Energy Efficiency Maximization for Full-Duplex UAV Secrecy Communication

Bin Duo, Qingqing Wu, Xiaojun Yuan, and Rui Zhang

Abstract

This letter proposes a new full-duplex (FD) secrecy communication scheme for the unmanned aerial vehicle (UAV) and investigates its optimal design to achieve the maximum energy efficiency (EE) of the UAV. Specifically, the UAV receives the confidential information from a ground source and meanwhile sends jamming signals to interfere with a potential ground eavesdropper. As the UAV has limited on-board energy in practice, we aim to maximize the EE for its secrecy communication, by jointly optimizing the UAV trajectory and the source/UAV transmit/jamming powers over a finite flight period with given initial and final locations. Although the problem is difficult to solve, we propose an efficient iterative algorithm to obtain its suboptimal solution. Simulation results show that the proposed joint design can significantly improve the EE of UAV secrecy communication, as compared to various benchmark schemes.

Index Terms

UAV secrecy communication, full-duplex, energy efficiency, jamming, trajectory design, power control.

I. INTRODUCTION

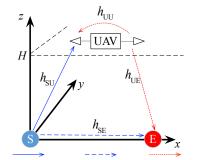
Unmanned aerial vehicles (UAVs) have been widely used in wireless communications, thanks to their line-of-sight (LoS) air-to-ground links and high controllable mobility [1]. Despite their

B. Duo and X. Yuan are with the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, Chengdu 611731, China (email: duo_bin@163.com; xjyuan@uestc.edu.cn). B. Duo is also with the College of Information Science & Technology, Chengdu University of Technology, Chengdu 610059, China. Q. Wu and R. Zhang are with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117583 (e-mail: elewuqq, elezhang@nus.edu.sg).

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numerous applications, UAV communications face new challenges. Among others, due to the LoS links, the legitimate UAV communications are more prone to the interception by suspicious eavesdroppers on the ground [2]. Fortunately, the high mobility of UAVs provides a new opportunity to enhance the secrecy rate of UAV communications by leveraging proper trajectory design. The authors in [3] and [4] study secure UAV communications, where the average secrecy rate is significantly improved by jointly optimizing the UAV trajectory and power allocation over a given mission duration. Dual-UAV systems are proposed in [5] and [6], where one UAV communicates with legitimate ground users while the other UAV safeguards their transmission by cooperatively sending jamming signals to ground eavesdroppers. In addition, the propulsion energy required for the UAVs to keep airborne and enable high mobility is practically limited due to their finite on-board energy and thus needs to be taken into account for the trajectory design [7]. Therefore, the energy efficiency (EE) of fixed-wing UAVs has been maximized in [8], where the UAV serves as a mobile relay to assist in the secure communication between two ground nodes. However, different from rotary-wing UAVs, fixed-wing UAVs require a certain minimum speed to keep airborne and thus cannot hover at a fixed location to sustain the maximum secrecy rate [1]. Note that the above studies all consider half-duplex UAV communications under the secrecy setup. As such, it remains unaddressed whether full-duplex (FD) UAV communications can further improve the secrecy rate.

Motivated by the above, this letter investigates the EE-optimal joint secrecy communication and trajectory design for rotary-wing UAVs by exploiting the FD communication at the UAV. Specifically, we consider a scenario where a flying UAV intends to receive confidential information from a ground source and in the meanwhile avoid information leakage to a suspicious eavesdropper on the ground by sending jamming signals to interfere with it. To balance between the secrecy rate and the energy consumption of the UAV, we aim to maximize the EE for the UAV secrecy communication by jointly optimizing the UAV trajectory and the source/UAV transmit/jamming power allocations along its trajectory. In the proposed design, the UAV is subjected to its mobility as well as both the average and peak transmit power constraints. To resolve the non-convexity of the formulated problem, we propose an efficient iterative algorithm to obtain a high-quality suboptimal solution for it based on the block coordinate descent (BCD)



Information signal Leaked signal Jamming signal

Fig. 1. A full-duplex UAV secrecy communication system.

and successive convex approximation (SCA) techniques. Simulation results validate that the proposed joint design significantly improves the EE of the UAV, as compared to other benchmark schemes without FD transmission, power control, or trajectory optimization.

