Covert Wireless Data Collection Based on Unmanned Aerial Vehicles

Xiaobo Zhou[£†], Shihao Yan[‡*], Feng Shu[†‡], Riqing Chen[‡], and Jun Li[†]
[£]School of Physics and Electronic Engineering, Fuyang Normal University, Fuyang, China
[†]School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing, China
[*]School of Engineering, Macquarie University, Sydney, NSW, Australia
[‡]School of Computer and Information Sciences, Fujian Agriculture and Forestry University, Fuzhou, China
Email: {zxb, shufeng, jun.li,}@njust.edu.cn, shihao.yan@mq.edu.au, riqing.chen@fafu.edu.cn

***Abstract*—This work considers unmanned aerial vehicle (UAV) networks for collecting data covertly from ground users. The full-duplex UAV intends to gather critical information from a scheduled user (SU) through wireless communication and generate artificial noise (AN) with random transmit power in order to ensure a negligible probability of the SU's transmission being detected by the unscheduled users (USUs). To enhance the system performance, we jointly design the UAV's trajectory and its maximum AN transmit power together with the user scheduling strategy subject to practical constraints, e.g., a covertness constraint, which is explicitly determined by analyzing each USU's detection performance, and a binary constraint induced by user scheduling. The formulated design problem is a mixed-integer non-convex optimization problem, which is challenging to solve directly, but solved by a penalty successive convex approximation (P-SCA) scheme. Our examination shows that the P-SCA scheme significantly outperforms a benchmark scheme in terms of achieving a higher max-min average transmission rate subject to the same covertness constraint.**

I. Introduction

Unmanned aerial vehicles (UAVs) communications have attracted significant attention in both military and civilian applications, such as search and rescue, cargo delivery, aerial filming and inspection [1]. Different from the traditional terrestrial wireless communications, UAV-enabled wireless communications possess many advantages, such as on-demand and swift deployment, higher network flexibility with the controllable UAV movement, and high possibilities of line-of-sight (LoS) communication links between a UAV and ground users. In particular, the favorable LoS air-to-ground communication links can be efficiently exploited in various UAV-enabled wireless networks for performance enhancement by properly designing the UAV's flight trajectory (e.g., [2–4]). However, the LoS air-to-ground communication links also cause UAV communications to suffer from more stringent security issues than the conventional terrestrial wireless communications, since the confidential information transmitted by a UAV is more vulnerable to malicious users when the UAV is in sight.

Recently, several works addressed the wireless communication security of UAV networks from the perspective of physical layer security (e.g., [5–9]). In [5], the authors designed the UAV trajectory and transmit power to enhance the quality of the desired communication link and degrade the eavesdropping link in order to prevent the confidential information from being intercepted by eavesdroppers. Meanwhile, the use of a UAV as a friendly jammer to enhance the terrestrial wireless communication security was considered in [6, 7]. Along this direction, the authors of [8, 9] considered dual UAV-enabled wireless communications, where one UAV as a transmitter sends confidential information to intended users and the other UAV acting as a jammer generates artificial noise (AN) to create interference to eavesdroppers.

The aforementioned physical layer security technology only addresses protecting the contents of wireless communications in UAV networks. We note that, in some practical scenarios, hiding the transmission behavior of a transmitter is explicitly required (e.g., [10–12]), which is also desirable in some UAV networks. We note that, once the transmission behavior of a transmitter is detected by malicious users, its location information is exposed, which makes it vulnerable to physical or ongoing attacks. Fortunately, the emerging covert communication technology can hide the very existence of a wireless transmission, i.e., avoiding a wireless transmission being detected by a warden (e.g., [13–22]).

Data collection is an important application and research topic in the context of Internet of Things (IoT) [23]. In conventional IoT scenarios, a sensor node normally has to send its sensing information to a sink node via multi-hop communications, which costs a large amount of energy consumption at sensor nodes [24]. In addition, in some special application scenarios (e.g., remote mountainous or volcanic areas), it is difficult or even impossible to collect information data from all the sensor or sink nodes to the internet. Utilizing a UAV as a data collector, each sensor node can directly transmit its collected information to the UAV and the UAV can sequentially schedule the sensor nodes to collect data from them when it moves sufficiently close to them. Thus, the use of a UAV as a mobile data collector is highly appealing for saving energy and proving reliable data collection, which is a significantly important application scenario of UAV networks. In such data collection scenarios, the sensor nodes may prefer to preserve their privacy (e.g., location information) from each other while transmitting critical information to the UAV, when, for example, the sensor nodes are spies and prefer to hide from each other. In this work, we address this problem and design a UAV-enabled system based on covert communications.

