Recharging of Flying Base Stations using Airborne RF Energy Sources

Jahan Hassan  
School of Engineering and Technology  
Central Queensland University  
Australia  
Email: j.hassan@cqu.edu.au

Ayub Bokani  
School of Engineering and Technology  
Central Queensland University  
Australia  
Email: a.bokani@cqu.edu.au

Salil S. Kanhere  
School of Computer Science and Engineering, University of New South Wales, Australia  
Email: salil.kanhere@unsw.edu.au

Abstract—This paper presents a new method for recharging flying base stations, carried by Unmanned Aerial Vehicles (UAVs), using wireless power transfer from dedicated, airborne, Radio Frequency (RF) energy sources. In particular, we study a system in which UAVs receive wireless power without being disrupted from their regular trajectory. The optimal placement of the energy sources are studied so as to maximize received power from the energy sources by the receiver UAVs flying with a linear trajectory over a square area. We find that for our studied scenario of two UAVs, if an even number of energy sources are used, placing them in the optimal locations maximizes the total received power, while achieving fairness among the UAVs. However, in the case of using an odd number of energy sources are used, we can either maximize the total received power or achieve fairness, but not both at the same time. Numerical results show that placing the energy sources at the suggested optimal locations results in significant power gain compared to non-optimal placements.

Keywords—Unmanned Aerial Vehicle (UAV), wireless power transfer, charger placement for UAV recharging.

I. INTRODUCTION

Recent advances in miniaturization, robotics, sensor technology and communications have revolutionized Unmanned Aerial Vehicles (UAVs) and brought about their adoption in a wide range of applications. One such application is the use of UAVs carrying base station equipment acting as aerial base stations that can dynamically re-position themselves to improve coverage and capacity demands of existing networks [1]–[7]. Such aerial base stations could supplement terrestrial infrastructure when it is overloaded or unavailable, as presented in the context of 5G networks in [8], [9]. While the majority of these proposals considered non-mobile UAVs hovering over a service area, some recent works [1], [4], [10] have argued for the use of flying (or cruising) aerial base stations wherein the UAVs continue to service ground nodes while in flight. The trajectory, i.e., the movement patterns of the aerial base stations is tailored so as to maximize network performance in the presence of geospatial variation in user demand, or to improve spectral efficiency. A prototype demonstrating the use of flying aerial base stations was developed recently by Eurecom [11].

UAVs rely on an on-board battery for power, which limits their operational duration before recharging is required. Researchers have investigated power-efficient operations of UAVs to extend battery lifetime by reducing the energy consumed for communications (electronics) and mobility (mechanical), as summarized in [3]. Since extending the lifetime of the battery does not eliminate the need for recharging, a promising and parallel direction of research involves investigating ways for recharging UAVs to ensure service continuity. In particular, mechanisms for replenishing energy without disrupting the UAV’s usual trajectory (in the case of flying UAVs) or deployed locations (in the case of non-mobile UAVs) where the UAV is not required to move to a different location to receive power, is essential for uninterrupted service provisioning. In this paper, we propose an architecture for recharging cruising UAVs using energy harvesting from received Radio Frequency (RF) transmitted by dedicated, non-mobile airborne UAVs equipped with RF transmitters referred to as transmitter UAVs (tUAVs). In particular, we study the optimum placement of the tUAVs to maximize the received energy by the receiver UAVs (rUAVs).

Researchers in [12] have also explored RF energy harvesting for recharging UAVs. However, they rely on terrestrial energy sources for charging UAVs while we consider airborne chargers. As such, our approach can be used in a wide range of scenarios where deployment of terrestrial chargers may not always be possible, for example where UAVs are deployed to monitor ground sensors in a forest. The energy transfer efficiency is influenced by both distance and the presence of obstacles (line-of-sight vs no-line-of-sight). Our approach offers flexibility to address both these issues. We can position the airborne energy sources in a way that would minimize this distance and improve line-of-sight RF links thus increase energy transfer efficiency. Moreover, our work is the first to consider the optimal positioning of rUAVs which maximizes the total received energy in the rUAVs.

