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 a set of ground users (denoted $\mathcal{G}$, with $||\mathcal{G}|| = N$). ~~B lies~~ at the origin, with coordinates $\mathbf{w}_\mathsf{B} = [0,0,0]^T$. U circles at a height H meters above the y-axis, and flies on a circular path of radius r centered c meters away from B on the x-axis. The coverage dead zone is located A meters away from B on the x-axis.

To simplify calculation, we discretize the total flight time T into N_{slots} total time slots. The length of each time slot is $\delta_t = T/N_{\text{slots}}$, which is short enough that the channel can be considered approximately stationary during each time slot. The UAV's trajectory can then be thought of as a discrete sequence of positions, a function of the slot index, radius, and flight path position:

$$\mathbf{w}_\mathsf{U}(n,r,c) = \left[c + r\cos\left(\frac{v}{r}\cdot n \cdot \frac{T}{N_{\text{slots}}}\right),\ H,\ r\sin\left(\frac{v}{r}\cdot n\cdot \frac{T}{N_{\text{slots}}}\right)\right]^T$$

for $r_{max} > r > r_{min}$

An individual user g has coordinates which fall somewhere within the coverage deadzone, and are denoted

$r_{min} < r < r_{max}$

$$\mathbf{w}_g = [x_g, 0, z_g]^T$$

$v_{min} < v < v_{max}$

u = users
→ Don't need B

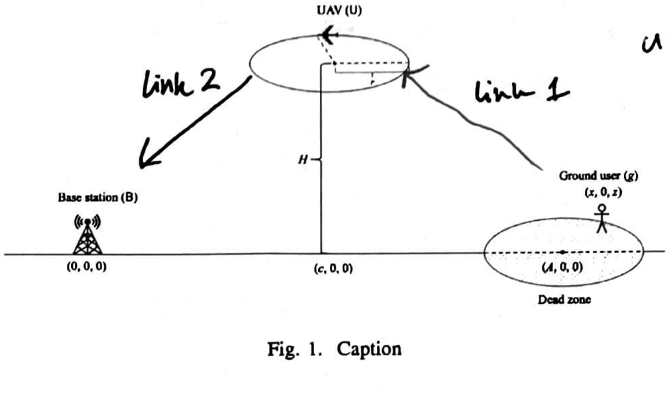


Fig. 1. Caption

The distance between g and U can be expressed as

$$d_{g\to\mathsf{U}}(n,r,c) = \|\mathbf{w}_\mathsf{U}(n,r,c) - \mathbf{w}_g\| = \sqrt{\left[c + r\cos\left(\frac{v}{r}\cdot n\cdot\frac{T}{N_\text{slots}}\right) - x_g\right]^2 + H^2 + \left[r\sin\left(\frac{v}{r}\cdot n\cdot\frac{T}{N_\text{slots}}\right) - z_g\right]^2}$$

and the distance between U and B can be expressed

$$d_{\mathsf{U}\to\mathsf{B}}(n,r,c) = \|\mathbf{w}_\mathsf{B} - \mathbf{w}_\mathsf{U}(n,r,c)\| = \sqrt{\left[c + r\cos\left(\frac{v}{r}\cdot n\cdot\frac{T}{N_\text{slots}}\right)\right]^2 + H^2 + \left[r\sin\left(\frac{v}{r}\cdot n\cdot\frac{T}{N_\text{slots}}\right)\right]^2}$$

B. Channel Model

We assume that both the g-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. 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 one time.

Consider the channel of an individual ground user g. If $P_{T,g}$ is the ground user transmission power (assumed to be constant over all users), then the power received by U can be expressed.

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

where G_T and G_R are antenna gains at g and U respectively, and λ is the wavelength. If $P_{T,\mathsf{U}}$ is the UAV transmission power, then the power received by B from U will be: should G_T and G_R be separate for g vs. U vs. B?