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II. System Model

A. Considered Scenario and Adopted Assumptions

In this work, we consider covert communications in a UAV network, where a UAV working in the full-duplex (FD) mode acts as a mobile data collector to gather information from K users on the ground. We assume that at most one ground user is scheduled for data transmission at one time instant t. The scheduled user (SU) intends to transmit information to the UAV covertly and does not wish this transmission to be detected by the unscheduled users (USUs) in order to preserve the privacy of the SU (e.g., hiding the location information of the SU from USUs). In this work, we consider that the UAV is equipped with a receive antenna and a transmit antenna, in which the receive antenna is used for data collection and the transmit antenna is used to assist the covert transmission from the SU to the UAV by generating AN. The UAV's flight period is set to a finite value T due to the limited battery capacity. During the flight period T, the UAV flies at a fixed altitude H, which should be properly selected to avoid obstacles. The UAV's trajectory projected onto the horizontal plane is denoted as $\{\mathbf{q}_u(t) \in \mathbb{R}^{2\times 1}, 0 \leq t \leq T\}$, while the horizontal coordinate of the k-th ground user is denoted by $\mathbf{w}_k \in \mathbb{R}^{2\times 1}$, $k \in \mathcal{K} \triangleq \{1, 2, \cdots, K\}$. To facilitate the UAV trajectory design, we divide the flight period T into N equal-time slots, i.e., $T = N\delta_t$, where δ_t is the duration of each time slot and should be chosen properly to balance the approximation accuracy and computational complexity. Thus, the UAV's trajectory $\mathbf{q}_u(t)$, $0 \leq t \leq T$, can be approximated by $\mathbf{q}_u[n]$, $n \in \mathcal{N} \triangleq \{1, 2 \cdots, N\}$, where $\mathbf{q}_u[n] = \mathbf{q}_u(n\delta_t)$ denotes the horizontal coordinate of the UAV at the n-th time slot. Then, the mobility constraints of the UAV can be written as

$$\mathbf{q}_u[1] = \mathbf{q}_u[N], \tag{1a}$$

$$\|\mathbf{q}_u[n+1] - \mathbf{q}_u[n]\| \leq V_{\max}\delta_t, \ n \in \mathcal{N} \setminus \{N\}, \tag{1b}$$

where (1a) implies that the UAV has to return the initial location by the end of the last time slot, and (1b) denotes the maximum flight distance during each time slot in which $V_{\max}$ denotes the maximum speed of the UAV.

B. Transmission from the Scheduled User to the UAV

We assume that the channels from ground users to a UAV are dominated by line-of-sight (LoS). Considering channel reciprocity, at the n-th time slot, the channel from the k-th ground user to the UAV or the channel from the UAV to the k-th ground user is given by

$$h_{k,u}[n] = h_{u,k}[n] = \sqrt{\frac{\beta_0}{\|\mathbf{q}_u[n] - \mathbf{w}_k\|^2 + H^2}}, \ \forall k, n, \tag{2}$$

where β_0 denotes the channel power gain at a reference distance 1 meter (m). The channel from the k-th user to the m-th user is denoted by $g_{k,m}[n]$, $\forall k, m$, $k \neq m$, and the self-interference channel of the UAV is denoted by $g_{u,u}[n]$, $\forall n$, which is subject to quasi-static Rayleigh fading, where $g_{k,m}[n] \sim \mathcal{CN}(0, \lambda_{k,m})$ and $g_{u,u}[n] \sim \mathcal{CN}(0, \lambda_{u,u})$. In this work, we assume that each ground user only knows the channel distribution information (CDI) between it and other ground users, while the exact instantaneous channel information is unavailable. In addition, we assume that the location information of all the ground users is known to the UAV, since all these users intend to transmit information to the UAV (i.e., the UAV will collect data from all the ground users). Thus, the UAV knows the channels to all the ground users. Furthermore, we also assume that each ground user knows the channel from itself to the UAV.