Our contributions in this paper are as follows: (i) we propose an UAV re-charging architecture using wireless power transfer from carefully positioned, airborne, stationary energy sources that provide power to the UAVs without disrupting their trajectories, (ii) we provide a mathematical model to derive optimal placement of the energy sources to maximize the total received energy in the system, and (iii) we consider a specific scenario.
of two $rUAV$s moving along a linear trajectory servicing ground nodes stationed within a square region and use our model to determine the optimal locations for two $tUAV$s. From our solutions to the optimal placement problem, we observed that for this specific scenario, the optimal placement of an even number of energy sources will also result in fairness in terms of equal amount of received energy by all $rUAV$s. However, we found that if we used an odd number of energy sources, either the fairness could be achieved or the total amount of received energy could be maximized, but not both at the same time. Our numerical results revealed that placing the charging nodes at the suggested optimal locations resulted in significant power gain compared to non-optimal placements.

The rest of the paper is organized as follows. Section II presents our proposed $UAV$ recharging architecture. We first present a general case of any number of $tUAV$s and $rUAV$s, followed by a specific case of two $tUAV$s and two $rUAV$s. We solve the specific case of energy source placement in Section III. We provide implications of our solutions in Section IV, ending our paper with some numerical results and conclusion in Sections V and VI.

II. UAV RECHARGING ARCHITECTURE: SYSTEM MODEL

Our $UAV$ charging architecture is shown in Figure 1 which is used for charging a number of cruising $UAV$s that fly back and forth with a linear trajectory over a square area of side length $l$. The trajectories of the cruising $UAV$s can be of any form, e.g., of geometric form (circular, linear), or can be of other forms, as shown in [1], [4]. In our work, we have assumed a linear trajectory for the cruising $UAV$s. These are the RF energy receiver $UAV$s- the $rUAV$s, and fly back and forth on a path parallel to the horizontal axis of the square area, with a constant speed $V$. The $rUAV$s harvest energy from the received RF signals while in service, from airborne, dedicated energy sources. We assume that these energy sources are specialized $UAV$s, equipped with wireless power transmitters, and are referred to as transmitter $UAV$s- $tUAV$s. The $tUAV$s are placed at fixed locations (i.e., non-mobile) over this area with their $(x, y)$ coordinates given by $(x_1, y_1)$ & $(x_2, y_2)$, etc., and their $z$ coordinate (the height) is the same as those of the $rUAV$s. The heights of the $tUAV$s and the $rUAV$s being same improves the amount of received RF power, which we can adjust since we are using airborne energy sources, as opposed to using terrestrial energy sources with non-adjustable heights. The $tUAV$s are assumed to have a wire-line connection to the ground for a constant power supply [13]. In order to avoid the chance of collision, the $tUAV$s must be placed outside the collision zone $R_1$, anywhere in zone $R_2$ as shown in Figure 1. By careful positioning of the $tUAV$s in terms of their $(x, y)$ coordinates, this architecture aims to maximize the received energy by the $rUAV$s during their flight time to travel one side of the square, achieving service continuity by the $rUAV$s without disrupting their trajectory. We provide a general model for this architecture next.

Time taken to travel one side length of the square area by a $rUAV$ is given by $T = l/V$. Locations of the $rUAV_1$ and $rUAV_2$ that are on the parallel edges of the square at time $t$ is given by $(Vt, 0)$ and $(Vt, l)$ respectively, for $t \in [0, T]$. The received power of far-field RF transmission attenuates as per the reciprocal of the squared distance between the transmitter and the receiver. Therefore, the harvested RF power ($P_R$) at the receiver can be calculated using Frii’s free space propagation model [14] as:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} \quad (1)$$

where $P_T$ is the transmit power, $G_T$ and $G_R$ are the antenna gains of the transmitter and the receiver, $\lambda$ is the power transfer wavelength, and $R$ is the distance between the transmitter and the receiver. Without the loss of generality, we can say that the received power varies inversely with the square of the distance between the transmitter and the receiver, which our model is based on. In Section IV, we use specific values of the other parameters of Frii’s equation to estimate received power.