II. SYSTEM MODEL AND PROBLEM FORMULATION

As shown in Fig. 1, we consider a UAV-enabled wireless communication system, where a ground source (S) transmits confidential information to a rotary-wing UAV, while a ground eavesdropper (E) tries to overhear it. To secure the ground-to-air communication, we assume that the UAV operates in FD mode under which it can send jamming signals to interfere with E while receiving the secrecy information from S. Without loss of generality, we consider a threedimensional (3D) Cartesian coordinate system, where S and E are located on the ground with horizontal coordinates $[0,0]^T$ and $\mathbf{w}_{\mathrm{E}} = [x_{\mathrm{E}}, y_{\mathrm{E}}]^T$, respectively, and their locations are assumed to be fixed and known to the UAV for the period of interest. Let T > 0 and $[x(t), y(t)]^T$ respectively denote a given finite flight period of the UAV and its horizontal coordinate at each time instant t, $0 \le t \le T$, where we assume that the UAV flies at a fixed altitude denoted by H. Similar to [3], T is divided into N time slots with equal length, i.e., $T = \delta_t N$, where δ_t denotes the duration of each time slot and is practically set sufficiently small. As such, the UAV's horizontal trajectory over T can be represented approximately by a sequence of locations denoted by $\mathbf{q} = {\mathbf{q}[n] \triangleq [x[n], y[n]]^T}$, with $x[n] = x(n\delta_t), y[n] = y(n\delta_t), n = 0, \dots, N$. We assume that the UAV 's initial and final locations are given by $\mathbf{q}_0 = [x_0, y_0]^T$ and $\mathbf{q}_F = [x_F, y_F]^T$, respectively. Let the maximum speed of the UAV be $V_{
m max}$ in meter/second (m/s) and thus $arOmega=V_{
m max}\delta_t$ is the maximum horizontal distance that the UAV can fly within each time slot. Then, the UAV trajectory needs to satisfy the following constraints:

$$||\mathbf{q}[n+1] - \mathbf{q}[n]||^2 \le \Omega^2, n = 0, \cdots, N-1,$$
 (1)

$$\mathbf{q}[0] = \mathbf{q}_0, \mathbf{q}[N] = \mathbf{q}_{\mathrm{F}}.$$
(2)

We assume that the transmission from S to the UAV and that from the UAV to E are both dominated by LoS channels [3]-[8]. Thus, the corresponding channel power gains in time slot *n* follow the free-space path loss model, given by $h_{SU}[n] = \rho_0/(H^2 + ||\mathbf{q}[n]||^2)$ and $h_{UE}[n] = \rho_0/(H^2 + ||\mathbf{q}[n] - \mathbf{w}_E||^2)$, respectively, where ρ_0 denotes the channel power gain at the reference distance $d_0 = 1$ m. The terrestrial channel between S and E is assumed to follow Rayleigh fading with the channel power gain denoted by $h_{SE} = \rho_0 ||\mathbf{w}_E||^{-\kappa} \zeta$, where $\kappa \ge 2$ is the path-loss exponent and ζ is an exponentially distributed random variable with unit mean accounting for small-scale Rayleigh fading. Since the residual self-interference (RSI) is difficult to be completely removed in practice for FD radios, we take into account its impact on the UAV secrecy communication performance. Let h_{UU} denote the channel gain that characterizes the RSI due to imperfect loop interference cancellation from the UAV's transmitting antenna to its receiving antenna. The RSI channel h_{UU} is commonly modeled as Rayleigh fading, i.e., h_{UU} is independently drawn from $\mathcal{CN}(0, \sigma_{RSI}^2)$, where σ_{RSI}^2 is regarded as the average loop interference level (LIL) with $\mathbb{E}[|h_{UU}|^2] = \sigma_{RSI}^2$ [9].