For the i-th channel use in the n-th time slot, if the k-th user is scheduled and transmits information, the signal received at the UAV is given by

$$y_u^{(i)}[n] = \sqrt{P_k}[n]h_{k,u}[n]s_k(i) + \sqrt{\rho P_u[n]}g_{u,u}[n]s_u(i) + n_u(i), \ \forall n, \tag{3}$$

where $i = 1, 2, \cdots, j$ denotes the index of each channel use, j denotes the total number of channel uses in each time slot, $0 \leq \rho \leq 1$ denotes the self-interference cancellation coefficient, and $n_u(i)$ is the AWGN at UAV with mean 0 and variance σ_u^2, $s_k(i)$ denotes the signal transmitted by the user k, following $\mathcal{CN}(0, 1)$, and $s_u(i)$ denotes the AN transmitted by the UAV, satisfying $\mathbb{E}[|s_u(i)|^2] = 1$. In addition, $P_k[n]$ is the transmit power of the SU k. In this work, we assume that $P_k[n]$, $\forall k, n$, is fixed and is publicly known. Furthermore, $P_u[n]$ is the transmit power of AN at the UAV and follows a uniform distribution over the interval $[0, P_{u,\max}[n]]$, where $P_{u,\max}[n]$ is the maximum transmit power of the AN. Specifically, the probability density function (pdf) of $P_u[n]$ is given by

$$f_{P_u[n]}(x) = \begin{cases} \frac{1}{P_{u,\max}[n]}, & 0 \leq x \leq P_{u,\max}[n], \\ 0, & \text{otherwise}. \end{cases} \tag{4}$$

We assume that the USUs only know the distribution information of the UAV's AN transmit power. We note that introducing the randomness of the AN transmit power is to create an uncertainty in the USU's receive power to assist the SU's covert transmission.

We use $x_k[n]$ to denote the scheduling variable, where $x_k[n] = 1$ if the ground user k is scheduled at time slot n, and $x_k[n] = 0$ otherwise. In addition, we note that at most one ground user is scheduled by the UAV at each time slot. As such, we have the following constraint

$$\sum_{k=1}^{K} x_k[n] \leq 1, \forall n, \quad x_k[n] \in \{0, 1\}, \forall k, n. \tag{5}$$

Following (3), if user k is scheduled for transmission at time slot n, the channel capacity from this user to the UAV is given by

$$C_k[n] = \log_2\left(1 + \frac{P_k[n]|h_{k,u}[n]|^2}{\rho P_u[n]|g_{u,u}[n]|^2 + \sigma_u^2}\right). \tag{6}$$

We note that $P_u[n]$ is controlled by the UAV and thus it is known to the UAV. The transmission from user k to the UAV can still suffer from outage due to the random self-interference channel $g_{u,u}[n]$. The transmission outage probability between user k and the UAV is given by

$$\begin{aligned}&\Pr\{C_k[n] < R_k[n]\}\\&= \Pr\left\{|g_{u,u}[n]|^2 > \frac{P_k[n]|h_{k,u}[n]|^2}{\rho P_u[n](2^{R_k[n]}-1)} - \frac{\sigma_u^2}{\rho P_u[n]}\right\}\\&= \exp\left[\frac{-1}{\rho P_u[n]\lambda_{u,u}}\left(\frac{P_k[n]|h_{k,u}[n]|^2}{2^{R_k[n]}-1} - \sigma_u^2\right)\right],\end{aligned} \tag{7}$$

where $R_k[n]$ is the transmission rate from user k to the UAV at time slot n. We note that transmission outage probability is an increasing function of $P_u[n]$. As such, an upper bound on the transmission outage probability from user k to the UAV at the n-th time slot is given by

$$\begin{aligned}&p_k^{out}[n] =\\&\exp\left[\frac{-1}{\rho P_{u,\max}[n]\lambda_{u,u}}\left(\frac{P_k[n]|h_{k,u}[n]|^2}{2^{R_k[n]}-1} - \sigma_u^2\right)\right], \forall k, n.\end{aligned} \tag{8}$$

In this work, we consider a reliability constraint on the transmission from user k to the UAV, i.e., the upper bound on the transmission outage probability is no more than ϵ ($p_k^{out}[n] \le \epsilon$), where ϵ denotes the maximum tolerable outage probability. From (8), we see that $p_k^{out}[n]$ is an increasing function of $R_k[n]$. As such, in order to maximize the transmission rate, $p_k^{out}[n] = \epsilon$ is always guaranteed. Therefore, the transmission rate of user k can be expressed as

$$R_k[n] = \log_2\left(1 + \frac{P_k[n]|h_{k,u}[n]|^2}{-\rho P_{u,\max}[n]\lambda_{u,u}\ln\epsilon + \sigma_u^2}\right), \forall k, n. \tag{9}$$

