Fixed-winged UAV relay optimization for coverage improvement in deadzones

I. Briefly prior work

Here, we can briefly summarize key assumptions about ground user distribution, TDD or FDD, relay architecture and problem formulation, what is optimized. The prior work overviewed so far are

- In [1] it is assumed that the locations of the ground users are known, but no other assumptions are made about their distribution. The paper optimizes UAV trajectory to maximize the minimum average rate for the users. It is different from our paper as UAVs are treated as mobile base stations rather than relays, meaning the only link considered is UAV to ground user. The paper uses neither TDD or FDD because it only considers downlink.
- In [2] it is assumed that the UAV is always directly above the user, i.e., the UAV altitude H is the distance from the UAV to GUs. The paper jointly optimizes UAV relay transmission power and the radius of the UAVs circular flight trajectory to achieve the highest energy-efficiency (bits/Joule). In this paper, the user is reachable by both the UAV and the base station, and will pick the one with a higher channel capacity. The paper uses FDD.
- In [3] it is assumed that the users are evenly distributed on a line. With the goal of maximizing the minimum throughput experienced by GUs, the paper proposes a cyclic time division scheme in which transmission time is allocated to GUs when the UAV is nearby. In doing so, they reveal a tradeoff between maximizing throughput and minimizing access delay. The UAV is a mobile base station rather than a relay, so there is no TDD/FDD.
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II. System model

A. System Model

We consider the scenario of a base station (denoted B), a UAV relay (denoted U), and N ground users (the nth ground user is denoted G_n). B lies at the origin, with coordinates $[0,0,0]$. U circles at a height H meters above the y-axis on a circular path centered A meters away from B on the x-axis. The coverage dead zone is located B meters away from B on the x-axis.

We assume that U has a constant linear velocity v. Then U's position is a function of time and radius:

$w_u(t,r)$

$$\cancel{\mathbf{U}}(t,r) = \left[A + r\cos\left(v \cdot \frac{t}{r}\right),\ H,\ r\sin\left(v \cdot \frac{t}{r}\right)\right]^T$$

The coordinates of G_n fall somewhere within the dead zone and are denoted

$$\mathbf{G}_n = [x_n, 0, z_n]$$

The distance between G_n and U can be expressed as w_g

$$d_{\mathsf{G}_n \to \mathsf{U}}(t,r) = ||\cancel{\mathbf{U}}_{u}(t,r) - \cancel{\mathbf{G}}_{n,g}|| = \sqrt{\left[A + r\cos\left(v \cdot \frac{t}{r}\right) - x_n\right]^2 + H^2 + \left[r\sin\left(v \cdot \frac{t}{r}\right) - z_n\right]^2}$$

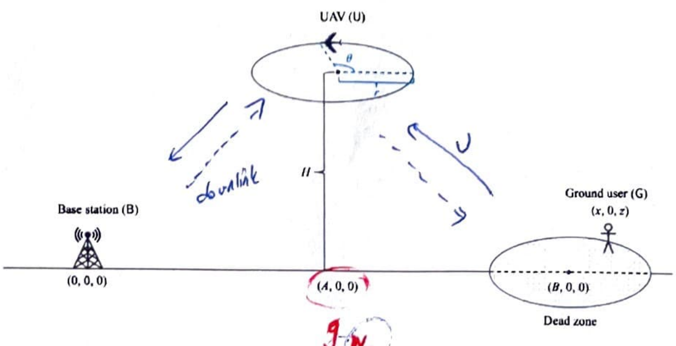


Fig. 1. Caption

$P_{t,G}$: user TX power in uplink

\newcommand{\center}{\mathbf{w}_{-\text{c}}} and the distance between U and B can be expressed

$$d_{\mathsf{U}\to\mathsf{B}}(t,r) = ||\mathbf{B} - \mathbf{U}(t,r)|| = \sqrt{\left[A + r\cos\left(v \cdot \frac{t}{r}\right)\right]^2 + H^2 + \left[r\sin\left(v \cdot \frac{t}{r}\right)\right]^2}$$

B. Channel Model

We assume that both the G_n-to-U and the U-to-B links are line of sight and that the channel gain follows a free-space propagation model. Throughout this paper we use a decode-and-forward architecture where the ground user transmits a message to the UAV which is then decoded and retransmitted to the base station.