Let $p_{\rm S}[n]$ and $p_{\rm U}[n]$ denote the source transmit power and the UAV jamming power in time slot *n*, respectively. In practice, they should satisfy both the average and peak power constraints given as follows

$$\frac{1}{N}\sum_{n=1}^{N} p_{\mathbf{S}}[n] \le \bar{P}_{\mathbf{S}}, 0 \le p_{\mathbf{S}}[n] \le P_{\mathbf{S}}^{\max},$$
(3)

$$\frac{1}{N}\sum_{n=1}^{N} p_{\rm U}[n] \le \bar{P}_{\rm U}, 0 \le p_{\rm U}[n] \le P_{\rm U}^{\rm max},\tag{4}$$

where $\bar{P}_{S} \leq P_{S}^{\text{max}}$ and $\bar{P}_{U} \leq P_{U}^{\text{max}}$. Then, the achievable rates in bits/second/Hertz (bps/Hz) of

the UAV and the eavesdropper in time slot n are respectively given by

$$R_{\mathrm{U}}[n] = \mathbb{E}_{h_{\mathrm{UU}}} \left[\log_2 \left(1 + \frac{p_{\mathrm{S}}[n]h_{\mathrm{SU}}[n]}{p_{\mathrm{U}}[n]|h_{\mathrm{UU}}|^2 + \sigma^2} \right) \right]$$

$$\stackrel{(a)}{\geq} \log_2 \left(1 + \frac{p_{\mathrm{S}}[n]h_{\mathrm{SU}}[n]}{p_{\mathrm{U}}[n]\sigma_{\mathrm{RSI}}^2 + \sigma^2} \right) \triangleq \check{R}_{\mathrm{U}}[n], \qquad (5)$$

$$R_{\mathrm{E}}[n] = \mathbb{E}_{\zeta} \left[\log_2 \left(1 + \frac{p_{\mathrm{S}}[n]h_{\mathrm{SE}}}{p_{\mathrm{U}}[n]h_{\mathrm{UE}}[n] + \sigma^2} \right) \right]$$
$$\stackrel{(b)}{\leq} \log_2 \left(1 + \frac{p_{\mathrm{S}}[n]\rho_0 ||\mathbf{w}_{\mathrm{E}}||^{-\kappa}}{p_{\mathrm{U}}[n]h_{\mathrm{UE}}[n] + \sigma^2} \right) \triangleq \hat{R}_{\mathrm{E}}[n], \tag{6}$$

where $\mathbb{E}_{h_{UU}}[\cdot]$ and $\mathbb{E}_{\zeta}[\cdot]$ are the expectation operators with respect to h_{UU} and ζ , respectively, and σ^2 is the additive white Gaussian noise power at the corresponding receiver. Note that due to the convexity of $R_{U}[n]$ and concavity of $R_{E}[n]$ with respect to the corresponding random variables, (a) in (5) and (b) in (6) hold based on Jensen's inequality. Hence, the achievable secrecy rate for each time slot n is lower-bounded by

$$R_{\text{sec}}[n] = \left[\check{R}_{\text{U}}[n] - \hat{R}_{\text{E}}[n]\right]^+,\tag{7}$$

where $[x]^+ = \max(x, 0)$. Note that the operation $[\cdot]^+$ can be dropped since the practical value of (7) is at least zero by setting $p_{\rm S}[n] = 0$ for any n.

In practice, the communication-related energy is much smaller than the propulsion energy of UAVs, and thus is ignored in this letter. Based on [7], the propulsion energy consumption $E_p[n]$ in Joule (J) for rotary-wing UAVs with speed v[n] in time slot n can be modeled as

$$E_{\rm p}[n] = \delta_t (P_0 \phi[n] + P_i \varphi^{1/2}[n] + \frac{1}{2} d_0 \rho s A v^3[n]), \tag{8}$$

where the UAV (horizontal) flying speed is given by $v[n] = ||\mathbf{q}[n+1] - \mathbf{q}[n]||/\delta_t$, $\phi[n] = 1 + 3v^2[n]/U_{tip}^2$, $\varphi[n] = (1 + v^4[n]/(4v_0^4))^{1/2} - v^2[n]/(2v_0^2)$, P_0 , P_i and v_0 are constants, which represent the blade profile power, induced power, and the mean rotor induced speed when the UAV is hovering, respectively, U_{tip} is the tip speed of the UAV's rotor blade, s and d_0 denote the rotor solidity and fuselage drag ratio, respectively, and A and ρ are the rotor disc area and air density, respectively. Note that (8) is practically valid for the straight and level flight of rotary-

wing UAVs, which is satisfied in each time slot n due to the approximated piecewise-linear UAV trajectory over time slots.

