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Cognitive UAV Communication via Joint Trajectory and Power Control

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1. Introduction

Background: Unmanned aerial vehicle (UAVs) or drones are anticipated to have abundant civil applications in the future [1], for e.g. cargo delivery, agriculture inspection, surveillance, rescue and search, and communication relay. There are generally two approaches to realize the UAV's communication with their grounds users, namely the conventional direct UAV-to-ground communication and the newly proposed cellular-connected UAV communication [2].

Challenge: Due to the scarcity of wireless spectrum, UAVs may need to share the spectrum with existing wireless devices. This resembles spectrum sharing in cognitive radio (CR) networks, in which secondary users share the same frequency bands with existing primary users. In this case, the UAV-to-ground communication may cause severe interference to the existing terrestrial users. As a result, how to optimize the UAV communication performance while effectively controlling the air-to-ground co-channel interference is a new and challenging problem to be solved.

Contribution: This paper considers a cognitive UAV communication system, where a cognitive/secondary UAV transmitter communicates with a ground secondary receiver (SR), in the presence of a number of primary terrestrial communication links that operate over the same frequency band. The main results are summarized as follows.

- We adopt the interference temperature (IT) method in CR networks to protect the primary communication links, based on which the received interference power at each primary receiver (PR) cannot exceed a prescribed IT threshold.
- We maximize the average achievable rate of the cognitive UAV communication over a finite UAV mission/communication period, by jointly optimizing the UAV trajectory and transmit power allocation, subject to the maximum speed, initial/final locations and average transmit power constraints of the UAV, as well as the average IT constraints at the PRs.
- To tackle the non-convex problem, we propose an efficient algorithm that ensures to obtain a locally optimal solution by applying the techniques of alternating optimization and successive convex approximation (SCA).

2. System Model

2.1 System Setup: A cognitive/secondary UAV transmitter sends information to a ground SR, in the presence of a set of $K \geq 1$ primary users that operate over the same frequency band.

- **Communication duration:** $\mathcal{T} = [0, T]$, $T \geq 0$.
- **Locations:** 1) The SR and each PR k: $\boldsymbol{w} = (x, y)$ and $\boldsymbol{w}_k = (x_k, y_k)$ (The UAV perfectly knows the locations of the ground SR and PRs); 2) The time-varying horizontal location of the UAV with a constant flight altitude H in meter (m): $\hat{\boldsymbol{q}}(t) = (\hat{x}(t), \hat{y}(t))$, $t \in \mathcal{T}$; 3) The UAV's initial and final (horizontal) locations: $\hat{\boldsymbol{q}}_I = (x_I, y_I)$ and $\hat{\boldsymbol{q}}_F = (x_F, y_F)$.
- **Maximum speed:** $\hat{V}$, leading to $\sqrt{\dot{\hat{x}}^2(t) + \dot{\hat{y}}^2(t)} \leq \hat{V}, \forall t \in \mathcal{T}$, where $\dot{\hat{x}}(t)$ and $\dot{\hat{y}}(t)$ denote the first derivatives of $\hat{x}(t)$ and $\hat{y}(t)$, respectively.
- **Discretization:** 1) Discretize the mission/communication period $\mathcal{T}$ into N time slots each with equal duration $\delta_t = T/N$; 2) The horizontal UAV location at time slot $n \in \mathcal{N} \triangleq \{1, \ldots, N\}$: $\boldsymbol{q}[n] = (x[n], y[n])$.

2.2 Problem Formulation:

- The constraints on the UAV trajectory are expressed as

$$\|\boldsymbol{q}[n] - \boldsymbol{q}[n-1]\|^2 \leq V^2, \tag{1}$$
$$\boldsymbol{q}[0] = \hat{\boldsymbol{q}}_I, \tag{2}$$
$$\boldsymbol{q}[N] = \hat{\boldsymbol{q}}_F, \tag{3}$$

where $V \triangleq \hat{V}\delta_t$ denotes the maximum UAV displacement during each time slot, and $\|\cdot\|$ denotes the Euclidean norm.

- The distance between the UAV and the SR and that between the UAV and each PR $k \in \mathcal{K}$ is

$$d(\boldsymbol{q}[n]) = \sqrt{H^2 + \|\boldsymbol{q}[n] - \boldsymbol{w}\|^2}, \tag{4}$$
$$d_k(\boldsymbol{q}[n]) = \sqrt{H^2 + \|\boldsymbol{q}[n] - \boldsymbol{w}_k\|^2}. \tag{5}$$

- The channel power gain from the UAV to the SR and that to each PR $k \in \mathcal{K}$ is

$$h(\boldsymbol{q}[n]) = \beta_0 d^{-2}(\boldsymbol{q}[n]) = \frac{\beta_0}{H^2 + \|\boldsymbol{q}[n] - \boldsymbol{w}\|^2}, \tag{6}$$
$$g_k(\boldsymbol{q}[n]) = \beta_0 d_k^{-2}(\boldsymbol{q}[n]) = \frac{\beta_0}{H^2 + \|\boldsymbol{q}[n] - \boldsymbol{w}_k\|^2}, \tag{7}$$

where β_0 denotes the channel power gain at the reference distance of $d_0 = 1$ m.