C. Binary Hypothesis Testing at Unscheduled Users

We note that, each of the USUs faces a binary hypothesis testing problem, i.e., each USU has to decide whether the SU transmitted to the UAV. Here, the USUs do not cooperate to conduct the detection, since the ground users are distributed and each of them potentially serves as a SU in some specific time slot. For the i-th channel use in the n-th time slot, the received signal at the m-th USU from the k-th SU is given by

$$\begin{aligned}&y_m^{(i)}[n] =\\&\begin{cases}\sqrt{P_u[n]}h_{u,m}[n]s_u(i) + n_m(i), & \mathcal{H}_0,\\ \sqrt{P_k[n]}g_{k,m}[n]s_k(i) + \sqrt{P_u[n]}h_{u,m}[n]s_u(i) + n_m(i), & \mathcal{H}_1,\end{cases}\end{aligned} \tag{10}$$

where $m \in \mathcal{K}\setminus\{k\}$, $n_m(i)$ is the AWGN at the m-th USU with mean 0 and variance σ_m^2, $\mathcal{H}_0$ is the null hypothesis where the k-th SU did not transmit information, while $\mathcal{H}_1$ is the alternative hypothesis where the k-th SU did transmit information to the UAV. We assume that each of USUs uses a radiometer as the detector at each time slot. This assumption is justified by the fact that the radiometer is the optimal detector in the considered system model, which can be proved along the same line as the proof in [25]. Thus, each USU conducts a threshold test on the average power received in time slot n, which is given by

$$T_m[n] \triangleq \frac{1}{j}\sum_{i=1}^{j}|y_m^{(i)}[n]|^2 \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \tau_m[n],\ m \in \mathcal{K}\setminus\{k\}, \tag{11}$$

where $T_m[n]$ and $\tau_m[n]$ are the average power received at the m-th USU and its corresponding detection threshold at the n-th time slot, respectively, while $\mathcal{D}_0$ and $\mathcal{D}_1$ are the decisions in favor of $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively. In this work, we adopt a widely used assumption in covert communications, which is that $j \to \infty$. This allows each of USUs to observe an infinite number of samples, which is an upper bound on the number of samples that each USU can receive in practice. As $j \to \infty$, $T_m[n]$ can be rewritten as

$$T_m[n] = \begin{cases}P_u[n]|h_{u,m}[n]|^2 + \sigma_m^2, & \mathcal{H}_0,\\ P_k[n]|g_{k,m}[n]|^2 + P_u[n]|h_{u,m}[n]|^2 + \sigma_m^2, & \mathcal{H}_1.\end{cases} \tag{12}$$

Following (12), at the n-th time slot, the false alarm rate and miss detection rate at the m-th USU when the k-th user is scheduled are denoted as $\alpha_m[n] = \Pr\{\mathcal{D}_1|\mathcal{H}_0\}$ and $\beta_{k,m}[n] = \Pr\{\mathcal{D}_0|\mathcal{H}_1\}$, respectively, which are given as

$$\alpha_m[n] = \Pr\left\{P_u[n]|h_{u,m}[n]|^2 + \sigma_m^2 \ge \tau_m[n]\right\}, \tag{13}$$

$$\beta_{k,m}[n] = \Pr\left\{P_k[n]|g_{k,m}[n]|^2 + P_u[n]|h_{u,m}[n]|^2 + \sigma_m^2 \le \tau_m[n]\right\}, \tag{14}$$

respectively. Then, the detection error rate for the m-th USU's detection at the n-th time slot when the k-th user is scheduled is given by

$$\xi_{k,m}[n] = \alpha_m[n] + \beta_{k,m}[n],\ \forall n. \tag{15}$$

In covert communications, each USU aims to achieve the minimum detection error rate, denoted by $\xi_{k,m}^*[n]$, while the SU tries to ensure this minimum detection error rate at each USU being no less than a specific value, i.e., $\xi_{k,m}^*[n] \ge 1 - \varepsilon$, $\forall n$, where ε is an arbitrary small constant to determine the required covertness.

III. Detection Performance Analysis at the Unscheduled Users and Optimization Framework

In this section, we first derive the explicit expressions for the false alarm rate and miss detection rate. Then, we derive the optimal detection threshold for each USU and the corresponding minimum detection error rate. Finally, we develop an optimization framework to design the user scheduling and the UAV's trajectory as well as the UAV's maximum AN transmit power to ensure that the UAV can collect data from each ground user reliably and covertly.

A. False Alarm Rate

Following (4) and (13), the false alarm rate $\alpha_m[n]$ for the m-th USU at the n-th time slot when user k is scheduled, is given by

$$\alpha_m[n] = \begin{cases}1, & \tau_m[n] \le \sigma_m^2,\\ 1 - \frac{\tau_m[n] - \sigma_m^2}{\varrho_{u,m}[n]}, & \sigma_m^2 < \tau_m[n] \le \varrho_{u,m}[n] + \sigma_m^2,\\ 0, & \tau_m[n] > \varrho_{u,m}[n] + \sigma_m^2,\end{cases} \tag{16}$$

where $\varrho_{u,m}[n] \triangleq P_{u,\max}[n]|h_{u,m}[n]|^2$.

