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Energy Efficient Optimization for Solar-Powered UAV Communications System

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***Abstract*—In this work, we explore the energy efficiency optimization for a solar-powered unmanned aerial vehicle (UAV) communications system. We consider a scenario where a number of ground users (GUs) connect with a solar-powered multi-antenna UAV over a wireless link. First, we are able to derive the relations between the uplink data rate and heading angle of UAV and transmission power of GUs. In addition, the harvested energy from solar light is also affected by UAV's angle. Accordingly, with the objective to maximize the energy efficiency that is related to uplink data rate and energy consumption, we propose to dynamically adjust the UAV trajectory and gesture, by optimizing its velocity, acceleration, heading angle and ground user transmission power. Performance evaluations demonstrate the advantages of the presented scheme on the design of solar-powered UAV communications system.**

***Index Terms*—UAV communication systems, solar energy harvesting, energy efficiency**

I. Introduction

In order to provide unlimited access to wireless data anywhere and anytime for anything, the recent emerging unmanned aerial vehicle (UAV)-based flying platforms are able to break the limitations of traditional network infrastructure [1]. Because of its high flying attitude, the UAV-based platform can establish the effective Line-of-Sight (LoS) links with the ground-users (GUs), thus to reduce energy consumption for reliable connectivity [2].

Developing a UAV-enabled wireless communications system has received attracted a large amount of research interests. The current research on the UAV-based wireless communication systems have mainly concentrated on the resource optimization and placement [2]-[9], with the assumptions that UAV can serve as aerial BSs or aerial relay to support GUs. For the trajectory design, the altitude of the UAV can be optimized with or without the horizontal location based on different considerations and QoS requirements. The authors of [3] utilize stochastic geometry to analyze two-tier wireless network consisting of BSs and aerial BS. The coverage probability and spectral efficiency are derived with the consideration of the height of the aerial BS. In [4], the authors aim to optimize the resource allocation and node placement for a single UAV relay network. In [5], the authors investigate the energy efficient design of UAV network via optimizing the UAV's trajectory. In [6], by jointly optimizing UAV's location and antenna beamwidth, and transmission bandwidth and transmit power, the sum uplink power of all GUs is minimized. Considering a wireless powered [7] or rechargeable UAV [8] network, the authors present different trajectory design, time and/or resource allocation schemes. The authors of [9] investigate the resource allocation and trajectory problem for maximizing the throughput of a solar powered UAV system over a given time period.

We can observe that implementing energy harvesting technique can prolong the lifetime of UAV service. In particular, harvesting solar light for UAV is of research interests [11], while the related research on as UAV networking development does not receive equal attentions. In this work, we can find that the flying gesture, i.e. heading angle of the UAV, has impact on both uplink data rate from GU and energy harvested from solar light. Based on this observation, our main objective is to maximize the energy efficiency of a solar-powered UAV communications system considering uplink transmission data and energy consumption of UAV. Bearing the above mentioned works in mind, we can summarize the main contributions of this paper in the following.

- We consider a scenario where a number of single-antenna GUs are served by a solar-powered multi-antenna UAV. The GUs have uplink transmission demand. We first investigate the impact of UAV's flying gesture (heading angle) and GUs's transmission power on the uplink transmission data rate.
- Then the energy consumption model considering the flying velocity and acceleration of the UAV is presented. In addition, the energy harvesting model for solar light is built based on the heading angle of the UAV.
- Accordingly, a joint transmission power, velocity, acceleration, and flying angle optimization problem for solar-powered UAV communication system is formulated with the objective to maximize its energy efficiency that is related to the uplink data rate and energy consumption.
- Since the formulated problem has a non-convex structure, we propose to utilize the fractional programming-based scheme to derive the solution. Extensive simulations are conducted to demonstrate the advantages of proposed scheme.

The rest of this paper is organized as follows. Section II depicts the considered solar-power UAV communications system. In Section III, the formulated problem is presented and we present the proposed solution. The performance evaluation is conducted in Section IV, and Section V concludes this work.