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

If N_g is the noise power over the g-to-U channel, the spectral efficiency (bps/Hz) between g and U can be calculated using Shannon's formula as:

$$\text{SE}_{g\to\mathsf{U}}(n,r,c) = \log_2\left(1 + \frac{P_{R,\mathsf{U}}(n,r,c)}{N_g}\right)$$

The bandwidth of the U-to-B channel is M times as large as any individual g-to-U channel, and therefore experiences $N_\mathsf{B} = M\cdot N_g$ noise power. Therefore, the spectral efficiency between U and B can be expressed:

$$\text{SE}_{\mathsf{U}\to\mathsf{B}}(n,r,c) = \log_2\left(1 + \frac{P_{R,\mathsf{B}}(n,r,c)}{N_\mathsf{B}}\right)$$

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.

Each time slot is split into two phases: the first phase is for transmission from M ground users to U, and the second for transmission from U to B. If T_G is the duration of the first phase, then $T_C - T_G$ is the duration of the second phase. We can further normalize these by defining $\alpha = T_\mathsf{G}/T_C$. The proportion of the timeslot reserved for the first phase is α, and the proportion of the timeslot reserved for the second phase is $1-\alpha$. If $\mathcal{G}_M$ is the set of users being served in a given timeslot, then the average spectral efficiency over the timeslots can be expressed:

$$\overline{\text{SE}}(\alpha,r,c) = \frac{1}{N_\text{slots}}\sum_{n=0}^{N_\text{slots}}\min\left[\alpha\sum_{g\in\mathcal{G}_{M,n}}\text{SE}_{g\to\mathsf{U}}(n,r,c)\ ,\ (1-\alpha)\cdot\text{SE}_{\mathsf{U}\to\mathsf{B}}(n,r,c)\right]$$

$r \sim f(r)$ r.v. pdf

We would like to maximize this mean spectral efficiency. Initially, we will focus on the case where α is set as 0.5, and c is set as $B/2$, and focus on finding

$$\arg\max_r\ \overline{\text{SE}}(\alpha,r,c)$$

Because the locations of the users are unknown, we would like the maximize the expected value of the mean spectral efficiency. The UAV location is deterministic, meaning that the U-to-B spectral efficiency is as well. Therefore, we can write the expected mean SE as:

g is iid r.v.

$G_{m,n}$ set of user

$f_n(g_1,\dots,g_m) = f(g_1)f(g_2)\cdots f(g_m)$

$f_{G_{m,n}}(G_{m,n}) = \prod f_n(g_1,\dots,g_m)$ $G_{n,\text{Mtot}}$

$f_{G_{m,n}}(G_{m,n} \mid G_{m,n-1},\dots G_{m,n-0})$

max η

s.t. $R_{gU} > \eta$

$R_{UB} > \eta$

$$\mathbb{E}\{\overline{\mathrm{SE}}(\alpha, r, c)\} = \frac{1}{N_{\text{slots}}}\sum_{n=0}^{N_{\text{slots}}} \min\left[\alpha \cdot M \cdot \overbrace{\mathbb{E}\{\mathrm{SE}_{g\to \mathrm{U}}(n, r, c)\}}^{R_{gU}}\ ,\ (1-\alpha)\cdot \overbrace{\mathrm{SE}_{\mathrm{U}\to \mathrm{B}}(n, r, c)}^{R_{UB}}\right]$$

If we assume the users are uniformly distributed in a square of side length L, then we can calculate this as

$$\mathbb{E}\{\overline{\mathrm{SE}}(\alpha, r, c)\} = \frac{1}{N_{\text{slots}}}\sum_{n=0}^{N_{\text{slots}}} \min\left[\alpha \cdot M \cdot \frac{1}{L^2}\int_0^L\int_0^L \mathrm{SE}_{g\to \mathrm{U}}(n, r, c)dz_g\, dx_g\ ,\ (1-\alpha)\cdot \mathrm{SE}_{\mathrm{U}\to \mathrm{B}}(n, r, c)\right]$$

This is the objective function, constraints are $r_{\min} \le r \le r_{\max}$?