We aim to maximize the EE for the UAV secrecy communication in bits/J over N time slots by jointly optimizing the source transmit power $\mathbf{p}_{S} \triangleq \{p_{S}[n]\}_{n=1}^{N}$, the UAV jamming power $\mathbf{p}_{U} \triangleq \{p_{U}[n]\}_{n=1}^{N}$ and the UAV trajectory **q**. This optimization problem can be formulated as

$$\max_{\mathbf{p}_{s},\mathbf{p}_{U},\mathbf{q}} \frac{B \sum_{n=1}^{N} R_{sec}[n]}{\sum_{n=1}^{N} E_{p}[n]}$$
s.t. (1) - (4), (9)

where B denotes the system bandwidth. Problem (9) is difficult to be optimally solved in general since the objective function is not jointly concave with respect to the optimization variables.

III. PROPOSED ALGORITHM

In this section, we propose an efficient iterative algorithm to obtain a high-quality suboptimal solution to problem (9) by applying BCD and SCA methods. Specifically, problem (9) is tackled by iteratively solving three subproblems to optimize each of the source transmit power p_s , the UAV jamming power p_U , and the UAV trajectory q with the other two being fixed, until the algorithm converges.

A. Source Power Optimization

For any given jamming power p_U and UAV trajectory q, problem (9) is reduced to

$$\max_{\mathbf{p}_{S}} \sum_{n=1}^{N} \left[\log_{2} \left(1 + a_{n} p_{S}[n] \right) - \log_{2} \left(1 + b_{n} p_{S}[n] \right) \right]$$
(10)
s.t. (3),

where $a_n = \gamma_0/((H^2 + ||\mathbf{q}[n]||^2)(p_U[n]\beta_0 + 1)), b_n = \gamma_0||\mathbf{w}_E||^{-\kappa}/(\frac{\gamma_0 p_U[n]}{H^2 + ||\mathbf{q}[n] - \mathbf{w}_E||^2} + 1), \gamma_0 = \rho_0/\sigma^2$ is the reference signal-to-noise ratio (SNR), and $\beta_0 = \sigma_{RSI}^2/\sigma^2$ is defined as the LIL-to-noise ratio. According to [3], the optimal solution is given by $p_S^*[n] = \min([\eta_n]^+, P_S^{max})$ if $a_n > b_n$; otherwise $p_S^*[n] = 0$, where $\eta_n = [(1/(2b_n) - 1/(2a_n))^2 + (1/b_n - 1/a_n)/(\mu \ln 2)]^{\frac{1}{2}} - 1/(2a_n) - 1/(2b_n)$. Note that $\mu \ge 0$ is a constant that ensures $\sum_{n=1}^{N} p_{s}^{*}[n] \le N\bar{P}_{s}$, which can be obtained efficiently via the bisection method.

B. Jamming Power Optimization

To solve this subproblem for any given \mathbf{p}_{s} and \mathbf{q} , we notice that each term in $R_{sec}[n]$ can be expressed by a difference of two concave functions with respect to \mathbf{p}_{U} , i.e.,

$$R_{\text{sec}}[n] = \log_2 \left(\beta_0 p_{\text{U}}[n] + 1 + c_n\right) - \log_2 \left(\beta_0 p_{\text{U}}[n] + 1\right) - \log_2 \left(e_n p_{\text{U}}[n] + 1 + d_n\right) + \log_2 \left(e_n p_{\text{U}}[n] + 1\right),$$
(11)

where $c_n = p_{\rm S}[n]\gamma_0/(H^2 + ||\mathbf{q}[n]||^2)$, $d_n = p_{\rm S}[n]\gamma_0||\mathbf{w}_{\rm E}||^{-\kappa}$ and $e_n = \gamma_0/(H^2 + ||\mathbf{q}[n] - \mathbf{w}_{\rm E}||^2)$. Despite the non-convexity of (11), we can employ the SCA method to approximately solve it. Denote by $\mathbf{p}_{\rm U}^k = \left\{ p_{\rm U}^k[n] \right\}_{n=1}^N$ the jamming power of the UAV in the *k*-th iteration. Due to the concavity of $\log_2 \left(\beta_0 p_{\rm U}[n] + 1 \right)$ and $\log_2 \left(e_n p_{\rm U}[n] + 1 + d_n \right)$ in (11), we can obtain their respective globally upper bounds by applying the first-order Taylor expansion at $p_{\rm U}^k[n]$, i.e.,