II. System Model

A. Signal Model

We consider there are N single antenna GUs who need uplink transmission. The fixed-wing UAV which can act as the relay or aerial BS for the GUs is equipped with M antennas. As a fixed-wing UAV is considered, it has to maintain a forward velocity. Thus, in our model, we consider the UAV is flying at fixed altitude H. For simplicity, in this work, we assume that the each GU transmits with power P_i. In order to solve the problem more simply, the time horizon $\mathcal{T}$ will be divided into N_t sufficiently small time periods δ_{N_t}. At nth time slot, the received signal at the UAV is given as

$$\mathbf{y}_n = \sum_{i=1}^{N} \sqrt{P_i}\mathbf{h}_{i,n} x_{i,n} + \mathbf{n}_n, \tag{1}$$

where $\mathbf{h}_{i,n} \in C^{M\times 1}$ is the channel vector between GU i and UAV, and $x_{i,n}$ is the transmitted signal. $\mathbf{n}_n$ is zero-mean additive Gaussian noise with covariance $\sigma^2\mathbf{I}_M$ where $\mathbf{I}_M$ denotes an $M\times M$ identity matrix. A channel equalizer $\mathbf{w}_{i,n}$ is used to retrieve the data from the GU i. Assuming that UAV has the channel knowledge of all the GUs (e.g., via training data), $\mathbf{w}_{i,n}$ that maximizes the signal-to-interference-plus-noise ratio (SINR) $\gamma_{i,n}$ is presented as [10]

$$\mathbf{w}_{i,n} = \mathbf{Q}_{i,n}^{-1}\mathbf{h}_{i,n} \tag{2}$$

where

$$\mathbf{Q}_{i,n} = \sum_{j=1, j\neq i}^{N} P_i \mathbf{h}_{i,n}\mathbf{h}_{i,n}^H + \sigma^2\mathbf{I}_M. \tag{3}$$

$()^H$ denotes the complex conjugate transpose. Then $\gamma_{i,n}$ is given as

$$\gamma_{i,n} = P_i\mathbf{h}_{i,n}\mathbf{Q}_{i,n}^{-1}\mathbf{h}_{i,n}^H \tag{4}$$

B. Channel Model

Correlated Rician fading channel is considered between the UAV and GU, thus

$$\mathbf{h}_{i,n} = \mathbf{g}_{i,n}/d_{i,n}^{\alpha}, \tag{5}$$

where $\mathbf{g}_{i,n}$ is the normalized channel vector, $d_{i,n}$ is the distance between UAV and GU i, and α is the path loss exponent. The three-dimensional (3D) Cartesian coordinates of UAV are $(x_{u,n}, y_{u,n}, H)$ and GU i are $(x_{i,n}, y_{i,n}, 0)$. We use $\mathbf{q}_{u,n} = [x_{u,n}, y_{u,n}]^T$ and $\mathbf{q}_{i,n} = [x_{i,n}, y_{i,n}]^T$, and the distance $d_{i,n}$ is

$$d_{i,n} = \sqrt{\|\mathbf{q}_{u,n} - \mathbf{q}_{i,n}\|^2 + H^2}. \tag{6}$$

For GU i, the channel vector $\mathbf{g}_{i,n}$ consists of a Rayleigh fading component $\breve{\mathbf{g}}_{i,n}$ and a LoS component $\tilde{\mathbf{g}}_{i,n}$, i.e. $\mathbf{g}_{i,n} = \tilde{\mathbf{g}}_{i,n} + \breve{\mathbf{g}}_{i,n}$. The LoS component depends on the angle of arrival (AoA) of the signal, which means it is related to the positions of the UAV and GUs, and the heading of the UAV. In this work, UAV is assumed with a uniform linear array (ULA) with antennas separated by one-half wavelength. Then, the phase delay between adjacent antennas for the signal from GU i is $\xi_{i,n} = \pi\cos(\phi_{i,n})\sin(\theta_{i,n})$, where $\phi_{i,n}$ is the elevation angle and $\theta_{i,n}$ is the azimuth angle of GU i [10]. Correspondingly, LoS component is given as