B. Miss Detection Rate

We recall that the USUs only have the CDI of the channels to the SU. As such, the miss detection rate $\beta_{k,m}[n]$, defined in (14), involves two random variables with different distributions, where $P_k[n]|g_{k,m}[n]|^2$ follows an exponential distribution with parameter $\frac{1}{P_k[n]\lambda_{k,m}}$ and $P_u[n]|h_{u,m}[n]|^2$ follows a uniform distribution over the interval $\left[0, P_{u,\max}[n]|h_{u,m}[n]|^2\right]$. As a result, we need to derive the pdf of $Z_{u,k,m}[n]$, which is defined as

$$Z_{u,k,m}[n] \triangleq X_{u,m}[n] + Y_{k,m}[n], \tag{17}$$

in order to derive the miss detection rate, where $X_{u,m}[n] \triangleq P_u[n]|h_{u,m}[n]|^2$ and $Y_{k,m}[n] \triangleq P_k[n]|g_{k,m}|^2$. To this end, we first present the following lemma.

***Lemma** 1:* The pdf of the random variable $Z_{u,k,m}[n]$ defined in (17) is given by

$$f_{z_{u,k,m}[n]}(z) = \begin{cases} \frac{1-\exp\left(\frac{-z}{P_k[n]\lambda_{k,m}}\right)}{\varrho_{u,m}[n]}, & 0 < z \leq \varrho_{u,m}[n], \\ \frac{\exp\left(\frac{z-\varrho_{u,m}[n]}{-P_k[n]\lambda_{k,m}}\right)-\exp\left(\frac{-z}{P_k[n]\lambda_{k,m}}\right)}{\varrho_{u,m}[n]}, & z > \varrho_{u,m}[n], \\ 0, & z \leq 0. \end{cases} \tag{18}$$

Proof: The pdf of $Z_{u,k,m}[n]$ can be written as

$$f_{z_{u,k,m}[n]}(z) = \int_{-\infty}^{\infty} f_{x_{u,m}[n]}(x) f_{y_{k,m}[n]}(z-x)\mathrm{d}x, \tag{19}$$

where $f_{x_{u,m}[n]}(x)$ and $f_{y_{k,m}[n]}(y)$ are the pdfs of the random variables $X_{u,m}[n]$ and $Y_{k,m}[n]$, respectively. As such, we have $0 \leq x \leq \varrho_{u,m}[n]$ and $x \leq z \leq \infty$. For $0 < z \leq \varrho_{u,m}[n]$, the pdf of $Z_{u,k,m}[n]$ can be written as

$$\begin{aligned} f_{z_{u,k,m}[n]}(z) &= \int_0^z \frac{\exp\left(\frac{z-x}{-P_k[n]\lambda_{k,m}}\right)}{\varrho_{u,m}[n]P_k[n]\lambda_{k,m}}\mathrm{d}x \\ &= \frac{1}{\varrho_{u,m}[n]}\left[1-\exp\left(\frac{-z}{P_k[n]\lambda_{k,m}}\right)\right]. \end{aligned} \tag{20}$$

For $\varrho_{u,m}[n] < z < \infty$, the pdf of $Z_{u,k,m}[n]$ is given by

$$\begin{aligned} f_{z_{u,k,m}[n]}(z) &= \int_0^{\varrho_{u,m}[n]} \frac{\exp\left(\frac{z-x}{-P_k[n]\lambda_{k,m}}\right)}{\varrho_{u,m}[n]P_k[n]\lambda_{k,m}}\mathrm{d}x \\ &= \frac{1}{\varrho_{u,m}[n]}\left[\exp\left(\frac{\varrho_{u,m}[n]-z}{P_k[n]\lambda_{k,m}}\right)-\exp\left(\frac{-z}{P_k[n]\lambda_{k,m}}\right)\right]. \end{aligned} \tag{21}$$

In addition, for $Z_{u,k,m}[n] \leq 0$, the pdf of $Z_{u,k,m}[n]$ is given by $f_{z_{u,k,m}[n]}(z) = 0$. Combining the results under these three cases leads to the desired result in (18). ■

In order to derive the miss detection rate for the m-th USU at the n-th time slot when the k-th user is scheduled, we first rewrite the miss detection rate $\beta_{k,m}[n]$ as

$$\beta_{k,m}[n] = \Pr\left\{Z_{u,k,m}[n] \leq \tau_m[n] - \sigma_m^2\right\}. \tag{22}$$