$$\log_2(\beta_0 p_{\rm U}[n] + 1) \le \log_2(\beta_0 p_{\rm U}^k[n] + 1) + A^k[n], \tag{12}$$

$$\log_2\left(e_n p_{\rm U}[n] + 1 + d_n\right) \le \log_2\left(e_n p_{\rm U}^k[n] + 1 + d_n\right) + B^k[n],\tag{13}$$

where $A^k[n] = \beta_0(p_U[n] - p_U^k[n]) / (\ln 2(\beta_0 p_U^k[n] + 1))$ and $B^k[n] = e_n(p_U[n] - p_U^k[n]) / (\ln 2(e_n p_U^k[n] + 1 + d_n))$. Based on (12) and (13), problem (9) can be approximately reformulated as the following problem,

$$\max_{\mathbf{p}_{U}} \sum_{n=1}^{N} \left[\log_{2}(\beta_{0} p_{U}[n] + 1 + c_{n}) + \log_{2}(e_{n} p_{U}[n] + 1) - A^{k}[n] - B^{k}[n] \right]$$
s.t. (4),
$$(14)$$

Note that subproblem (14) is convex and thus can be solved efficiently by the CVX solver. Since the upper bounds in (12) and (13) suggest that any feasible solution $\mathbf{p}_{\mathrm{U}}^{k}$ to (9) is also feasible

for (14), the optimal value obtained by solving (14) serves as a lower bound for that of problem (9).

C. UAV Trajectory Optimization

Even with given \mathbf{p}_{S} and \mathbf{p}_{U} , problem (9) is still difficult to be solved optimally, due to the non-convexity of its objective function with respect to \mathbf{q} . To tackle the non-convexity of $R_{sec}[n]$ in (9), we first introduce slack variables $\mathbf{g} = \{g[n]\}_{n=1}^{N}$ and $\mathbf{m} = \{m[n]\}_{n=1}^{N}$, where $g[n] \ge H^{2} + ||\mathbf{q}[n]||^{2}$ and $m[n] \ge H^{2} + ||\mathbf{q}[n] - \mathbf{w}_{E}||^{2}$. Thus, $R_{sec}[n]$ can be written as

$$R_{\text{sec}}[n] = \sum_{n=1}^{N} \left[\log_2 \left(1 + \frac{f_n}{g[n]} \right) - \log_2 \left(1 + \frac{d_n m[n]}{\gamma_0 p_{\text{U}}[n] + m[n]} \right) \right],\tag{15}$$

where $f_n = \gamma_0 p_{\rm S}[n]/(\beta_0 p_{\rm U}[n]+1)$. Note that the constraints for g and m must hold with equalities to obtain the optimal solution to problem (9), since otherwise g[n] and m[n] can be increased to decrease the objective value. Similarly, by using the first-order Taylor expansion, the first and second terms in (15) can be replaced by their respective convex lower and concave upper bounds, at given local points denoted by $\mathbf{g}^k = \{g^k[n]\}_{n=1}^N$ and $\mathbf{m}^k = \{m^k[n]\}_{n=1}^N$ in the k-th iteration. Specifically, we have

$$\log_2\left(1 + \frac{f_n}{g[n]}\right) \ge R_{\text{sec}}^{\text{lb}}[n],\tag{16}$$

$$\log_2\left(1 + \frac{d_n m[n]}{\gamma_0 p_{\mathrm{U}}[n] + m[n]}\right) \le R_{\mathrm{sec}}^{\mathrm{ub}}[n],\tag{17}$$

where $R_{\text{sec}}^{\text{lb}}[n] = \log_2(1+f_n/g^k[n]) - f_n(g[n]-g^k[n])/(\ln 2(g^k[n]+f_n)g^k[n]), R_{\text{sec}}^{\text{ub}}[n] = C^k[n](m[n]-m^k[n]) + D^k[n], \ C^k[n] = d_n\gamma_0 p_{\text{U}}[n]/(\ln 2(\gamma_0 p_{\text{U}}[n] + (d_n + 1)m^k[n])(\gamma_0 p_{\text{U}}[n] + m^k[n]))$ and $D^k[n] = \log_2(1+d_nm^k[n]/(\gamma_0 p_{\text{U}}[n] + m^k[n])).$