Distance of $rUAV_1$ from $tUAV_1$ at time $t$ is $\sqrt{(Vt-x_1)^2 + y_1^2}$. So, energy received by $rUAV_1$ from the $tUAV_1$ over $[0, T]$ is

$$\propto \int_0^T \frac{dt}{(Vt-x_1)^2 + y_1^2}. \quad (2)$$

For a general $rUAV$ path $(x(t), y(t))$, $0 \leq t \leq T$, i.e., the $rUAV$ located anywhere in the considered area, energy received by an $rUAV$ from a $tUAV$ located at $(x_1, y_1)$ is

$$\propto \int_0^T \frac{dt}{(x(t)-x_1)^2 + (y(t)-y_1)^2}. \quad (3)$$

Let $E_{rUAV_i, tUAV_j}$ be the energy received by $rUAV_k$ from $tUAV_j$ over time $0 \leq t \leq T$. Then the total energy received by $rUAV_k$ is:

$$E_k = \sum_j E_{rUAV_k, tUAV_j} \propto \sum_j \int_0^T \frac{dt}{(x_k(t)-x_j)^2 + (y_k(t)-y_j)^2}. \quad (4)$$
The total energy received by all \( rUAVs \) from all \( tUAVs \) is given by:

\[
E_{\text{total}} = \sum_k E_k = \sum_k \sum_j E_{rUAV_k, tUAV_j}
\]  
(5)

where \((x_k(t), y_k(t))\) is the flight path of \( rUAV_k \) for \( 0 \leq t \leq T \) and \((x_j, y_j)\) is the \( j^{th} \) transmitter UAV’s \((tUAV_j)\) location. The \( E_{\text{total}} \) can also be calculated by summing up the given energy by all \( tUAVs \) to all \( rUAVs \), as:

\[
E_{\text{total}} = \sum_j \sum_k E_{rUAV_k, tUAV_j}
\]  
(6)

where \( \sum_k E_{rUAV_k, tUAV_j} \) is the energy provided by \( tUAV_j \) to all \( rUAVs \). In order to gain an insight into solving the energy source placement problem, we focus on a specific case of two transmitters and two receivers next.

A. The Case of Two \( tUAVs \) and Two \( rUAVs \)

In this section, we consider a scenario where two \( tUAVs \) \((tUAV_1 \) and \( tUAV_2)\) are placed at locations \((a_1, b_1) \) & \((a_2, b_2)\), at the same height level of two \( rUAVs \) \((rUAV_1\) and \( rUAV_2)\). The \( rUAVs \) fly back and forth over straight-line paths of two parallel edges of the square, separated from each other with a distance \( l \) which is the length of the square. Note that the paths of the two \( rUAVs \) are given by \((x_1(t), y_1(t)) = (Vt, 0)\), and \((x_2(t), y_2(t)) = (Vt, l)\) for \( 0 \leq t \leq T \). Total energy received by \( rUAV_1 \) is given by

\[
E_1 \propto \int_0^T dt \frac{dt}{(x_1(t) - a_1)^2 + (y_1(t) - b_1)^2}
\]  
(7)

Replacing the path position values of \( rUAV_1 \), we get

\[
E_1 \propto \int_0^T dt \frac{dt}{(Vt - a_1)^2 + b_1^2}
\]  
(8)

Similarly,

\[
E_2 \propto \int_0^T dt \frac{dt}{(x_2(t) - a_2)^2 + (y_2(t) - b_2)^2}
\]  
(9)

So, our objective is to maximize \( E_1 \) or \( E_2 \), or equivalently

\[
P: \max_{a_1, b_1, a_2, b_2} E_1 + E_2
\]

s.t. \( 0 \leq a_j \leq l \quad j = 1, 2 \)

\( \varepsilon \leq b_j \leq l - \varepsilon \quad j = 1, 2 \)

(10)

Here, \( \varepsilon \in (0, l/2) \) is the width of the region \( R1 \) as in Figure 1 representing the collision area width of each \( rUAV \) within which no \( tUAVs \) are to be placed.