$$\tilde{\mathbf{g}}_{i,n} = \beta\left(\phi_{i,n}\right)\sqrt{\frac{K}{1+K}}\left[1, e^{j\xi_{i,n}}, ..., e^{j(M-1)\xi_{i,n}}\right]^T. \tag{7}$$

where K is the Rician K-factor and the use of $\beta(\phi_{i,n})$ can take the variations of antenna gain into consideration. Based on the positions of UAV and GUs, $\cos(\phi_{i,n})$ and $\sin(\theta_{i,n})$ are calculated as

$$\begin{aligned} \cos(\phi_{i,n}) &= \sqrt{\frac{\|\mathbf{q}_{u,n} - \mathbf{q}_{i,n}\|^2}{\|\mathbf{q}_{u,n} - \mathbf{q}_{i,n}\|^2 + H^2}}, \\ \sin(\theta_{i,n}) &= \cos(\delta_n - \epsilon_{i,n}). \end{aligned} \tag{8}$$

where δ_n is UAV's heading angle, $\delta_n - \epsilon_{i,n}$ is the angle between the UAV heading and the LoS to GU i. We have

$$\epsilon_{i,n} = \begin{cases} \psi_{i,n}, & x_{u,n} - x_{i,n} \geq 0 \text{ and } y_{u,n} - y_{i,n} \geq 0, \\ \psi_{i,n} + \pi, & x_{u,n} - x_{i,n} \leq 0, \\ \psi_{i,n} + 2\pi, & otherwise. \end{cases} \tag{9}$$

In the following, we consider the LOS component dominant the channel effect, i.e. $\mathbf{g}_{i,n} \approx \tilde{\mathbf{g}}_{i,n}$, to investigate the impact of heading angle on the data rate and energy efficiency.

C. Uplink Data Rate

With the above analysis on the signal and channel, we are able to reach the uplink data rate at time slot n of all the GUs, i.e.

$$C_n = \sum_{i=1}^{N} \log_2\left(1 + \gamma_{i,n}\right). \tag{10}$$

Then, during the entire duration along the trajectory, the overall uplink data rate in bits/Hz is given as

$$R = \sum_{j=1}^{N_t}\sum_{i=1}^{N} \delta_{N_t}\log_2\left(1 + \gamma_{i,n}\right) \tag{11}$$

Given the fixed transmit power, it can be found that the overall data rate is related to the heading angle δ_n. To avoid frequently changing the flying gesture, we assume that during the considered time duration, δ_n remains the same. Thus, we have $\delta_n = \delta$, and we expect to optimize it to improve the energy efficiency which is the total uplink data rate of all the GUs and energy consumption of UAV.

D. Energy Model of UAV

The energy model of the UAV comprises of two parts. The first one is about energy consumption, which consists of communication-related energy and propulsion energy. The other part of energy model is the harvested energy from the solar light. In the following, we provide analysis on both parts.

1) Energy Consumption of UAV: First, we assume that the UAV's communication-related power consumption is fixed to be $P_{u,n}$, which is used for signal processing and data forwarding etc. Then for the whole time duration, the communication-related energy is $E_{u,c} = \sum_{j=1}^{N_t} P_{u,n}$.

Next, we analyze the propulsion energy, which is to ensure that the fixed-wing UAV remains airborne. We can define velocity as $\mathbf{v}_{u,n} = \mathbf{q}'_{u,n}$ and acceleration as $\mathbf{a}_u = \mathbf{q}''_{u,n}$, which means velocity and acceleration is the first and second derivative of the position with respect to n, respectively. In this work, we assume the speed of the UAV is constant. The UAV generates a centrifugal acceleration, which is used to control the direction of the UAV's velocity and make its horizontal trajectory change. Correspondingly, we can get $\mathbf{a}_u{}^T \mathbf{v}_{u,n} = 0$.