Then, to tackle the non-convexity of $E_p[n]$ in problem (9), we further introduce slack variable $\mathbf{s} = \{s[n]\}_{n=1}^N$ such that $s[n] \ge [(1 + v^4[n]/(4v_0^4))^{\frac{1}{2}} - v^2[n]/(2v_0^2)]^{\frac{1}{2}}$, which is equivalent to

$$\frac{1}{s^2[n]} \le s^2[n] + \frac{v^2[n]}{v_0^2} = s^2[n] + \frac{||\mathbf{q}[n+1] - \mathbf{q}[n]||^2}{v_0^2 \delta_t^2}.$$
(18)

Note that the constraint (18) should hold with equality to obtain the optimal solution, since otherwise s[n] can be increased to decrease the objective value of problem (9). Next, we focus

on addressing the non-convex constraint (18). Since $s^2[n]$ and $||\mathbf{q}[n+1] - \mathbf{q}[n]||^2$ are convex with respect to s[n] and $\mathbf{q}[n]$, respectively, we can apply the first-order Taylor expansion to the right hand side (RHS) of (18) at any given points $\mathbf{s}^k = \{s^k[n]\}_{n=1}^N$ and $\mathbf{q}^k = \{\mathbf{q}^k[n]\}_{n=1}^N$ in the *k*-th iteration to obtain the following lower bound, i.e.,

$$s^{2}[n] + \frac{||\mathbf{q}[n+1] - \mathbf{q}[n]||^{2}}{v_{0}^{2}\delta_{t}^{2}} \ge (s^{k}[n])^{2} + 2s^{k}[n](s[n] - s^{k}[n]) - \frac{||\boldsymbol{\psi}^{k}[n]||^{2}}{v_{0}^{2}\delta_{t}^{2}} + \frac{2}{v_{0}^{2}\delta_{t}^{2}}(\boldsymbol{\psi}^{k}[n])^{T}(\mathbf{q}[n+1] - \mathbf{q}[n]) \triangleq F^{k}[n],$$
(19)

where $\psi^{k}[n] = q^{k}[n+1] - q^{k}[n]$.

With (16)-(19), we obtain the following optimization problem

$$\max_{\mathbf{q},\mathbf{g},\mathbf{m},\mathbf{s}} \frac{\sum_{n=1}^{N} \left[R_{\text{sec}}^{\text{lb}}[n] - R_{\text{sec}}^{\text{ub}}[n] \right]}{\sum_{n=1}^{N} \left[P_0 \phi[n] + P_i s[n] + \frac{1}{2} d_0 \rho s A v^3[n] \right]}$$
(20)

s.t.
$$\frac{1}{s^2[n]} \le F^k[n], \tag{21}$$

$$g[n] \ge H^2 + ||\mathbf{q}[n]||^2,$$
 (22)

$$m[n] \ge H^2 + ||\mathbf{q}[n] - \mathbf{w}_{\mathrm{E}}||^2,$$
 (23)

$$s[n] \ge 0, \tag{24}$$

$$(1) - (2)$$

It is observed that problem (20) is a quasi-convex optimization problem since its objective function is composed of a linear numerator and a convex denominator and all constraints are convex. As such, it can be optimally and efficiently solved via fractional programming techniques, e.g., the Dinkelbach's algorithm. Note that the lower bound in (16) and the upper bound in (17) suggest that the feasible set of g^k and m^k for problem (20) is always a subset of that of problem (9). As a result, the optimal value obtained by solving problem (20) is a lower bound for that of problem (9).

To sum up, we solve the three subproblems (10), (14), and (20) alternately in an iterative manner to obtain the suboptimal solution to problem (9) until the fractional increase of the objective value is less than a given threshold, $\epsilon > 0$.