III. OPTIMAL SOLUTION TO PROBLEM P

In this section, we solve the \( tUAV \) placement problem for the specific case of two \( tUAVs \) and two \( rUAVs \) as per the description in the previous section, with the restriction of not placing any \( tUAV \) in the region \( R1 \) of each \( rUAV \). We show that the optimal placement of the \( tUAVs \) are one transmitter on each boundary of the restricted zones of each \( rUAV \), and in the middle of the horizontal axis of the zone boundary which is shown in Figure 2. Our main result is the following Theorem.

**Theorem 1.** The physically unique solution to Problem (P) is

\( (a_1, b_1) = (l/2, \varepsilon), \quad (a_2, b_2) = (l/2, l - \varepsilon) \).

In order to help prove the theorem, we state a series of useful Lemmas that we prove in the Appendix.

**Lemma 1.** Let \( c : [0, l] \to \mathbb{R} \) be a (strictly) concave function. Let \( g : [0, l] \to \mathbb{R} \) \( g(x) = c(x) + c(l - x) \quad \forall x \in [0, l] \).

Then \( g \) is (strictly) maximized at \( x = \frac{l}{2} \).

**Proof.** See Appendix A.

**Lemma 2.** Let \( f : [\varepsilon, l - \varepsilon] \to \mathbb{R} \) be (strictly) convex, where \( \varepsilon \leq l/2 \).

Let \( h : [\varepsilon, l - \varepsilon] \to \mathbb{R} \) \( h(x) = f(x) + f(l - x) \quad \forall x \in [\varepsilon, l - \varepsilon] \).

Then \( h \) is (strictly) maximized at the endpoints (i.e., at \( x = \varepsilon \) and \( x = l - \varepsilon \)).

**Proof.** See Appendix B.

Below we provide the proof of Theorem 1.

**Proof.** We have to maximize total energy received by the \( rUAVs \) from \( tUAV_1 \) and \( tUAV_2 \), which is given by

\[
\text{Total Energy} = (\text{Energy provided by } tUAV_1) + (\text{Energy provided by } tUAV_2).
\]

Energy provided by \( tUAV_j \) is

\[
= \int_0^T dt \frac{dt}{(Vt - a_j)^2 + b_j^2} + \int_0^T dt \frac{dt}{(Vt - a_j)^2 + (l - b_j)^2}
\]

\[= \phi(a_j, b_j) + \phi(a_j, l - b_j), \]

where \( \phi(a_j, b_j) \) and \( \phi(a_j, l - b_j) \) are the energy terms from the two flight paths of \( rUAV_j \) in the region \( R1 \) of \( tUAV_j \). By the properties of \( \phi(a_j, b_j) \) and \( \phi(a_j, l - b_j) \), they are both (strictly) maximized at the endpoints (i.e., at \( a_j \) and \( l - b_j \)).
where \( \phi(a, b) := \int_0^T \frac{dt}{(V't^2 + b^2)}, \quad 0 \leq a \leq l, \quad \varepsilon \leq b \leq l-\varepsilon \)
and so,
\[ E_{\text{total}} \propto \phi(a_1, b_1) + \phi(a_1, l-b_1) + \phi(a_2, b_2) + \phi(a_2, l-b_2). \]

Since total energy received are additions of energy contributed by each tUAV, which come from the same function \( \phi(a, b) + \phi(a, l-b) \) with independent values of \((a, b)\), it suffices to find how to maximize \( \phi(a, b) + \phi(a, l-b) \) for \( 0 \leq a \leq l \) and \( \varepsilon \leq b \leq l-\varepsilon \). Let \( F(a, b) = \phi(a, b) + \phi(a, l-b) \). Note that \( F(a, b) \) is proportional to total energy received by both rUAVs in travelling one side length of the square, from one tUAV located at \( (a, b) \). We want to maximize \( F \) over \((a, b)\).