In the work, we assume that the UAV is with a constant speed during the time duration $\mathcal{T}$. Thus, we have $\|\mathbf{v}_{u,n}\| = \|\mathbf{v}_u\|$. Then according to [5], the energy consumption of propulsion for UAV is derived as

$$E_{u,cm} = \sum_{j=1}^{N_t} \delta_{N_t} \left[k_1 \|\mathbf{v}_u(n)\|^3 + \frac{k_2}{\|\mathbf{v}_u(n)\|} \left(1 + \frac{\|\mathbf{a}_u(n)\|^2}{g^2} \right) \right] \tag{12}$$

where g is the gravity. k_1 and k_2 are two constant factors depending on the UAV's wing size and weight, and air density. Accordingly, the total energy consumption of UAV $E_u = E_{u,c} + E_{u,cm}$.

2) Energy Harvesting of UAV: We consider UAV is capable of harvesting energy from solar light by implementing solar cells on its wings. Basically, the amount of harvested energy depends on different aspects, such as the sun incidence angle, size of solar cell and its efficiency. We consider the harvested power from the solar cell can be expressed as [12]

$$P_{in,n} = \eta P_{sun} S_u cos(\rho_n), \tag{13}$$

where η is the efficiency of the solar cell, and S_u is cell size, P_{sun} is the solar spectral density, ρ_n is incidence angle that depends on elevation and azimuth angles of the sun. To ease the analysis, we assume the sun is roughly vertical to the UAV, so $\rho_n = \delta$. Then total harvested energy is

$$E_{in} = \sum_{j=1}^{N_t} \delta_{N_t} P_{in,n}. \tag{14}$$

E. Energy Consumption of GUs

During the execution of the UAV mission,the transmission power of each ground user P_i,we have the user's transmission energy consumption is:

$$E_g = \sum_{j=1}^{N_t} \sum_{i=1}^{N} \delta_{N_t} P_i \tag{15}$$

Accordingly, the total energy consumption of UAV communications system:

$$E_s = E_g + E_u - E_{in}. \tag{16}$$

III. Problem Formulation and Solution

A. Problem Formulation

With the above analysis on the data transmission and energy models, the energy efficiency $\mathcal{E}(\mathbf{v}_u, \mathbf{a}_u, \delta, P_i)$ is defined as the transmitted data of all the GUs normalized by the total energy consumption of UAV over $\mathcal{T}$, i.e.,

$$\mathcal{E}(\mathbf{v}_u, \mathbf{a}_u, \delta, P_i) = \frac{R(\delta, P_i)}{E_s(\mathbf{v}_u, \mathbf{a}_u, \delta, P_i)}. \tag{17}$$

Then, we are able to reach the energy efficiency maximization problem **P1**, as follows,

$$\max_{(\mathbf{v}_u, \mathbf{a}_u, \delta, P_i)} \mathcal{E}(\mathbf{v}_u, \mathbf{a}_u, \delta, P_i), \tag{18}$$

s.t.

$$\begin{aligned} &C1 : \|\mathbf{v}_u\| \geq v_{\min}, \\ &C2 : \|\mathbf{v}_u\| \leq v_{\max}, \\ &C3 : P_i \leq P_{i\max}, \\ &C4 : \delta \leq \frac{\pi}{2}, \end{aligned} \tag{19}$$

where v_{min} and v_{max} are the minimum and maximum velocity required for maintaining the fixed-wing UAV airborne. $P_{i\max}$ represents the maximum power transmitted by the ground user.It is worth noticing that (18) with (19) is a nonlinear fractional programming problem. To address the formulated problem, the objective function is transformed to subtractive form. Then we are able to solve the transformed objective accordingly.

B. Proposed Solution

During the flight of the UAV, the velocity remains unchanged, but the trajectory is a variable that changes with time. At this time, the discrete state space model of UAV motion can be obtained as follows:

$$\mathbf{q_u}[n+1] = \mathbf{q_u}[n] + \mathbf{v}_u[n]\,\delta_{N_t} + \frac{1}{2}\mathbf{a_u}[n]\,\delta_{N_t}^2, n = 0, 1.....N_t \tag{20}$$

where $\mathbf{q_u}[n], \mathbf{v_u}[n], \mathbf{a_u}[n]$ respectively represent the flight trajectory, velocity and acceleration of the UAV in the nth time period.(The magnitude of $\mathbf{v_u}[n]$ stays the fixed.)