IV. NUMERICAL RESULTS

In this section, we show simulation results on comparing the proposed joint power control and trajectory design algorithm (denoted as P&T) with three benchmark algorithms: 1) UAV trajectory optimization without jamming (denoted as NJ/T); 2) UAV trajectory design without power control (denoted as NP/T); and 3) best-effort trajectory with power control (P/BET). Specifically, the NJ/T algorithm jointly optimizes the source transmit power $p_{\rm S}[n]$ and the UAV trajectory by setting $p_{\rm U}[n] = 0, \forall n$ in P&T. Note that if the UAV energy consumption is not considered, the NJ/T algorithm is the same as that given in [3]. In NP/T, the powers of the UAV and the source are set as $p_{\rm U}[n] = \bar{P}_{\rm U}$ and $p_{\rm S}[n] = \bar{P}_{\rm S}, \forall n$, respectively, and the UAV trajectory is optimized by iteratively solving (20) until convergence. The best-effort trajectory in P/BET is designed as follows (not shown separately in Fig. 2 due to space limitation): the UAV first flies along a straight line towards the location right above the source at speed $V_{\rm max}$, then (if time permits) stays stationary as long as possible, and finally flies at speed V_{max} to its final location by the end of T. With given best-effort trajectory in P/BET, the powers $p_{\rm S}[n]$ and $p_{\rm U}[n]$ are optimized by solving problems (10) and (14), respectively. The simulation parameters are set as $\mathbf{q}_0 = [50, -800]^T$ m, $\mathbf{q}_{\mathrm{F}} = [50, 800]^T$ m, $\mathbf{w}_{\mathrm{E}} = [200, 0]^T$ m, H = 100 m, $V_{\mathrm{max}} = 40$ m/s, $\delta_t = 0.5$ s, $\rho_0 = -60$ dB, $\bar{P}_{\rm S} = 20$ dBm, $P_{\rm S}^{\rm max} = 26$ dBm, $\bar{P}_{\rm U} = 10$ dBm, $P_{\rm U}^{\rm max} = 16$ dBm, B = 1 MHz, $\sigma^2 = -110$ dBm, and $\epsilon = 10^{-4}$. The values of all required parameters in (8) are set according to the example given in [7].

Fig. 2 shows the optimized UAV trajectories by different algorithms with different values of T when the LIL is $\sigma_{RSI}^2 = -80$ dBm. For the case with T = 40 s, the duration is only sufficient for the UAV to fly from the initial location q_0 to final location q_F at speed V_{max} , thus the trajectories of the three considered algorithms in Fig. 2(a)-(c) are identical. However, with increased T, especially when T is sufficiently large (e.g. T = 160 s), it is observed that the trajectories of the three algorithms become significantly different. In particular, for the proposed P&T algorithm in Fig. 2(a), the UAV first flies towards S, then circles around between locations A and B, and finally reaches q_F by the end of T. Along this optimized trajectory (including both the path and UAV speed), the UAV can achieve the higher EE for the secrecy communication

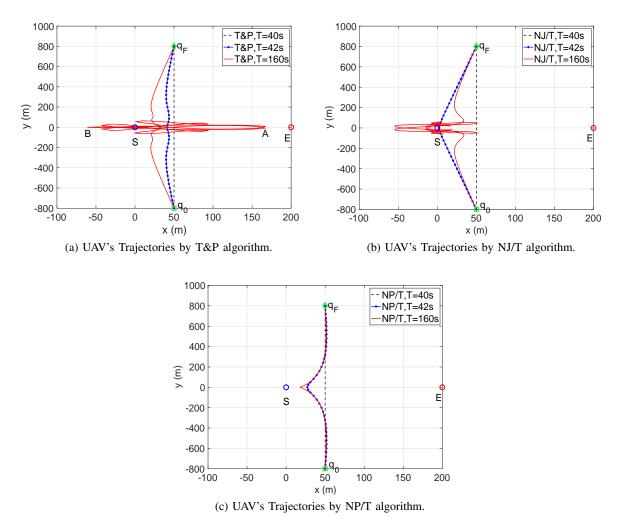


Fig. 2. Optimized trajectories of the UAV by different algorithms.

than that of other algorithms, since it more efficiently balances between information reception from S versus jamming signal transmission to E via power control, with less propulsion energy consumption. Specifically, since the UAV at the location A is far away from S but close to E, the UAV and S jointly transmit with their maximum powers to ensure a higher secrecy rate. By contrast, although the UAV at the location B and S jointly decrease their transmit powers due to the farther distance from the location B to E, a higher secrecy rate can also be guaranteed by appropriate power allocation. In Fig. 2(b), since jamming is not available in NJ/T, the UAV mainly hovers around S to balance the secrecy rate and the propulsion energy consumption, with only necessary time left for traveling. For the NP/T algorithm in Fig. 2(c), we observe