We prove the following two properties of \( F(a, b) \):

**Property 1.** \( \arg \max_{a \in [0, l]} F(a, b) = \frac{1}{2} \forall b \in [\varepsilon, l - \varepsilon] \)

We have
\[
\phi(a, b) = \int_0^T \frac{dt}{(V't^2 + b^2)} = \frac{1}{Vb} \left( \tan^{-1} \left( \frac{a}{b} \right) + \tan^{-1} \left( \frac{l-a}{b} \right) \right).
\]

Recall, \( F(a, b) = \phi(a, b) + \phi(a, l-b) \). Hence to show \( \arg \max_{a \in [0, l]} F(a, b) = \frac{1}{2} \forall b \in [\varepsilon, l - \varepsilon] \), it suffices to show that
\[
\arg \max_{a \in [0, l]} \phi(a, b) = \frac{1}{2} \forall b \in [\varepsilon, l - \varepsilon]. \quad (11)
\]

Because \( \forall b \in [\varepsilon, l - \varepsilon] \) we have \( \frac{1}{Vb} > 0 \) and \( \tan^{-1} \left( \frac{a}{b} \right) \) is strictly concave in \( a \) for \( a \in [0, l] \). Lemma 1 implies the desired result of Equation 11.

**Property 2.** \( \arg \max_{b \in [\varepsilon, l - \varepsilon]} F(a, b) = \{ \varepsilon, l - \varepsilon \} \forall a \in [0, l] \)

We first show for any constant \( k > 0 \), \( \frac{1}{Vb} \tan^{-1} \left( \frac{k}{b} \right) \) is strictly convex in \( b \) for \( b \in [\varepsilon, l - \varepsilon] \). Observe
\[
\frac{1}{Vb} \tan^{-1} \left( \frac{k}{b} \right) = f(g(b))
\]
where \( f(x) = \frac{k}{x} \tan^{-1} \left( kx \right) \) and \( g(b) = \frac{1}{Vb} \) (for \( b \in [\varepsilon, l - \varepsilon] \)). Since if \( f \) is a convex and strictly increasing function, and \( g \) is a strictly convex function, then \( f(g(b)) \) is strictly convex, it suffices to show:

- \( g \) is strictly convex. It is clear that \( g(b) \) is strictly convex.
- \( f \) is convex, and strictly increasing. We see that \( f \) is strictly increasing because \( f(x) \) is a product of two strictly increasing positive functions (for \( x > 0 \)). To show \( f \) is convex, we observe that its second derivative \( f''(x) = 2k \sqrt{1 + k^2 x^2} > 0 \) for \( k > 0 \).

Since
\[
\phi(a, b) = \frac{1}{Vb} \tan^{-1} \left( \frac{a}{b} \right) + \frac{1}{Vb} \tan^{-1} \left( \frac{l-a}{b} \right)
\]
the above implies that \( \phi(a, b) \) is the sum of two strictly convex functions in \( b \) for fixed \( a \in (0, l) \). For \( a = 0 \) or \( l \), \( \phi(a, b) = \frac{V}{b} \tan^{-1} \left( \frac{b}{l-a} \right) \), which is also a strictly convex function of \( b \). Therefore, for any \( a \in (0, l) \), \( \phi(a, b) \) is strictly convex in \( b \). Since \( F(a, b) = \phi(a, b) + \phi(a, l-b) \), Lemma 2 now implies Property 2.

These properties prove \( F(a, b) \) is maximized precisely at \((l/2, \varepsilon)\) and \((l/2, l-\varepsilon)\). Recall \( F(a, b) \) is proportional to total energy received by both rUAVs in travelling one side length of the square, from one tUAV located at \((a, b)\). Total received energy is maximized if we place the (one) tUAV at either of these two points. As such, if we have two tUAVs, we need to place one tUAV at \((l/2, \varepsilon)\) and the other tUAV at \((l/2, l-\varepsilon)\) for the total received energy to be maximized, as total energy is the sum of energy received by the rUAVs from both of the tUAVs.

Thus, Theorem 1 is proved.