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.

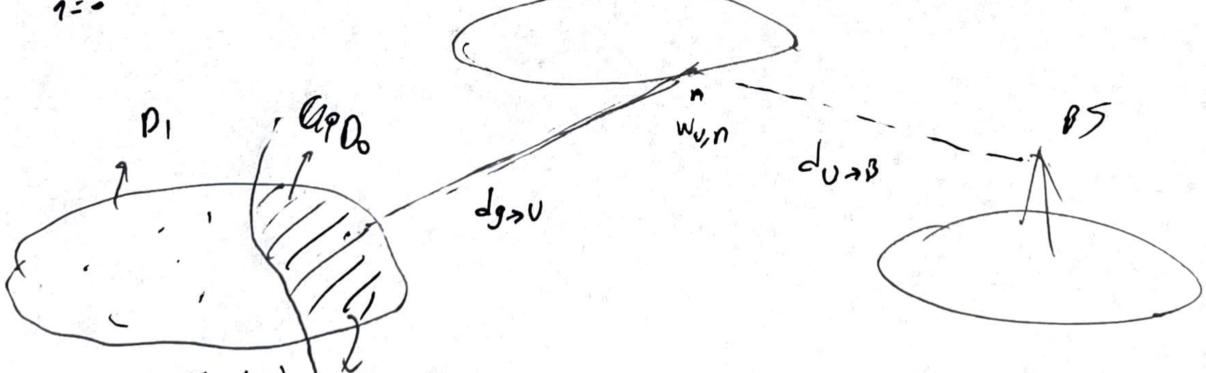
[2] X. Chenxiao and X.-L. Huang, "Energy-efficiency maximization for fixed-wing uav-enabled relay network with circular trajectory," *Chinese Journal of Aeronautics*, vol. 35, no. 9, pp. 71–80, 2022.

[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.

① Numerically Monte Carlo

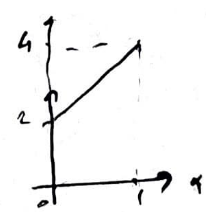
② $M=1$

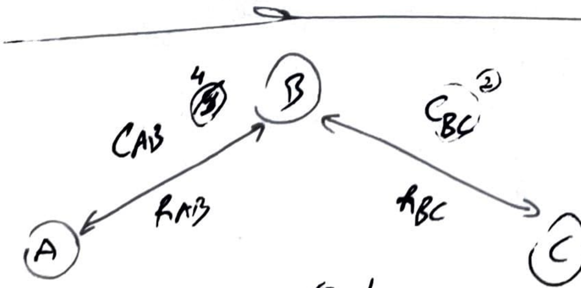
$$\frac{1}{N_{slots}}\sum_{n=0}^{N_{slots}} \min\{\alpha \cdot SE_{g\to U}(n,r,c),\ (1-\alpha)\, SE_{U\to B}(n,r,c)\}$$



α fixed $\Rightarrow \alpha = \alpha_0 = \frac{SE_{U\to B}(n,r,c)}{SE_{g\to U}(n,r,c) + SE_{U\to B}(n,r,c)}$

$$\overline{SE}(\alpha,r,c) = \begin{cases} \frac{1}{N_{slots}}\sum_{n=0}^{N_{slots}} \cancel{\min}(1-\alpha_0)\, SE_{U\to B}(n,r,c) & w_g \in D_0 \\ \frac{1}{N_{slots}}\sum_{n=0}^{N_{slots}} \alpha \cdot SE_{g\to U}(n,r,c) & w_g \in D_1 \end{cases}$$





$R_{AB} \le C_{AB}$

$R_{BC} \le C_{BC}$

$\alpha = 1$

$T = \alpha + 1 - \alpha$

max $\min\{\alpha \cdot R_{AB}, (1-\alpha) R_{BC}\}$

$\alpha \cdot R_{AB} = (1-\alpha) R_{BC}$

$R_{AB} = (\frac{1}{\alpha} - 1) R_{BC}$