Therefore, the energy efficiency optimization problem **P2** can be modeled as:

$$\max_{(\mathbf{v}_u[n],\mathbf{a}_u[n],\delta,P_i)} \mathcal{E}\left(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i\right) \tag{21}$$

s.t.

$$\begin{aligned} & C1-C4 \\ & C5:\mathbf{q}_u\left[n+1\right]=\mathbf{q}_u\left[n\right]+\mathbf{v}_u\left[n\right]\delta_{N_t}+\tfrac{1}{2}\mathbf{a}_u\left[n\right]\delta_{N_t}^2 \end{aligned} \tag{22}$$

where

$$\mathcal{E}\left(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i\right)=\frac{R\left(\delta,P_i\right)}{E_s\left(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i\right)} \tag{23}$$

$$R\left(\delta,P_i\right)=\sum_{j=1}^{N_t}\sum_{i=1}^{N}\delta_{N_t}\log_2\left(1+SINR_{i,n}\right) \tag{24}$$

Due to constraint condition $C1$ is non-convex, so adding slack variables $\{\tau_n\}$, The final constraint condition is

$$\begin{aligned} & C2-C5 \\ & \text{C6}:\tau_n\geq v_{\min} \end{aligned} \tag{25}$$

In order to transform the original problem, the following theorem is presented.

Theorem 1. *The objective function (21) is quasi-concave function with respect to the velocity, acceleration, heading angle and transmission power of GUs.*

Theorem 1 can be proved via the definition of quasi-concave function. Thus, there exist unique global optimal solutions of $\mathbf{v}_u,\mathbf{a}_u,\delta,P_i$. The optimal solution can be reached via exhaustive searching or other similar methods [14]. In the following, nonlinear fractional programming method [13] is applied to address **P2** for velocity, acceleration, gesture control and transmission power.

1) Problem Transformation: The global optimal solution of ϑ^* is presented as

$$\begin{aligned} \vartheta^* &= \mathcal{E}\left(\mathbf{v}_u^*\left[n\right],\mathbf{a}_u^*\left[n\right],\delta^*,P_i^*\right) \\ &= \max_{\mathbf{v}_u[n],\mathbf{a}_u[n],\delta,P_i,\tau_n}\frac{R\left(\delta,P_i\right)}{E_s\left(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i\right)} \end{aligned} \tag{26}$$

where $\mathbf{v}_u^*\left[n\right],\delta^*$ represent the optimal velocity and heading angle in the nth time period, respectively; $\mathbf{a}_u^*\left[n\right]$represent the variation of the acceleration when velocity is v_u; P_i^* represent the optimal transmission power of GUs i; $\mathbf{q}_u^*\left[n\right]$ represent the optimal trajectory.

To find ϑ^*, we have following theorem.

Theorem 2. *The optimal solution ϑ^* of (21) is reached iff [13]*

$$\max_{\mathbf{v}_n[n],\mathbf{a}[n],\delta,P_i,\tau_n} R\left(\delta,P_i\right)-\vartheta^*\left(E_s(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i)\right) \tag{27}$$

Theorem 2 gives a necessary and sufficient condition to find the solution. **Theorem 2** means that we are able to transform the an objective function of **P2** to a subtractive form, i.e., $R\left(\delta,P_i\right)-\vartheta^*\left(E_s(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i)\right)$, and the solutions of the optimization problem remain the same. Then, according to [13], we can apply iterative algorithm with guaranteed convergence to obtain optimal ϑ^*, which is presented in Alg.1.

Algorithm 1 Proposed algorithm for obtaining ϑ^*

```
Initialize maximum tolerance τ;
while (!Convergence) do
    For a given ϑ, problem (28) is solved, and velocity,acceleration,heading angle and transmission power of GUs {v_u'[n], a_u'[n], δ', P_i'} are obtained;
    if R(δ', P_i') − ϑ(E_s(v_u'[n], a_u'[n], δ', P_i')) < τ then
        Convergence = true;
        return {v_u*[n], a_u*[n], δ*, P_i*} = {v'_u[n], a'_u[n], δ', P'_i} and q_j*[n] = q_j[n]; obtain ϑ* by (26);
    else
        Convergence = false;
        return Obtain ϑ = R(δ', P_i') / E_s(v'_u[n], a'_u[n], δ', P'_i)
    end if
end while
```