**IV. RAMIFICATIONS OF THE MODEL**

Figure 3 shows the values of \( F(a, b) \), which is proportional to the received energy by two rUAVs for various placements of one tUAV within zone R2. We observe that placing the tUAV anywhere but at either of the two mid-points of the boundaries of R1 and R2 results in lower values of \( F(a, b) \). As such, placing the tUAVs at these optimal locations will result in maximum total received energy by the two rUAVs. If we place an even number of tUAVs by equally distributing these at these two locations, we will achieve an equal amount of received energy in each rUAV (fairness). However, if we have an odd number of tUAVs, there will be an imbalance of energy received individually by the rUAVs, since after distributing the tUAVs equally in these two locations, if we place the leftover tUAV in one of these two locations, received total energy will be maximized, however, this will also mean that the rUAV closer to the last tUAV will receive more energy than the other (unfair). If we place the last tUAV in the middle position from both the rUAVs, they will receive an equal amount of energy but the total received energy will not be maximized since the last tUAV is at a non-optimal location. Thus, we make the following observations:

**Observation 1.** To recharge two rUAVs with an even number of tUAVs, it is possible to place the tUAVs in such a way that maximizes \( E_{\text{total}} \), i.e., \( E_1 + E_2 \), and also achieves fairness, i.e., \( E_1 = E_2 \).

**Observation 2.** To recharge two rUAVs with an odd number of tUAVs, it is possible to achieve either maximized \( E_{\text{total}} \), or fairness \( (E_1 = E_2) \), but not both at the same time.

**Observation 3.** The optimal placement locations are valid for recharging two rUAVs by any number of tUAVs, i.e., not only by two tUAVs, since new tUAVs contribute to the total energy in an additive manner.

**V. NUMERICAL RESULTS**

In order to gain an insight into the average power that the optimal placement of one tUAV can provide to the two
rUAVs compared to the non-optimal placements, we report the numerical results for a similar scenario as used in our model but with one tUAV. The parameter values are listed in Table I. The calculation is based on Equation 1, however, we replaced \( \lambda \) with \( \frac{s}{f} \) where \( c \) is the speed of light, and \( f \) is the frequency.

For the tUAV power transmission frequency, we have used 433 MHz, which belongs to the non-licensed ISM band. This frequency is commonly found to be generated by garage door openers, however, we use this in our numerical experiments for the RF power transmission. Using this frequency in a remote location should not cause interference with other devices. Note that the commercially available RF transmitters that are used for charging low-power devices use higher frequencies, for example, Powercaster transmitters [15] use 915 MHz. Our requirement of charging UAVs demanding higher power, the tUAVs need to transmit power at lower frequencies, since lower frequencies result in higher received power. Moreover, due to the significant reduction of RF power at the receiver compared to the transmitted power, we also need the tUAV to transmit at a higher power, which we have taken to be 1 kW. This can be justified by our assumption that the tUAVs have ground power supply connections, thus it can transmit at this level. Results discussed below assumes full energy conversion efficiency.

Figure 4 shows the average power over the time taken to traverse one side of the square (for the rUAV) in dBm, received by the two rUAVs from one tUAV placed at different \((x, y)\) coordinates within the safe placement zone \(R2\) of the square area. The optimal placement of the tUAV as per our model, which is the middle of either of the boundary of \(R1\) and \(R2\) (the mid point of the horizontal lines of the coloured zone) resulted in the maximum average received power of 25.5121 dBm by the two rUAVs. If the tUAV is placed at the middle of the area, i.e., at \((40, 40)\), the average received power became 16.7425 dBm. Placing the tUAV at the middle of the vertical axes, i.e., at \((0, 40)\), or \((80, 40)\) resulted in the average received power of 15.2233 dBm. As we can see, the optimal placement of the tUAV resulted in a power gain of 8.7696 dBm and 10.2888 dBm over the reported two non-optimal placements.

In order to observe the level of power received by one rUAV from one power source, in Figure 5 we have reported the average power over the time taken to traverse one side of the square when the tUAV is placed at different \((x, y)\) coordinates.

In this case, the average power received by the rUAV is found to be 25.4152 dBm when the tUAV is placed at the optimal location which is at \((40, 5)\) in this case, and 12.2130 dBm when it is located at the middle of the vertical axes. A gain of 13.2022 dBm was achieved in this case by placing the tUAV at the optimal location.

