sum rate of all users, meaning the total data rate of all users cannot exceed the backhaul rate. This paper maximizes the minimum rate among all users by jointly optimizing the bandwidth and power of backhaul and data links, as well as UAV trajectories. Although the proposed problem is non-convex and difficult to solve optimally, we propose an efficient algorithm to find a suboptimal solution. Simulation results demonstrate that the rate performance of the proposed algorithm is significantly better than several benchmark algorithms, illustrating the necessity of joint bandwidth, power, and trajectory optimization in multi-UAV networks.

1 System Model

Consider a multi-UAV base station assisted wireless communication network system as shown in [Figure 1: see original paper], where J UAVs provide service to K ground users. The sets of users and UAVs are denoted as 1J 1K 1,K and {1„}Jj,jjKK ,kk , respectively, where different UAVs serve different users, such as BH,0TTw and ,0TTkw. The links between UAVs and the backhaul node are called wireless backhaul links. This paper focuses on downlink communication from UAVs to ground users, though the study can be directly extended to uplink scenarios.

A Cartesian coordinate system is applied to represent position relationships. The horizontal positions of the backhaul link node and users are 21BH00,Txy = w and 21,Tkkkxy = w, respectively. Assume UAV j flies at altitude H (in meters), with its horizontal position at time t denoted as (),0TTkts. To facilitate deployment, UAVs are required to return to their initial takeoff positions at the end of the flight period, and their trajectories are also constrained by maximum velocity Vmax and collision avoidance. Therefore, the flight trajectory of UAV j has the following constraints:

Since UAV trajectories are continuous in time, involving infinite variables, optimization is extremely difficult. Therefore, to facilitate trajectory optimization, this paper discretizes the flight time T into N equal-length time slots and approximates the trajectory as a sequence „0,jnnNj s, where „„Tjnjnjnxy=s represents the horizontal position of UAV j in time slot n. When the number of time slots N is sufficiently large, the length of each time slot can be negligible, allowing UAV base stations to be considered static within each time slot. Consequently, the mobility constraints for UAV j, i.e., equations (1), (2), and (3), become as follows, where Lmax is the maximum distance a UAV can travel within each time slot.

Therefore, the distances between UAV j and user k, and between UAV j and the backhaul link node in time slot n are, respectively:

Test results show that UAV-to-ground-node communications are dominated by line-of-sight links [23]. This paper applies a free-space propagation model to approximate the channel between UAVs and all ground users, as well as between UAVs and the backhaul link node. Therefore, the channel power gain between UAV j and user k in time slot n can be written as:

where \$ \$0 represents the channel power gain at reference distance d0 = 1m. Similarly, the channel power gain between UAV j and the backhaul link node in time slot n is:

Assume that due to spectrum scarcity, there is no dedicated spectrum for backhaul links in the considered UAV base station network. Therefore, an in-band backhaul scheme is applied, where backhaul links and user data links share the same spectrum with bandwidth B Hz. To avoid interference, different links are allocated orthogonal frequency bands. Let xj,nk and xj,nBH denote the bandwidth allocation portions for the data link and backhaul link of UAV j in time slot n, respectively, which should satisfy the following bandwidth constraints:

Let pj,nk and pj,nBH denote the transmit power from the backhaul link node to UAV j and from UAV j to user k in time slot n, respectively, subject to the following total power constraints and non-negative constraints:

where Pmax represents the maximum total transmit power of the backhaul link node and UAVs. Therefore, the achievable data rate (bits/sec/Hz) for the data link of UAV j serving user k in time slot n is:

where N0 represents the power spectral density of additive white Gaussian noise at the receiver. The achievable data rate for the backhaul link in time slot n is:

Since UAV base stations can only transmit to users the data received from the core network (via backhaul links), the total rate of all users should not exceed the backhaul link rate in any time slot. This is called the backhaul rate constraint:

2.1 Optimization Problem

To improve user data rates and ensure fairness among users, the objective of this paper is to maximize the minimum average rate among all users by jointly optimizing the bandwidth and power of backhaul and all data links, as well as the UAV flight trajectories S, subject to UAV mobility constraints (4), (5), and (6), bandwidth constraints (11) and (12), transmit power constraints (13) and (14), and backhaul rate constraint (17). By introducing a slack variable to represent the minimum average rate allowed for all users, the problem is formulated as (P1):

Due to the presence of variables X, P, and S, both the left and right sides of inequality (17) are non-concave constraints. Therefore, problem (P1) is a nonconvex problem that is difficult to solve optimally. To address this, we propose an efficient algorithm to optimize it, as described below.