The ground user transmission power, $P_{T,\mathsf{G}}$ is assumed to be constant across ground users. Consider the channel of an individual ground user g. The power received by U from g will be

$$P_{R,\mathsf{U}}(t,r) = P_{T,\mathsf{G}} \cdot G_T G_R \left(\frac{\lambda}{4\pi \cdot d_{g\to\mathsf{U}}(t,r)}\right)^2$$

where G_T and G_R are antenna gains at g and U respectively, and λ is the wavelength. Similarly, if $P_{T,\mathsf{U}}$ is the UAV transmission power, then the power received by B from U will be

$$P_{R,\mathsf{B}}(t,r) = P_{T,\mathsf{U}} \cdot G_T G_R \left(\frac{\lambda}{4\pi \cdot d_{\mathsf{U}\to\mathsf{B}}(t,r)}\right)^2$$

We assume that noise power, P_N, is constant and equivalent for all channels. With this in mind, the spectral efficiency (bps/Hz) between g and U can be calculated using Shannon's formula as

$$\mathrm{SE}_{g\to\mathsf{U}}(t,r) = \log_2\left(1 + \frac{P_{R,\mathsf{U}}(t,r)}{P_N \; N_0}\right)$$

noise different for individual user vs UAV/BS

And the spectral efficiency between U and B can be expressed:

$$\mathrm{SE}_{\mathsf{U}\to\mathsf{B}}(t,r) = \log_2\left(1 + \frac{P_{R,\mathsf{B}}(t,r)}{P_N \; N_2}\right)$$

III. Problem Formulation

A. Problem 1

Given the system and channel models described in the previous section, our objective for Problem 1 is as follows. Given N users in a coverage dead zone, we use a frequency-division duplexing strategy such that the total bandwidth available for the ground users is evenly split into M bands, allowing U to serve $M << N$ users at any given time.

Consider Δ_{max}, the maximum displacement of U over which the channel can be considered stationary. Then we can split the total flight time (excluding takeoff and landing) into blocks where the channel is estimated to be stationary. The ~~length~~ duration of these blocks, T_C, can be expressed

$$T_C = \frac{\Delta_{\mathsf{max}}}{v}$$

Because the channel is considered stationary during each coherence block, we can estimate the SE of the system during that block using its start time. To help with this, let $\mathbf{T}$ be the set of starting times for each coherence block.

Timeslots split using N_C

Let N_C be the total number of coherence blocks required to **serve** (define better) M users. If $\mathbf{T}_M$ is the set of coherence block starting times reserved for those M users, then the mean spectral efficiency achieved by this group is:

$$\overline{\mathrm{SE}}(r) = \sum_{t\in\mathbf{T}_M} \frac{1}{M} \sum_{g\in\mathbf{M}} \min\left[\mathrm{SE}_{g\to\mathsf{U}}(t,r)\,,\, \mathrm{SE}_{\mathsf{U}\to\mathsf{B}}\right]$$

Each user gets fixed number of coherence blocks

Consider a scheduling system where each user is allocated a fixed set of coherence blocks during one period. Let $\mathbf{T}_g$ be the starting times of those coherence blocks reserved for the user g. Then the mean spectral efficiency of our system can be expressed

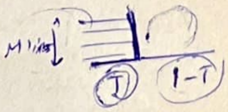
$$\overline{\mathrm{SE}}(r) = \frac{1}{N} \sum_{g\in\mathbf{N}} \sum_{t\in\mathbf{T}_g} \min\left[\mathrm{SE}_{g\to\mathsf{U}}(t,r)\,,\, \mathrm{SE}_{\mathsf{U}\to\mathsf{B}}(t,r)\right]$$

mathcal: Sets

mathbf: if bold capital matrices.