Clearly the optimal placement of the tUAV must be used in our considered scenario for the best outcome of the en-

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**Figure 3.** \( F(a, b) \) within \( R2 \), for \( l = 80m \), \( e = 5m \), \( V = 10m/s \). The two rUAVs are flying over the opposite horizontal axes of the square area.

**Figure 4.** Average power (dBm) received by two rUAVs from one tUAV located at \((a, b)\), over the time interval \([0, T]\). The two rUAVs are flying over the opposite horizontal axes of the square area.

**Figure 5.** Average power (dBm) received by one rUAV from one tUAV located at \((a, b)\), over the time interval \([0, T]\). The tUAV is flying over the lower horizontal axis of the square area.

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**Table I.** Parameter Values

| Parameter | Value       |
|-----------|-------------|
| \( f \)    | 433 MHz     |
| \( c \)    | 299792458 m/s |
| \( P_t \)  | 1 kW        |
| \( G_r, G_t\) | 6 dBi      |
| \( V \)    | 10 m/s      |
| \( l \)    | 80 m        |
| \( e \)    | 5 m         |

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ergy transmission system, however, received level of energy harvested from RF signals is still quite low, and will require multiple dedicated RF sources to power the UAVs [16]. For the fixed-wing drones consuming much less power than the rotary-wing drones since the fixed-wing drones only need energy to move forward but not to keep aloft in air, our system can certainly be considered to extend the operation duration of such drones using multiple tUAVs, all placed at (or closer to) the suggested optimal locations. For the placements of multiple tUAVs, Section IV provided some insights.

VI. CONCLUSION

This paper considered the problem of in-situ recharging aerial base stations without disrupting their regular trajectory. We proposed a solution that leverages wireless power transfer via carefully positioned airborne but stationary energy sources. We presented a mathematical model for solving the optimal placement of these energy sources so as to maximize the total received power at the UAVs while simultaneously achieving fairness. Our numerical results showed that placing the charging nodes at the suggested optimal locations resulted in significant power gain compared to non-optimal placements. In our future work, we will consider an optimization model that takes the number of rUAVs and tUAVs as well as their multidimensional trajectories as tuning parameters to find the optimum solution.

APPENDIX

A. Proof of Lemma 1

Since $c$ is a strictly concave function, therefore $c(l - x)$ is also strictly concave. As such, $g$ being the sum of two strictly concave functions, $g$ is also strictly concave. For $g$ to be (strictly) maximized at $x = l/2$, we have to show that $g(x) < g(l/2) \forall x \in [0, l]$, and $x \neq l/2$. Let $x \in [0, l]$, and $x \neq l/2$. We have

$$g(x) = c(x) + c(l - x)$$

$$= 2\left(\frac{1}{2}c(x) + \frac{1}{2}c(l - x)\right)$$

$$< 2\left(\frac{1}{2}x + \frac{1}{2}(l - x)\right)$$

by strict concavity,

and since $x \neq l - x$

$$= 2\left(\frac{l}{2}\right)$$

$$= g\left(\frac{l}{2}\right).$$

Thus, Lemma 1 is proved.

B. Proof of Lemma 2

Since $f$ is a strictly convex function, therefore $f(l - x)$ is also strictly convex. As such, $h$ being the sum of two strictly convex functions, $h$ is also strictly convex. We have to show that if $\epsilon < x < l - \epsilon$ then $h(x) < h(\epsilon)$ (note $h(\epsilon) = h(l - \epsilon)$). Suppose $\epsilon < x < l - \epsilon$. Then there exists $\theta \in (0, 1)$ such that

$$x = \theta \epsilon + (1 - \theta)(l - \epsilon).$$

So,

$$h(x) = h\left(\theta \epsilon + (1 - \theta)(l - \epsilon)\right)$$

$$< \theta h(\epsilon) + (1 - \theta)h(l - \epsilon)$$

by strict convexity,

and since $\epsilon \neq l - \epsilon$

$$= h(\epsilon).$$

Thus, Lemma 2 is proved.

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