- Accordingly, by denoting $p[n] \geq 0$ as the transmit power by the UAV, the achievable rate from the UAV to the SR is

$$R(p[n], \boldsymbol{q}[n]) = \log_2\left(1 + \frac{\eta_0 p[n]}{H^2 + \|\boldsymbol{q}[n] - \boldsymbol{w}\|^2}\right), \tag{8}$$

where $\eta_0 = \beta_0/\sigma^2$ denotes the reference signal-to-noise ratio (SNR) and σ^2 denotes the noise power at the SR receiver.

- By letting P denote the maximum average transmit power at the UAV, the transmit power constraints are

$$\frac{1}{N}\sum_{n=1}^{N} p[n] \leq P. \tag{9}$$

- The IT constraints at each PR $k \in \mathcal{K}$ are

$$\frac{1}{N}\sum_{n=1}^{N} \frac{\beta_0 p[n]}{H^2 + \|\boldsymbol{q}[n] - \boldsymbol{w}_k\|^2} \leq \Gamma_k, \ \forall k \in \mathcal{K}. \tag{10}$$

- By combining all the constraints above, the problem can be formulated as

$$\text{(P1)}: \max_{\{p[n], \boldsymbol{q}[n]\}} \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{\eta_0 p[n]}{H^2 + \|\boldsymbol{q}[n] - \boldsymbol{w}\|^2}\right)$$
$$\text{s.t. } p[n] \geq 0, \ \forall n \in \mathcal{N}, \tag{11}$$
$$(1), (2), (3), (9), \text{ and } (10).$$

Note that problem (P1) is a non-convex optimization problem, and thus this problem is generally difficult to be solved optimally.

3. Proposed Solution to Problem (P1)

We present an efficient algorithm based on alternating optimization, to obtain a locally optimal solution to (P1), by optimizing one of the transmit power $\{p[n]\}$ and the UAV trajectory $\{\boldsymbol{q}[n]\}$ with the other fixed in an alternating manner.

3.1 Transmit Power Optimization Under Given Trajectory:
With the fixed trajectory, (P1) can be reduced to

$$\text{(P2)}: \max_{\{p[n]\}} \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{\eta_0 p[n]}{H^2 + \|\boldsymbol{q}[n] - \boldsymbol{w}\|^2}\right)$$
$$\text{s.t. } (9), (10), \text{ and } (11).$$

Notice that (P2) is a convex problem, which can be solved optimally by standard convex optimization techniques, such as the interior point method.

3.2 Trajectory Optimization Under Given Transmit Power:
With any given transmit power, (P1) can be reduced to

$$\text{(P3)}: \max_{\{\boldsymbol{q}[n]\}} \frac{1}{N}\sum_{n=1}^{N} \log_2\left(1 + \frac{\eta_0 p[n]}{H^2 + \|\boldsymbol{q}[n] - \boldsymbol{w}\|^2}\right)$$
$$\text{s.t. } (1), (2), (3), \text{ and } (10).$$

Notice that problem (P3) is non-convex, and we adopt the SCA technique to obtain a locally optimal solution to (P3) in an iterative manner.

- Considering the non-concave objective function of (P3) and applying the first-order Taylor expansion, we have the following lemma.

Lemma 1: For any given $\{\boldsymbol{q}^{(j)}[n]\}$, $j \geq 0$, it follows that

$$R(p[n], \boldsymbol{q}[n]) \geq R^{\text{lb}}(p[n], \boldsymbol{q}[n]), \tag{12}$$

where

$$R^{\text{lb}}(p[n], \boldsymbol{q}[n]) \triangleq \log_2\left(1 + \frac{\eta_0 p[n]}{H^2 + \|\boldsymbol{q}^{(j)}[n] - \boldsymbol{w}\|^2}\right) - \frac{\eta_0 p[n]\left(\|\boldsymbol{q}[n] - \boldsymbol{w}\|^2 - \|\boldsymbol{q}^{(j)}[n] - \boldsymbol{w}\|^2\right)\log_2 e}{\left(H^2 + \|\boldsymbol{q}^{(j)}[n] - \boldsymbol{w}\|^2\right)\left(\left(H^2 + \|\boldsymbol{q}^{(j)}[n] - \boldsymbol{w}\|^2\right) + \eta_0 p[n]\right)},$$

and the inequality in (12) is tight for $\boldsymbol{q}[n] = \boldsymbol{q}^{(j)}[n]$.