2.2 Joint Optimization Algorithm

In this section, we propose an effective algorithm to solve problem (P1) based on the alternating optimization method. First, the proposed algorithm divides all optimization variables into two modules, where the first module includes bandwidth variables X and transmit power variables P, and the second module includes UAV trajectory variables S. Through this variable division, problem (P1) can be separated into two subproblems, denoted as subproblem 1 and subproblem 2. The former optimizes variables S with fixed X and P, while the latter optimizes variables X and P with fixed S. The proposed algorithm solves subproblems 1 and 2 alternately until the objective value of problem (P1) converges. In the following, we present detailed methods for solving subproblems 1 and 2.

2.2.1 Fixed UAV Trajectory, Optimize Bandwidth and Transmit Power

First, we address subproblem 1, which optimizes bandwidth and transmit power allocation for the UAV network with fixed trajectories. The problem can be formulated as (P2):

In problem (P2), since the right side of constraint (23) is concave with respect to variables X and P, problem (P2) is non-convex and cannot be solved using standard optimization techniques. To solve problem (P2), we introduce a slack variable a and propose the following problem (P3):

We can prove that problem (P3) and problem (P2) have the same optimal solution for X and P, because there exists an optimal solution that makes the equality in constraint (28) hold.

Proof: Assume there exists an optimal solution for (P3) where constraint (28) holds as a strict inequality. We can adjust the solution to make the equality in constraint (28) always hold. Since this adjustment does not reduce the objective value of problem (P3), the adjusted solution remains optimal for problem (P3). Moreover, when equality holds in constraint (28), the feasible regions of problems (P3) and (P2) for X and P are identical, so they have the same optimal solution for X and P. Therefore, solving problem (P3) yields the solution for X and P that also solves problem (P2). Since the objective function and constraints (26) and (29) of problem (P3) are linear, and the left side of constraint (27) and the right side of constraint (28) are concave with respect to X and P, problem (P3) is a convex optimization problem that can be solved using the interior-point method [24].

2.2.2 Fixed Bandwidth and Transmit Power, Optimize UAV Trajectory

This section addresses subproblem 2, which optimizes UAV trajectories with fixed bandwidth and transmit power allocation. The problem can be formulated as (P4):

In (P4), constraint (32) originates from (17). Note that both (31) and (32) are non-convex constraints, making (P4) a non-convex problem that is difficult to solve optimally. We propose a suboptimal method as follows.

First, we introduce a slack variable b into problem (P4) and propose the following problem (P5):

Similar to how problems (P3) and (P2) have the same optimal solution for X and P, we can prove that there exists an optimal solution for problem (P5) that makes constraint (37) hold with equality. Therefore, problems (P5) and (P4) have the same solution for S. Thus, the solution for S can be obtained by solving problem (P5).

However, problem (P5) remains difficult to solve because the left side of (36) and the right side of (38) are non-concave with respect to S. Next, we approximate the solution to problem (P5) using iterative successive convex optimization techniques. Specifically, in each iteration, the successive convex optimization technique uses an initial point and obtains an approximate solution to problem (P5) by maximizing the objective function of problem (P5) within its convex feasible region using the initial point. The approximate solution obtained in the current iteration is used as the initial value for the next iteration, and the iteration process stops when the objective value of problem (P5) converges.