Then, following Lemma 1, the miss detection rate for m-th USU at the n-th time slot when the k-th user is scheduled is given by

$$\beta_{k,m}[n] = \begin{cases} 0, & \tau_m[n] \leq \sigma_m^2, \\ \varsigma_{k,m}[n], & \sigma_m^2 < \tau_m[n] \leq \varrho_{u,m}[n] + \sigma_m^2, \\ \phi_{k,m}[n], & \tau_m[n] > \varrho_{u,m}[n] + \sigma_m^2, \end{cases} \tag{23}$$

where

$$\begin{aligned} \varsigma_{k,m}[n] &= \int_0^{\tau_m[n]-\sigma_m^2} \frac{\exp\left(\frac{z-x}{-P_k[n]\lambda_{k,m}}\right)}{\varrho_{u,m}[n]P_k[n]\lambda_{k,m}}\mathrm{d}x \\ &= \frac{\tau_m[n]-\sigma_m^2}{\varrho_{u,m}[n]} - \frac{P_k[n]\lambda_{k,m}}{\varrho_{u,m}[n]}\left[1-\exp\left(\frac{\tau_m[n]-\sigma_m^2}{-P_k[n]\lambda_{k,m}}\right)\right], \end{aligned} \tag{24}$$

$$\begin{aligned} \phi_{k,m}[n] &= \int_0^{\varrho_{u,m}[n]} f_{z_{u,k,m}[n]}(z)\mathrm{d}z + \int_{\varrho_{u,m}[n]}^{\tau_m[n]-\sigma_m^2} f_{z_{u,k,m}[n]}(z)\mathrm{d}z \\ &= 1 - \frac{P_k[n]\lambda_{k,m}}{\varrho_{u,m}[n]}\left[\exp\left(\frac{\tau_m[n]-\sigma_m^2-\varrho_{u,m}[n]}{-P_k[n]\lambda_{k,m}}\right)\right. \\ &\qquad \left. - \exp\left(\frac{\tau_m[n]-\sigma_m^2}{-P_k[n]\lambda_{k,m}}\right)\right]. \end{aligned} \tag{25}$$

C. Minimum Detection Error Rate

***Theorem** 1:* The optimal detection threshold for m-th USU at the n-th time slot when user k is scheduled is given by $\tau_m^*[n] = \varrho_{u,m}[n] + \sigma_m^2$ and the corresponding minimum detection error rate is given by

$$\xi_{k,m}^*[n] = 1 - \frac{P_k[n]\lambda_{k,m}}{\varrho_{u,m}[n]}\left[1-\exp\left(\frac{-\varrho_{u,m}[n]}{P_k[n]\lambda_{k,m}}\right)\right]. \tag{26}$$

Proof: Following (16) and (23), the detection error rate for the m-th user at the n-th time slot is given by

$$\xi_{k,m}[n] = \begin{cases} 1, & \tau_m[n] \leq \sigma_m^2, \\ 1-\hat{\varsigma}_{k,m}[n], & \sigma_m^2 < \tau_m[n] \leq \varrho_{u,m}[n] + \sigma_m^2, \\ \phi_{k,m}[n], & \tau_m[n] > \varrho_{u,m}[n] + \sigma_m^2, \end{cases} \tag{27}$$

where

$$\hat{\varsigma}_{k,m}[n] \triangleq \frac{P_k[n]\lambda_{k,m}}{\varrho_{u,m}[n]}\left[1-\exp\left(\frac{\tau_m[n]-\sigma_m^2}{-P_k[n]\lambda_{k,m}}\right)\right]. \tag{28}$$

We note that $\xi_{k,m}[n] = 1$ is the worst scenario for the m-th USU, i.e., its detection performance is the same as that of a random guess. As such, the m-th USU will not set its detection threshold as $\tau_m[n] \leq \sigma_m^2$. As per (27), we note that $\xi_{k,m}[n]$ monotonically decreases with $\tau_m[n]$ for $\sigma_m^2 < \tau_m[n] \leq \varrho_{u,m}[n] + \sigma_m^2$, while $\xi_{k,m}[n]$ monotonically increases with $\tau_m[n]$ for $\tau_m[n] > \varrho_{u,m}[n] + \sigma_m^2$. Considering that $\xi_{k,m}[n]$ is a continuous function of $\tau_m[n]$ in (27), we conclude that the optimal detection threshold is given by $\tau_m^*[n] = \varrho_{u,m}[n] + \sigma_m^2$. Substituting $\tau_m^*[n]$ into (27), we obtain the minimum detection error rate at the m-th USU as given in (26). This completes the proof. ■