As can be seen from the presented algorithm, in order to obtain optimal ϑ^*, following **P3** should be addressed, i.e.

$$\begin{aligned} \max_{\mathbf{v}_n[n],\mathbf{a}[n],\delta,P_i,\tau_n} & R\left(\delta,P_i\right)-\vartheta E_s(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i) \\ & s.t.C2-C6 \end{aligned} \tag{28}$$

2) Dual Problem Formulation and Decomposition: After obtaining **P3**, it can be found that **P2** has been transformed into a convex optimization problem, which can be addressed by solving its dual for a given value of ϑ. The Lagrangian function of the primal problem (28) is presented as,

$$\begin{aligned} & L\left(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i,\tau_n,\mu_1,\mu_2,\mu_3,\mu_4,\mu_5\right)=R\left(\delta,P_i\right) \\ & -\vartheta E_s(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i)+\mu_1\left(\|\mathbf{v}_u\|-v_{\max}\right) \\ & +\mu_2\left(P_i-P_{i\max}\right)+\mu_3\left(\delta-\tfrac{\pi}{2}\right)+\mu_4\left(v_{\min}-\tau_n\right) \\ & +\mu_5\left(\mathbf{q}_u\left[n+1\right]-\mathbf{q}_u\left[n\right]-\mathbf{v}_n\left[n\right]\sigma_{N_t}-\tfrac{1}{2}\mathbf{a}_u\left[n\right]\sigma_{N_t}^2\right) \end{aligned} \tag{29}$$

where $\mu_1-\mu_4$ are the KKT multipliers, μ_5 is Lagrange multipliers; Accordingly, the dual problem is given as

$$\min_{\mu_1-\mu_5}\max_{\substack{\mathbf{v}_u[n],\mathbf{a}_u[n] \\ \delta,\tau_n}} L\left(\mathbf{v}_u\left[n\right],\mathbf{a}_u\left[n\right],\delta,P_i,\tau_n,\mu_1,\mu_2,\mu_3,\mu_4,\mu_5\right) \tag{30}$$

We can see that the dual problem (30) is decomposed into two layers by applying Lagrange dual decomposition. The inner problem is maximization of (29) and the outer problem is minimization of (30). By addressing the inner and outer problems iteratively, we are able to solve the dual problem (30). In each iteration, the inner problem is addressed by applying the Karush-Kuhn-Tucker (KKT) conditions for a given set of Lagrange multipliers. The outer problem can be solved by applying the subgradient method with guaranteed convergence[14].

Therefore, by applying the KKT conditions, velocity, acceleration, heading angle and transmission power of GUs can be solved by the following equation:

$$\begin{cases} C2-C6 \\ \mu_i>0, i=1,2,3,4,5 \\ \mu_5\left(\mathbf{q}_u\left[n+1\right]-\mathbf{q}_u\left[n\right]-\mathbf{v}_u\left[n\right]\delta_{N_t}-\frac{1}{2}\mathbf{a}_u\left[n\right]\delta_{N_t}^2\right)=0 \\ \frac{\partial L(\mathbf{v}_u[n],\mathbf{a}_u[n],\delta,P_i,\tau_n,\mu_1,\mu_2,\mu_3,\mu_4,\mu_5)}{\partial v}=0 \\ \frac{\partial L(\mathbf{v}_u[n],\mathbf{a}_u[n],\delta,P_i,\tau_n,\mu_1,\mu_2,\mu_3,\mu_4,\mu_5)}{\partial a}=0 \\ \frac{\partial L(\mathbf{v}_u[n],\mathbf{a}_u[n],\delta,P_i,\tau_n,\mu_1,\mu_2,\mu_3,\mu_4,\mu_5)}{\partial \delta}=0 \\ \frac{\partial L(\mathbf{v}_u[n],\mathbf{a}_u[n],\delta,P_i,\tau_n,\mu_1,\mu_2,\mu_3,\mu_4,\mu_5)}{\partial P_i}=0 \end{cases} \tag{31}$$