The detailed process is as follows. Assume S(r) is the UAV trajectory solution obtained in the r-th iteration. In the (r+1)-th iteration, we use S(r) as the initial point and find the following approximate solution. Note that although the left side of (36) and the right side of (37) are non-concave, they are convex. Therefore, we use the first-order Taylor expansions of the left side of (36) and the right side of (37) with respect to S as their lower bounds. Similarly, the lower bound of the right side of (37) is obtained through first-order Taylor expansion as follows:

By replacing the left side of (36) and the right side of (37) with their lower bounds, we derive the approximate problem of (P5) as follows (P6):

2.2.3 Overall Algorithm

Since the left side of constraint (42) and the right side of constraint (43) are concave with respect to variables S, while other constraints are linear, the feasible region of problem (P6) is a convex set. Moreover, the objective function of problem (P6) is linear, making problem (P6) a convex optimization problem that can be solved using the interior-point method to obtain the optimal solution [23].

The lower bounds are the left side of (36) and the right side of (37). Therefore, constraints (42) and (43) represent constraints (36) and (37), respectively. Thus, the optimal solution obtained by solving problem (P6) is a feasible solution to problem (P5). Furthermore, since the solution obtained in the (r+1)-th iteration is the optimal solution of problem (P6) and the initial point is within the feasible region, the objective value of problem (P6) is not less than the objective value of problem (P5). Therefore, we can conclude that the objective value of problem (P5) does not decrease during the iteration process.

Algorithm 1 summarizes the proposed algorithm, where f(X,P,S) denotes the objective value of problem (P1) and represents the convergence accuracy threshold. First, as analyzed in the previous subsection, the objective value of problem

(P1) does not decrease during the iterations by performing steps c)~h) of Algorithm 1. Second, since the objective value has a finite upper bound, Algorithm 1 is guaranteed to converge. Finally, the computational complexity of Algorithm 1 is O(ite $\cdot$ N^3.5), where ite is the number of iterations.

3 Simulation Results

This chapter provides computer simulation results to verify the performance of the proposed joint bandwidth, power, and trajectory optimization algorithm compared with the following benchmark schemes:

a) **Fixed bandwidth and power, optimize trajectory only**: Fix the bandwidth of different data links and the power allocated to different UAVs and users, and use steps 4-8 of Algorithm 1 to optimize UAV trajectories.

b) **Fixed bandwidth, optimize power and trajectory**: Fix the bandwidth of different data links and use an alternating optimization algorithm similar to Algorithm 1 to optimize transmit power and UAV trajectories.

c) **Given circular trajectory, joint optimization of bandwidth and power [22]**: Set the initial trajectory using the following method and jointly optimize bandwidth and power according to Section 2.2.1.

In the above schemes, the circular trajectory is generated as the initial UAV trajectory as follows. The trajectory' s center and radius are denoted by cj and rj, respectively, where UAVs fly at constant speed Vmax. For any time t [0,T], we have xj(t) = cj + rj $\cdot$ [cos(2πt/T), sin(2πt/T)]^T. First, the geometric center of users served by UAV j is determined as cj = (1/Kj) *{k Kj} wk. To better balance user rates, we use cj as the center of the minimum circle covering users served by UAV j, with radius rj equal to the maximum distance between cj and users served by UAV j, i.e., rj = max*{k Kj} ||cj - wk||. However, due to the UAV' s maximum speed limit, we require 2πrj/T $\leq$ Vmax, so the maximum feasible radius is rj = min(rj, Vmax $\cdot$ T/(2π)). Therefore, the radius of the initial circular trajectory is rj = min(max_{k Kj} ||cj - wk||, Vmax $\cdot$ T/(2π)). Based on center cj and radius rj, the initial trajectory of UAV j in time slot n is xj[n] = cj + rj $\cdot$ [cos(2πn/N), sin(2πn/N)]^T.

In the simulations, ground users are randomly located in a 2 km × 2 km area, with K = 6 users and J = 2 UAVs, where users 1~3 are served by UAV 1 and users 4~6 are served by UAV 2. To compare different schemes, the following results are obtained based on random user locations. The flight altitude and maximum speed of both UAVs are H = 100 m and Vmax = 50 m/s, respectively. The maximum total transmit power of UAVs and the backhaul link node is Pmax = 2 W. Other parameters are set as $ $0 = -60 dB and N0 = -169 dBm/Hz. The total network spectrum bandwidth is B = 10 MHz.