- Considering the non-convex constraints in (10) and introducing auxiliary variables $\{t_k[n]\}$, it follows that

$$t_k[n] \leq \|\boldsymbol{q}[n] - \boldsymbol{w}_k\|^2, \ \forall n \in \mathcal{N}, \ k \in \mathcal{K}, \tag{13}$$
$$t_k[n] \geq 0, \ \forall n \in \mathcal{N}, \ k \in \mathcal{K}, \tag{14}$$
$$\frac{1}{N}\sum_{n=1}^{N} \frac{\beta_0 p[n]}{H^2 + t_k[n]} \leq \Gamma_k, \ \forall k \in \mathcal{K}. \tag{15}$$

- Considering the non-convex constraints in (13) and applying the first-order Taylor expansion to the right-hand-side (RHS) of (13), we have

$$t_k[n] \leq \|\boldsymbol{q}^{(j)}[n] - \boldsymbol{w}_k\|^2 + 2\left(\boldsymbol{q}^{(j)}[n] - \boldsymbol{w}_k\right)^T\left(\boldsymbol{q}[n] - \boldsymbol{q}^{(j)}[n]\right), \forall n \in \mathcal{N}, \ k \in \mathcal{K}. \tag{16}$$

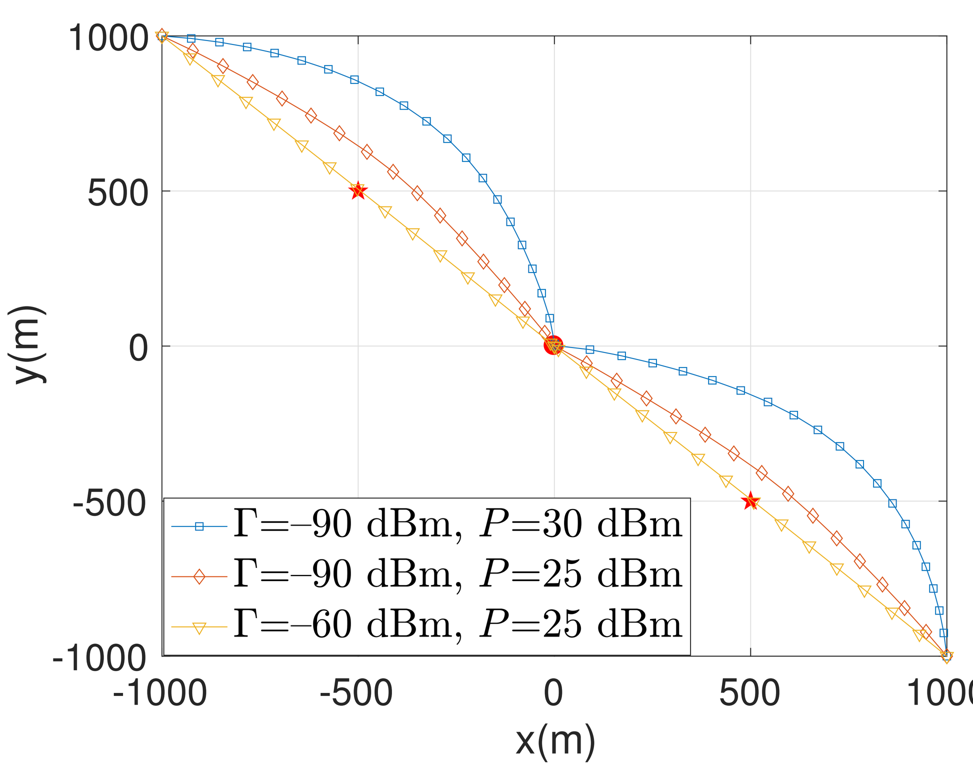
- By combining the above, problem (P3) is approximated as the following convex optimization problem (P3.1) at any local point $\{\boldsymbol{q}^{(j)}[n]\}$.

$$\text{(P3.1)}: \max_{\{\boldsymbol{q}[n], t_k[n]\}} \frac{1}{N}\sum_{n=1}^{N} R^{\text{lb}}(p[n], \boldsymbol{q}[n])$$
$$\text{s.t. } (1), (2), (3), (14), (15), \text{ and } (16).$$