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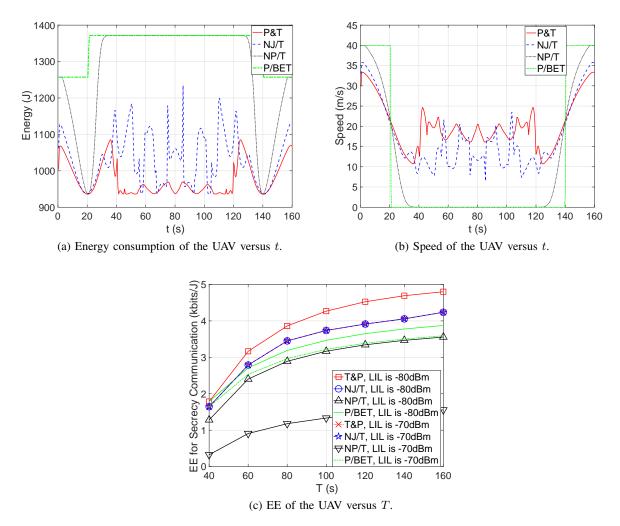


Fig. 3. UAV energy consumption, speed and EE for secrecy communication by different algorithms.

that the UAV first reaches a location close to S and then remains stationary there as long as possible. Despite the high propulsion energy consumption for remaining stationary, the UAV has to reconcile a trade-off to obtain the higher secrecy rate, due to the fixed source/UAV transmit/jamming powers.

Figs. 3(a) and 3(b) show the UAV energy consumption and speed over time in T, respectively. First, it is observed from Fig. 3(a) that the UAV in P&T consumes the least propulsion energy, since along its optimized trajectory, the UAV can adjust its speed more energy-efficiently to prevent flying at excessive large and low speeds (see Fig. 3(b)). By contrast, the energy consumption of the UAV in P/BET algorithm is highest among all of the other algorithms, due to its heuristic best-effort trajectory with the maximum speed for flying and zero speed for hovering. Second, although the UAV in NP/T has a different hovering location from that in P/BET, they have the same highest energy consumption when remaining stationary (e.g., from t = 40 s to 120 s). This indicates that hovering for rotary-wing UAVs is not energy conserving, which is consistent with [7]. Finally, by comparing Figs. 3(a) and 3(b), we can see that the most energy-efficient UAV speed is about 20 m/s and the energy consumption increases drastically when the UAV speed approaches zero.

Fig. 3(c) shows the EE for the secrecy communication versus T under different values of LIL. It is observed that the EE achieved by all algorithms increases with T while decreasing with the increase of LIL, due to the degraded loop channel at the UAV. In particular, when the value of LIL is -80 dBm, the proposed P&T algorithm always outperforms other benchmark algorithms due to its joint optimization of the trajectory and powers. However, as the LIL value becomes sufficiently large (e.g., $\sigma_{RSI}^2 = -70$ dBm), the EE of the P&T algorithm reduces to that of the NJ/T algorithm, since it is ineffective to send jamming signals in this case. Therefore, sending jamming signals or not from the UAV in P&T depends mainly on the level of RSI, and the NJ/T algorithm provides a performance lower bound for the proposed P&T algorithm. The above results validate the potential gain in EE brought by the proposed FD scheme and joint optimization of transmit/jamming powers and UAV trajectory.

V. CONCLUSIONS

Security, energy consumption, and spectral efficiency are key factors for next generation wireless networks with UAVs. Thus, a new FD scheme for the UAV secrecy communication with EE optimization was proposed and investigated in this letter. In particular, the EE of a rotary-wing UAV serving as both a legitimate receiver and a mobile jammer, was maximized by jointly designing the source/UAV transmit/jamming powers and the UAV trajectory. An efficient iterative algorithm was proposed by applying BCD and SCA techniques to solve the problem of the EE maximization over a given flight period. As compared with the benchmark schemes without FD transmission, power control or trajectory optimization, the proposed joint optimization algorithm with FD operation achieves the highest flexibility in adjusting the UAV

jamming power by considering its practical RSI. Numerical results showed that the EE of UAV secrecy communication is significantly improved by our proposed algorithm over the benchmark schemes.

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