[Figure 3: see original paper] shows the trajectories of schemes (a) and (c) when the UAV base station flight time T = 120 s, where ' ' represents users served by UAV 1, ' ' represents users served by UAV 2, and '+' represents the backhaul node. It can be observed that when the backhaul node transmits to both UAVs at maximum power, each UAV tries to fly along its served users. However, due to backhaul link constraints, the two UAVs cannot completely reach the top of the users. Specifically, UAV 1 starts near user 3 and flies in the order of users 3, 1, 2, 3, staying closer to users 1 and 3 but farther from user 2, resulting in a relatively lower rate for user 2. UAV 2 flies in a straight line among its three users but stays farther from users 4 and 5. Compared with the initial circular trajectory, the service range of the two UAVs' trajectories is smaller.

[Figure 4: see original paper] shows the trajectories of the proposed scheme and scheme (c). It can be seen that when bandwidth and power are also optimized, the UAV flight trajectory range significantly expands within the same time, allowing flight to the top of users or near user ends to improve user rates. For example, UAV 1 passes over the top of user 3 and stays between users 1 and 3 for some time, with its trajectory being closer to user 2 compared to [Figure 3: see original paper]. UAV 2 flies in an approximately straight line from the starting point in the order of users 5, 6, 4, 5. Although it cannot reach the user ends (due to backhaul link constraints), the turning points are closer to users 4 and 5 compared to [Figure 3: see original paper]. Compared with the circular trajectory of scheme (c), the trajectories of the two UAVs in the proposed scheme fly in straight lines when connecting with users that have line-of-sight connections to the backhaul node, making the flight more direct and time-efficient for serving users, thus achieving higher rates. Consequently, the entire system achieves the effect of maximizing the rates of all users.

[Figure 5: see original paper] and [Figure 6: see original paper] show the relationship between transmit power and bandwidth portion allocated by the backhaul link node to the two UAVs versus time in the proposed algorithm, with parameters identical to those in [Figure 4: see original paper]. It can be observed in [Figure 5: see original paper] that the transmit power from the base station to the two UAVs can reach the maximum value or be 0. When the power allocated to one UAV is at maximum, the power allocated to the other UAV is 0, and this maximum or minimum value persists for an extended period. This is because during these time slots, the channel condition between one UAV and the base station is the best, so more power is allocated to it. However, in each time slot, the sum of allocated transmit power equals the maximum power. In [Figure 6: see original paper], the bandwidth portion may be 0 but cannot reach the maximum value of 1. This is because the bandwidth between UAVs 1 and 2 uses orthogonal frequency division to avoid interference between UAVs.

For multi-UAV scenarios where the distance between UAVs is greater than or equal to dmin, the trajectory obtained in (47) is feasible for the original problem (P1). A feasible initial trajectory can be obtained by adjusting the size of dmin.

[Figure 7: see original paper] shows the relationship between the minimum rate of all users and UAV flight time for different schemes. It can be observed that the minimum user rate of all schemes increases with time. Additionally, the rate achieved by the proposed algorithm is significantly higher than the minimum user rates of the other three schemes. This is because in schemes (a) and (b), both UAVs allocate the same bandwidth to their served users, while scheme (c) uses a given initial trajectory. Obviously, scheme (c) has greater degrees of freedom, so its rate is higher than schemes (a) and (b). Comparing schemes (a) and (b), scheme (b) achieves only a small gain in minimum user rate, indicating that power allocation can only achieve marginal gains when bandwidth allocation is fixed.

4 Conclusion

This paper investigated joint bandwidth, transmit power, and trajectory optimization for multi-UAV networks with limited backhaul constraints. We proposed an effective algorithm that maximizes the minimum rate among all users by jointly optimizing the bandwidth and transmit power of backhaul and data links for all users, as well as UAV trajectories. Simulation results demonstrated that the proposed alternating optimization algorithm achieves higher minimum user rate performance compared with other benchmark schemes.

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