In addition, the subgradient method is advocated to address the Lagrange multipliers. Given $\xi_{\mu_1}-\xi_{\mu_5}$ as the step sizes, we have

$$\mu_1^{l+1}=\mu_1^l+\xi_{\mu_1}\left(\left\|\mathbf{v}_u\left[n\right]\right\|-v_{\max}\right), \tag{32}$$

$$\mu_2^{l+1}{=}\mu_2^l+\xi_{\mu_2}\left(P_i-P_{i\max}\right), \tag{33}$$

$$\mu_3^{l+1}{=}\mu_3^l+\xi_{\mu_3}\left(\delta-\frac{\pi}{2}\right), \tag{34}$$

$$\mu_4^{l+1}=\mu_4^l+\xi_{\mu_4}\left(v_{\min}-\tau_n\right), \tag{35}$$

$$\mu_5^{l+1}=\mu_5^{l+1}{+}\xi_{\mu_5}\left(\mathbf{q}_u\left[n+1\right]{-}\mathbf{q}_u\left[n\right]{-}\mathbf{v}_u\left[n\right]\delta_{N_t}^2{-}\frac{1}{2}\mathbf{a}_u\left[n\right]\delta_{N_t}^2\right) \tag{36}$$

Since the **P3** is a convex optimization problem, the iteration between the inner and outer problems can converge to the primal optimal solution of **P3**. We present the proposed scheme for addressing the velocity,acceleration and heading angle of **P3** in Alg. 2.

Algorithm 2 Proposed Solution with given ϑ

1: Initialize $\vartheta, \mathbf{v}_u\left[n\right], \mathbf{a}_u\left[n\right], \delta, P_i$ and KKT multipliers and Lagrange multipliers;
2: **while** (!Convergence) **do**
3: Address the problem (30) and obtain velocity, acceleration heading angle and transmission power of GUs;
4: Update Lagrange multipliers according to (32)-(36);
5: **end while**
6: **return** Optimal velocity ,acceleration and heading angle and transmission power of GUs.

IV. Simulation Results

In this section, the performance evaluation is conducted. The key parameters are listed in Table 1. In Fig. 1, we show the convergence of the presented algorithm. Moreover, we also vary the number of antennas equipped on the UAV. In general, it can be found that the proposed scheme has a fast convergence speed. Moreover, we can see that when the number of antennas on UAV increases, the energy efficiency becomes larger as well. This is mainly because that the uplink data rate increases with the number of antennas. While a fixed communication-related energy is considered, the energy consumption remains the same. Note that in this case, we are able to have optimal velocity is about $7m/s$ and heading angle $8°$.

TABLE I
KEY SIMULATION PARAMETERS

Notation	Value	Notation	Value
H	$100m$	P_{sun}	$560(w/m^2)$
η	80%	S_u	$0.25m^2$
k_1	6.465^{-2}	k_2	580

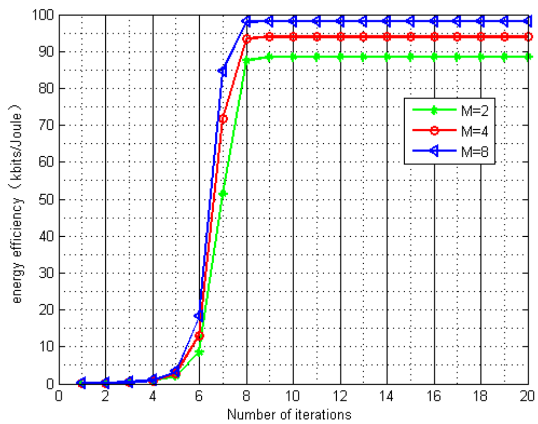

Fig. 1. Convergence performance

In Fig. 2, we plot the impact of heading angle and UAV velocity on the energy efficiency. In addition, the effectiveness of solar energy harvesting is also examined in this figure. First, it can be found that without solar energy harvesting, the system energy efficiency will be dramatically reduced, which demonstrates the importance of applying the energy harvesting techniques to the UAV. In addition, it can also be found that as the velocity of UAV becomes larger, the energy efficiency first increases, reaches its maximum and decreases. Such a phenomenon indicates the necessity of investigating efficient algorithm to find optimal value. Moreover, it can also be found that changing the heading angle also leads to a significant impact on the energy efficiency which also shows the importance of the proposed scheme.