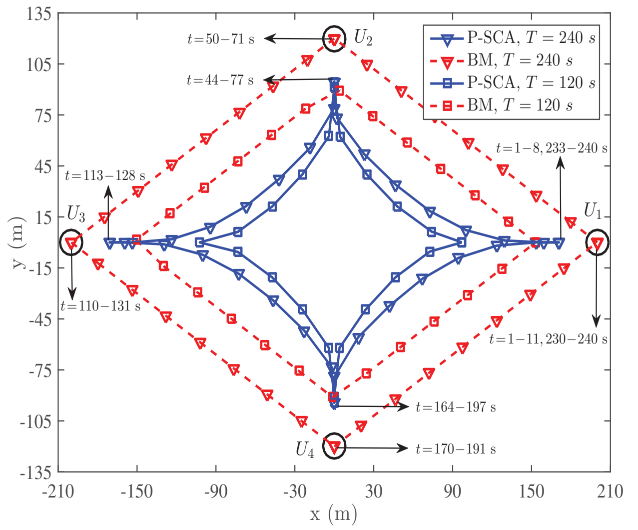

Fig. 1. UAV's trajectories achieved by the P-SCA amd BM schemes for different values of the flight period T.

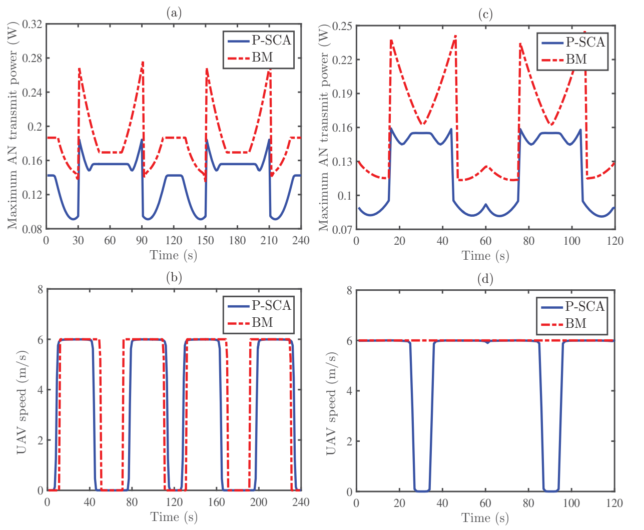

Fig. 2. The UAV's transmit power and speed for different values of the flight period T, where $T = 240$ s for (a) and (b), while $T = 120$ s for (c) and (d).

D. Optimization Problem Formulation

For ease of presentation, we define $\mathbf{X} = \{x_k[n], \forall k, n\}$, $\mathbf{Q} = \{\mathbf{q}_u[n], \forall n\}$, and $\mathbf{P}_{\text{U}} = \{P_{u,\max}[n], \forall n\}$, where we recall that $x_k[n]$ is the user scheduling variable, $\mathbf{q}_u[n]$ is the UAV trajectory, and $P_{u,\max}[n]$ is the UAV's maximum AN transmit power. In order to ensure that the UAV can collect data from each ground user and guarantee the fairness among all users, our design aim is to maximize the minimum average transmission rate (ATR) among all the ground users by jointly designing the user scheduling $\mathbf{X}$, the UAV trajectory $\mathbf{Q}$, and the UAV's maximum AN transmit power $\mathbf{P}_{\text{U}}$. Then, the design optimization problem at the UAV is formulated as

$$(\mathbf{P1}): \max_{\mathbf{Q},\mathbf{X},\mathbf{P}_{\text{U}}} \min_{k} \frac{1}{N}\sum_{n=1}^{N} x_k[n] R_k[n] \tag{29a}$$

$$\text{s.t.} \sum_{k=1}^{K} x_k[n] \min_{m\in\mathcal{K}\setminus\{k\}} \xi^*_{k,m}[n] \geq 1-\varepsilon,\ \forall n, \tag{29b}$$

$$\sum_{k=1}^{K} x_k[n] \leq 1,\ \forall n, \tag{29c}$$

$$x_k[n] \in \{0,1\},\ \forall k, n, \tag{29d}$$

$$P_{u,\max}[n] \leq P^u_{\max},\ \forall n, \tag{29e}$$

$$\mathbf{q}_u[1] = \mathbf{q}_u[N], \tag{29f}$$

$$\|\mathbf{q}_u[n+1] - \mathbf{q}_u[n]\| \leq V_{\max}\delta_t,\ n \in \mathcal{N}\setminus\{N\}, \tag{29g}$$

