Fixed-winged UAV relay optimization for coverage improvement in deadzones

I. Briefly prior work

- [1] studies the case of multiple rotary-wing UAVs serving multiple users, and jointly optimizes 2D UAV trajectory, transmission power, and user scheduling. We instead focus on a single fixed-wing UAV relaying between multiple users and a base station. Fixed-wing UAVs are more energy-efficient than rotary-wing ones, and a UAV acting as a relay is more realistic than a UAV acting as an independent base station.
- [2] examines a single fixed-wing UAV relaying between multiple users and a base station. They optimize flight radius and transmission power in order to maximize energy-efficiency. In their calculations, they assume users are located directly below the drone, a simplifying assumption that we avoid.
- In [3], they consider the case of a single fixed-wing UAV acting as a base station for multiple users. The user scheduling protocol is optimized to maximize minimum throughput. The paper has an extremely simplified model: users spaced evenly on a line, and the drone moving back and forth over that line.
- In [4], K stationary sources transmit to K stationary destinations, relaying through K rotary-wing UAVs. The 3D UAV trajectories and the transmit power at the sources and relays are optimized to maximize the minimum throughput. Our single-UAV-multiple-user scenario has different challenges, and we can focus on user throughput without worrying about interference from multiple relays.
- In [5], a single fixed-wing UAV circles between two stationary base stations. A variable-rate decode-and-forward approach is proposed which minimizes the outage probability of the system. Our setup is similar, but we consider multiple ground users and optimize for flight radius and location on top of timeshare.

II. System model

A. UAV trajectory

We consider a fixed-wing UAV relaying system that serves ground users in a coverage dead zone by connecting them with a distant base station. We use 3D Cartesian coordinates (x, y, z) to describe the locations of the base station, UAV, and ground users, where $(x, y, 0)$ represents the ground plane and thus z represents altitude.

As shown in Fig. 1, the base station is located at the origin of the plane, with coordinates given as

$$\mathbf{w}^{\mathrm{B}} = [0, 0, 0]^{\mathrm{T}}. \tag{1}$$

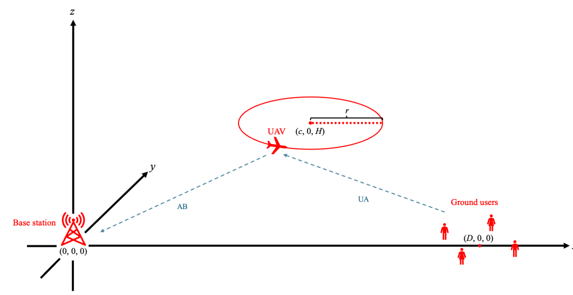

Fig. 1. Caption

Ground users are distributed within a dead zone centered D meters away from the base station on the x-axis. Let K be the total number of users, and the coordinates of the kth user denoted

$$\mathbf{w}_k^{\mathrm{U}} = [x_k, y_k, 0]^{\mathrm{T}}. \tag{2}$$

The UAV flies on a circular path of radius r located H meters above the ground and centered c meters away from the base station on the x-axis. We assume the UAV flies with constant speed v, which is subject to $v_{\text{min}} < v < v_{\text{max}}$. Here, v_{min} is the minimum speed of the fixed-wing UAV required to remain airborne, and v_{max} is determined by the build of the UAV and the radius of the flight path. Need to justify why we are choosing a circular flight path, and mention how velocity and radius are linked

We discretize the flight duration T into N equal timeslots since the UAV is serving distinct groups of users at distinct times. The length of each timeslot is $T_C = T/N$, which is short enough that the channel can be considered approximately stationary during each timeslot. This same approach is used in [1], [4], [6], [7], [8], and also helps to facilitate (radius optimization OR our optimizations).

As a result, the UAV's trajectory can be considered a discrete sequence of positions, each one a function of the flight path radius r and the flight path center point c. If the timeslots are indexed $1 \ldots N$, then the UAV's position during timeslot n is given by

$$\mathbf{w}_n^{\mathrm{A}}(r, c) = \left[c + r\cos\left(\frac{v \cdot n \cdot T_C}{r}\right),\ r\sin\left(\frac{v \cdot n \cdot T_C}{r}\right),\ H\right]^{\mathrm{T}}. \tag{3}$$

B. Channel Model

We assume that both the user-to-UAV and the UAV-to-BS links are line of sight and that the channel can be accurately expressed using a free-space propagation model. In order to serve multiple users at once, the UAV employs a frequency-divison duplexing strategy. Let K be the total number of users, and let $M << K$ be the number of users that the UAV can serve at once. We focus on the flight optimization problem rather than a frequency allocation one, and therefore uniformly allocate bandwidth across users to ensure fair frequency assignment. We use a decode-and-forward architecture where ground users transmit messages to the UAV which are then decoded and retransmitted to the base station. The UAV is assumed to have a data buffer that is large enough to satisfy the required data storage capacity for decode-and-forward relaying.