Fig. 3 presents the energy efficiency convergence performance when $v_u = 11m/s$. In this figure, we vary the number of GUs and heading angle. On x-axis, we vary the heading from 0 to $\pi/2$. Generally, serving more GUs can improve the uplink data rate and thus to improve the system energy efficiency. Moreover, the energy efficiency is affected by the heading angle as well.

In Fig. 4 shows the relationship between acceleration, velocity and energy efficiency. It can be observed that when the velocity is fixed, and acceleration changes, the energy efficiency

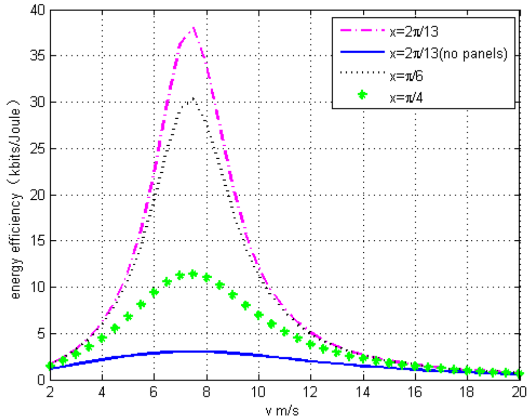

Fig. 2. Energy efficiency v.s. number of GUs and heading angle

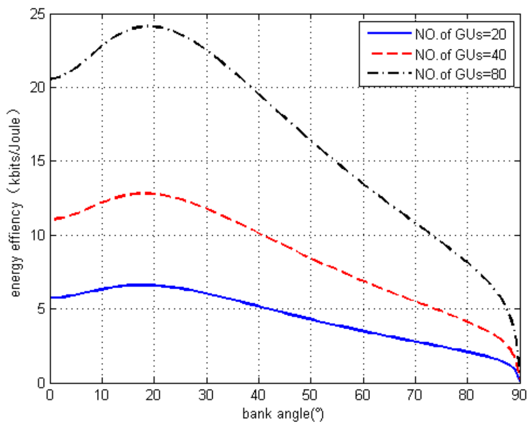

Fig. 3. Energy efficiency v.s. number of GUs and heading angle

of the UAV also changes. It is verified that acceleration affects the energy efficiency of the UAV. When an optimal value is selected for the UAV velocity and acceleration, the trajectory of the UAV is also determined as the optimal trajectory.

V. Conclusion

In this work, we explore the energy efficiency optimization for a solar-powered UAV communication system. In the considered system, a number of single-antenna ground users (GUs) are served by a solar-powered multi-antenna UAV and have uplink data transmission demand. First, we are able to derive the relations between the uplink data rate with GUs transmission power and heading angle of UAV. Moreover, the harvested energy from solar light is also affected by UAV's angle. Accordingly, with the objective to maximize the system energy efficiency, we propose an algorithm to optimize the UAV's velocity acceleration and heading angle. Finally, determine the optimal trajectory.Performance evaluations demonstrate the advantages of our presented scheme on the design of the solar-powered UAV communication system.

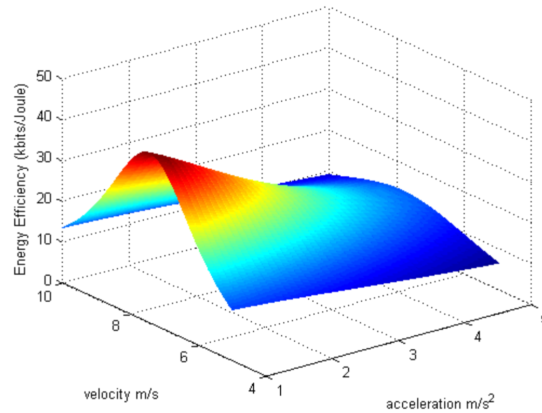

Fig. 4. Energy efficiency v.s.acceleration and velocity

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