where $R_k[n]$ defined in (9) denotes the transmission rate of user k. The constraint (29b) is to ensure the covertness of the uplink transmission from the SU to the UAV, where $\xi^*_{k,m}[n]$ is defined in (26) and ε is an arbitrarily small value determining the required covertness. In addition, (29c) and (29d) are the user scheduling constraints, which ensure that at most one ground user is scheduled at each time slot. Furthermore, (29e) denotes the maximum AN transmit power constraint of the UAV, while (29f) and (29g) are the UAV's mobility constraints. $(\mathbf{P1})$ is a mixed-integer non-convex optimization problem and is solved by a penalty successive convex approximation (P-SCA) scheme in this work, which is detailed in [26].

IV. Numerical Results

To demonstrate the benefit of our developed design, we compare our P-SCA scheme with a benchmark (BM) scheme, where in the latter scheme the UAV's trajectory is fixed as the successive hover-and-fly trajectory and only the UAV's maximum AN transmit power and user scheduling strategy are optimized.

In Fig. 1, we plot the trajectories of the UAV achieved by our P-SCA scheme and the BM scheme with different values of the flight period T, where the k-th ground user is denoted as U_k ($k \in \mathcal{K}$) and the location of each user is marked with $\bigcirc$. In this figure, we first observe that the trajectory achieved by the P-SCA scheme always shrinks inward relative to that achieved by the BM scheme. This is due to the fact that, when the UAV's trajectory is closer to the USUs, the UAV's maximum AN transmit power can be relatively smaller to reduce self-interference and improve the max-min ATR (i.e., average transmission rate) while maintaining a certain level of covertness. This is confirmed by Fig. 2(a) and Fig. 2(c), where the UAV's maximum AN transmit power in the P-SCA scheme is significantly smaller than that in the BM scheme.

In Fig. 3, we plot the max-min ATRs achieved by the P-SCA and BM schemes versus the flight period T for different values of ε. In this figure, we first observe that the achieved max-min ATR by the P-SCA scheme monotonically increases with T. This is due to the fact that a large flight period T offers a larger degree of freedom for us to design the UAV's covert data collection. However, we also observe that the max-min ATR achieved by the BM scheme is not monotonically increasing with respect to T. This is mainly due to the fact that

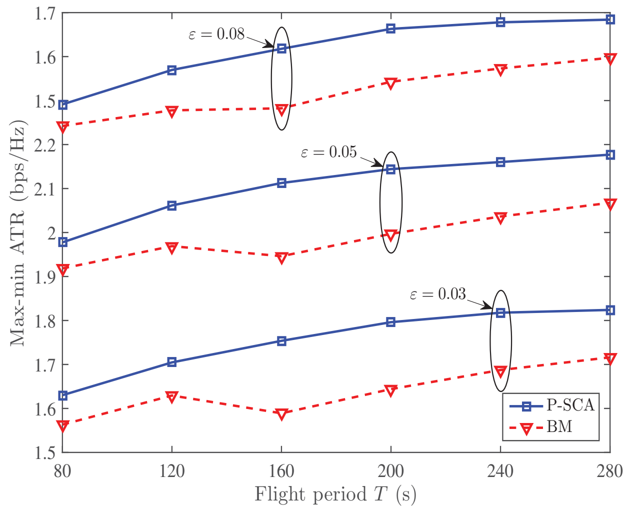

Fig. 3. Max-min ATR (i.e., average transmission rate) achieved by the P-SCA and BM schemes versus the flight period T for different values of ε.

the UAV's trajectory is hardly determined, not softly designed as in the P-SCA scheme. This observation demonstrates the necessity of designing the UAV's trajectory in the considered covert data collection system (as we did in the P-SCA scheme). Furthermore, in this figure we observe that the proposed P-SCA scheme always achieves a higher max-min ATR than the BM scheme, which demonstrates the advantages of the joint design of the UAV's trajectory, maximum AN transmit power, and the user scheduling strategy.

V. Conclusion

In this work, we considered covert data collection in UAV wireless networks based on covert communication techniques. We first determined the covertness constraint explicitly by analyzing the detection performance at each USU in terms of deriving the minimum detection error rate. Then, we formulated an optimization problem to maximize the minimum ATR among all ground users to the UAV subject to the covertness constraint and other practical constraints, e.g., the UAV's mobility constraints. Interestingly, we found that, as the covertness level increases, the UAV's trajectory achieved by the P-SCA schemes always shrinks inward to the centre determined by the locations of all the ground users.

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