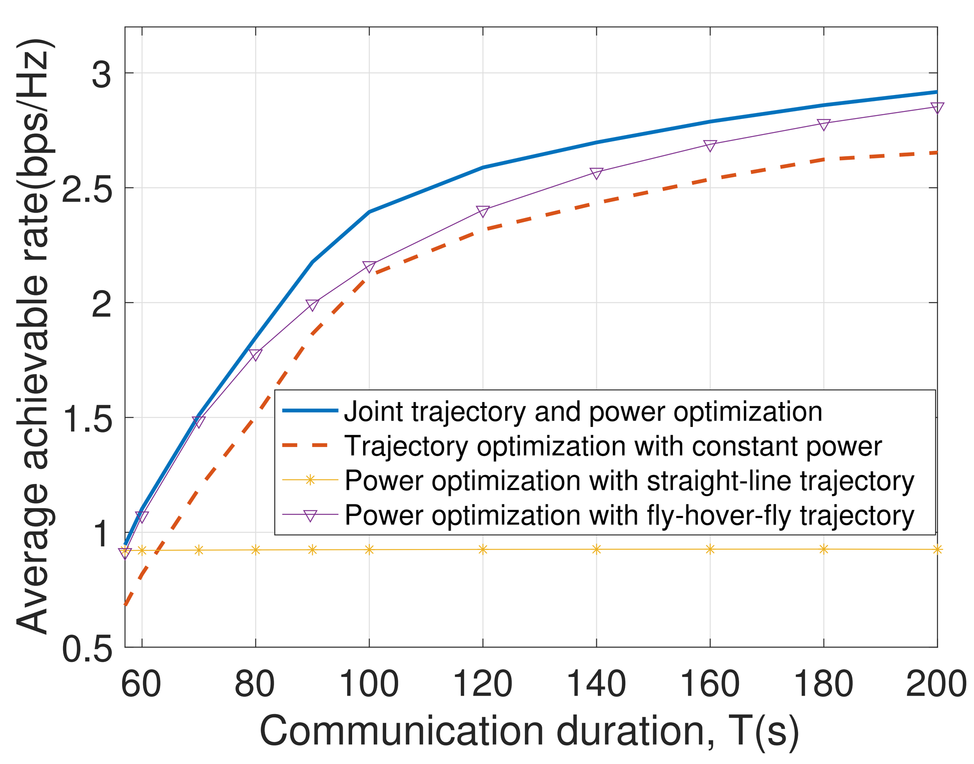
3.3 Alternating Optimization:
At last, we propose an alternating optimization algorithm to obtain locally optimal solution to (P1), which optimizes the UAV trajectory $\{\boldsymbol{q}[n]\}$ and transmit power $\{p[n]\}$ in an alternating manner, by considering the other to be given.

4. Numerical Results

We set $\hat{V} = 50$ m/s, $\sigma^2 = -50$ dBm, $\beta_0 = -30$ dB, $P = 30$ dBm, $H = 100$ m. The SR is located at $(0 \text{ m}, 0 \text{ m})$, the two PRs are located at $(-500 \text{ m}, 500 \text{ m})$ and $(500 \text{ m}, -500 \text{ m})$, respectively. We set $\hat{\boldsymbol{q}}_I = (-1000 \text{ m}, 1000 \text{ m})$ and $\hat{\boldsymbol{q}}_F = (1000 \text{ m}, -1000 \text{ m})$, respectively. We assume that IT constraints are identical for different PRs, i.e., $\Gamma_k = \Gamma$, $\forall k \in \mathcal{K}$. The initial UAV trajectory following a straight line, in which the UAV flies directly from the initial location to the final location with a constant speed.



(a) UAV trajectories projected onto the ground (horizontal) plane by the proposed design with joint UAV trajectory and power optimization. The red stars represent the locations of the two ground PRs, respectively, and the red circle denotes the location of the ground SR.



(b) The average achievable rate of the cognitive UAV communication versus the communication duration T.

5. Conclusion

This paper studied a new spectrum sharing scenario, where a cognitive/secondary UAV communication system coexisted with primary terrestrial wireless communication links.

- We optimized the UAV's trajectory, jointly with its transmit power allocation, to maximize the average achievable rate of the cognitive UAV communication system over a finite mission/communication period, subject to a set of IT constraints for protecting the PRs.
- To tackle this non-convex optimization problem, we proposed an efficient algorithm to obtain a locally optimal solution via alternating optimization and SCA.
- Numerical results validated the superior performance of our proposed design against other benchmark schemes.

References

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[2] S. Zhang, Y. Zeng, and R. Zhang, "Cellular-enabled UAV communication: Trajectory optimization under connectivity constraint," to appear in *Proc. IEEE ICC*, 2018, [Online] Available: https://arxiv.org/abs/1710.11619.