We assume users with a fixed transmission power P_{tx}^{U}. Let n denote the timeslot index with respect to the UAV's discrete positions along its trajectory, let λ denote the wavelength of the signal, and let G_{T}, G_{R} denote the antenna gain at the user and UAV respectively. The power of the signal received by the UAV from the user is then given as

$$P_{n,k}^{\text{A}}(r,c) = P_{\text{tx}}^{\text{U}} \cdot G_{\text{T}} G_{\text{R}} \left(\frac{\lambda}{4\pi \cdot ||\mathbf{w}_n^{\text{A}} - \mathbf{w}_k^{\text{U}}||} \right)^2 . \quad (4)$$

Let P_{tx}^{A} be the UAV transmission power. It follows that the power of the signal received by the base station during the nth timeslot is expressed

$$P_n^{\text{B}}(r,c) = P_{\text{tx}}^{\text{A}} \cdot G_{\text{T}} G_{\text{R}} \left(\frac{\lambda}{4\pi \cdot ||\mathbf{w}_n^{\text{A}}||} \right)^2 . \quad (5)$$

Let UA denote a user-to-UAV link, and let AB denote the UAV-to-BS link. We assume a common band for both links since the operation of each link is divided in time following decode-forward relaying system. Let N_0 be the noise power over the entire bandwidth. In the user-to-UAV link, there are M users transmitting simultaneously to the UAV, the channel for a single user experiences the noise with power N_0/M. Thus, the signal-to-noise ratio of the link from the kth user to the UAV during the nth timeslot can be expressed as

$$\text{SNR}_{n,k}^{\text{UA}}(r,c) = \frac{P_{n,k}^{\text{A}}}{N_0/M}. \quad (6)$$

The signal-to-noise ratio of the UAV-to-BS link during the nth timeslot can be expressed

$$\text{SNR}_n^{\text{AB}}(r,c) = \frac{P_n^{\text{B}}}{N_0}. \quad (7)$$

Assuming the transmitted signal and noise follow a Gaussian distribution, we can calculate the achievable spectral efficiency over the links using the Shannon-Hartley theorem. The spectral efficiency of the link from the kth user to the UAV during the nth timeslot is given by

$$\text{SE}_{n,k}^{\text{UA}}(r,c) = \log_2 \left(1 + \text{SNR}_{n,k}^{\text{UA}}\right). \quad (8)$$

The spectral efficiency of the link from the UAV to the base station during the nth timeslot is given as

$$\text{SE}_n^{\text{AB}}(r,c) = \log_2 \left(1 + \text{SNR}_n^{\text{AB}}\right). \quad (9)$$

Each timeslot is split into two phases: the first for transmission from the ground users to the UAV, and the second for transmission from the UAV to the BS. We assume that the decoding and re-encoding process is instantaneous. Let T_0 be the length of the first phase. Then we define $\alpha = T_0/T_C$, the proportion of each timeslot reserved for user-to-UAV transmission. The proportion of the timeslot reserved for UAV-to-BS transmission is $1 - \alpha$.

Don't start paragraph with Consider. Consider the M users being served in the nth timeslot. Let $\mathcal{U}_n$ be the set of indices of those M users. Assuming perfect time, symbol synchronization and channel knowledge, the average achievable spectral efficiency of the relay system over the timeslots is then given as

$$\overline{\text{SE}}(\alpha,r,c) = \frac{1}{N} \sum_{n=1}^{N} \min \left[\alpha \cdot \sum_{k \in \mathcal{U}_n} \text{SE}_{n,k}^{\text{UA}} , (1-\alpha) \cdot \text{SE}_n^{\text{AB}} \right]. \quad (10)$$

III. Problem formulation

A. Problem 1

Given the system and channel models from the previous section, our primary objective is to maximize the average spectral efficiency of the relay system given in (10). Initially, we will consider the case where α and c are fixed, and optimize for the flight path radius.

References

[1] Q. Wu, Y. Zeng, and R. Zhang, "Joint trajectory and communication design for multi-uav enabled wireless networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 2109–2121, 2018.

[2] X. Chenxiao and X.-L. Huang, "Energy-efficiency maximization for fixed-wing uav-enabled relay network with circular trajectory," *Chinese Journal of Aeronautics*, vol. 35, no. 9, pp. 71–80, 2022.

[3] J. Lyu, Y. Zeng, and R. Zhang, "Cyclical multiple access in uav-aided communications: A throughput-delay tradeoff," *IEEE Wireless Communications Letters*, vol. 5, no. 6, pp. 600–603, 2016.

[4] T. Liu, M. Cui, G. Zhang, Q. Wu, X. Chu, and J. Zhang, "3d trajectory and transmit power optimization for uav-enabled multi-link relaying systems," *IEEE transactions on green communications and networking*, vol. 5, no. 1, pp. 392–405, 2020.

[5] F. Ono, H. Ochiai, and R. Miura, "A wireless relay network based on unmanned aircraft system with rate optimization," *IEEE Transactions on Wireless Communications*, vol. 15, no. 11, pp. 7699–7708, 2016.

[6] C. Qiu, Z. Wei, Z. Feng, and P. Zhang, "Backhaul-aware trajectory optimization of fixed-wing uav-mounted base station for continuous available wireless service," *IEEE Access*, vol. 8, pp. 60 940–60 950, 2020.

[7] B. Li, R. Zhang, and L. Yang, "Joint user scheduling and uav trajectory optimization for full-duplex uav relaying," in *ICC 2021-IEEE International Conference on Communications*. IEEE, 2021, pp. 1–6.

[8] Y. Sun, D. Xu, D. W. K. Ng, L. Dai, and R. Schober, "Optimal 3d-trajectory design and resource allocation for solar-powered uav communication systems," *IEEE Transactions on Communications*, vol. 67, no. 6, pp. 4281–4298, 2019.