M users, T, $\underbrace{(1-T)}$

$g \to U$ $\quad$ $U \to B$



Problem Objective

In both cases, we would like to find

$$\arg\max_{r} \ \overline{\mathrm{SE}}(r)$$

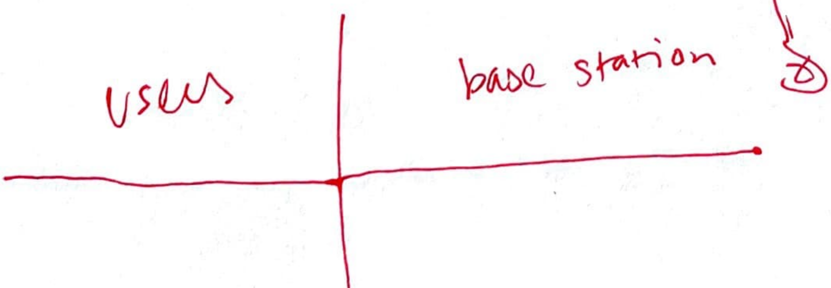
REFERENCES

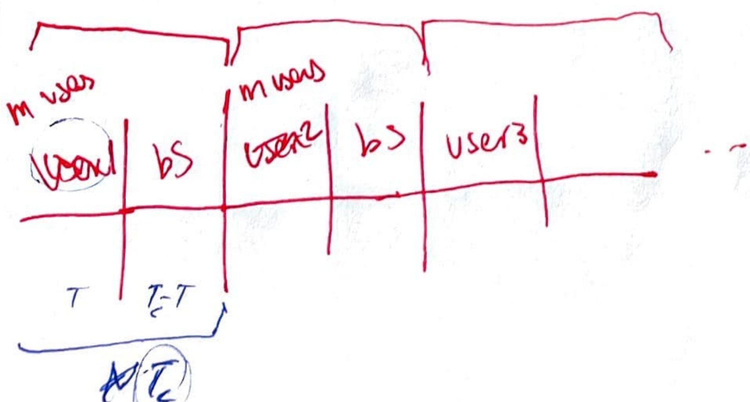
[1] Q. Wu, Y. Zeng, and R. Zhang, "Joint trajectory and communication design for multi-uav enabled wireless networks," *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 2109–2121, 2018.

[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.

• differentiate between user ($\frac{1}{M}$ bandwidth) and UAV (all bandwidth)





$$\frac{T}{T_c} = \delta$$

$$\mathrm{SE}(r) = \frac{1}{M N_{slots}} \sum_{t \in N_{slots}} \min\left[\left(\sum_{g\in M} SE_{g\to U}\right)\frac{T}{T_c},\ (SE_{U\to B})\frac{T_c - T}{T_c}\right]$$

$$= \sum_{g \in M} \min\left[SE_{g\to U},\ SE_{U\to B}\right]$$

$$\frac{\frac{2\pi r}{v}}{T_c} = N_{slots}$$

$$\frac{N_{slots}}{N/M} = N_c$$

$SE_{g \to U} \to$ bits/Hz

$SE_{U \to B} \to$ bits/Hz

$$\frac{1}{N_{slots}} \sum_{t \in N_{slots}} \left(\min \left[\overbrace{\underbrace{\left(\sum_{g \in M} SE_{g \to U}\right)\alpha_t}_{(bits/Hz)\cdot\alpha}}^{SE_{1,t}}, \; \overbrace{\underbrace{SE_{U \to B}(1-\alpha_t)}_{(bits/Hz)(1-\alpha)}}^{SE_{2,t}} \right] \right) / T_c$$

opt.

$$\alpha_t : \frac{SE_{2,t}}{SE_{1,t} + SE_{2,t}}$$

α_t is fixed over time slots α

bits over N_{slots}

$\alpha = \frac{1}{2}$, w_c fixed

opt r.

$$\max_{r, \alpha, w_c} SE(r, \alpha, w_c)$$

entire optimization problem

$M=1$, $w_q \in$ Uniform, $f_q(w_q)$

$$\underset{q \in f(x,y)}{E}\left[SE(\alpha, w_c)\right] = \int_{x,y \in D} x \cdot y \cdot SE(\alpha, w_c) \cdot f_q(w_q = (x,y,0)) \, dx\, dy = C$$