Performance Analysis of UAV-aided RF Energy Transfer

Suraj Suman
Electrical Engineering
Indian Institute of Technology (IIT) Delhi
New Delhi, India
Email: suraj.suman@ee.iitd.ac.in

Swades De
Electrical Engineering
Indian Institute of Technology (IIT) Delhi
New Delhi, India
Email: swadesd@ee.iitd.ac.in

***Abstract*—In this paper, the performance analysis of unmanned aerial vehicle (UAV)-aided RF energy transfer (RFET) in presence of hovering inaccuracy is investigated. Hovering inaccuracy of UAV refers to the error during the execution of mission due to imperfect hovering. This leads to change in distance and elevation angle between the transmitter (mounted on UAV) and the receiver (sensor node deployed on ground). A closed-form expression on received power is obtained for a generalized radiation pattern of transmitter antenna mounted on UAV. The simulation results reveal that, compared to the ideal scenario, power received at the sensor node reduces significantly in presence of hovering inaccuracy.**

***Index Terms*—Unmanned aerial vehicle, internet of things, radio frequency energy transfer, wireless sensor network**

I. Introduction

Recently, unmanned aerial vehicle (UAV) has gained significant attention due to its usage in various applications, such as logistics, health-care, agriculture, surveillance, data acquisition, and cellular infrastructure [1]. The choice of UAV lies in its several properties, like excellent maneuvering capability, remote control access, low cost, lightweight, and programming flexibility. UAV can easily access hard-to-reach locations where human intervention is not feasible. Also, UAV-aided systems can be deployed within short time span to facilitate on-demand service.

In this work, UAV is used for energy replenishment of internet of things (IoT) devices to ensure their perpetual operation, which is of utmost importance for deployments in inaccessible. Finite battery capacity of IoT devices does not ensure its perpetual operation in long run, as they consume significant energy in sensing, processing, and communication [2]. Towards this, UAV-aided radio frequency energy transfer (RFET) is found to be a promising alternative, where the transmitter mounted on UAV arrives to IoT device and charge through RFET.

1) Related Work: Recently, a few works related to UAV-aided RFET have been reported in [3]–[6]. The notion of RFET zone is defined in [3]; the sensor nodes lying inside the RFET zone are able to harvest energy. Accordingly, the charging times of the field sensor nodes are estimated. In [4], different charging mechanisms are presented to increase the number of healthy sensor nodes in the network. The trajectory of UAV is planned in [5] aiming to maximize the energy transferred to the ground nodes. The solution presented in [5] is not global optimal, which is improved in [6] for one-dimensional deployment scenario.

2) Motivation and Contributions: In view of the prior art [3]–[6], this work addresses the lacuna of performance studies of UAV-aided RFET in presence of hovering inaccuracy. Hovering inaccuracy of UAV refers to the error due to imperfect hovering during the execution of mission. Hovering inaccuracy may not affect the performance of UAV-aided cellular architecture due to much higher sensitivity margins (on the order of -90 dBm) in information transfer and higher operational altitude (up to a few hundred meters) [7]. On the other hand, UAV-aided RFET is realized at a much lower altitude (up to a few meters), and the receiver power threshold in energy transfer (-10 dBm) is very high compared to that in information transfer (as low as -100 dBm).

Therefore, it is important to incorporate the hovering inaccuracy while analyzing UAV-aided RFET system, which is taken into consideration in this work. To this end, performance deviation in presence of hovering inaccuracy compared to ideal one, i.e., without hovering inaccuracy, is analyzed. The simulation results indicate notable performance degradation and hence, its inclusion is essential in system design.

II. Hovering Inaccuracy of UAV

In UAV-aided RFET, the location of sensor node to be charged and the hovering altitude are fetched in the UAV. The UAV arrives at a given sensor's location and facilitates RFET. It is desired that, UAV hovers just above the given sensor node at the mentioned altitude and remains stationary while charging a sensor node in order to maximize the transferred energy. However, this does not happen due to positioning error (termed as localization mismatch (*LM*)), and angular displacement that arises from rotation of UAV (termed as orientation mismatch (*OM*)). Due to *LM*, UAV hovers above with a slightly different location of ground projection (O_u Fig. 1) other than the desired one (O_s Fig. 1) . This leads to change in distance between transmitter and receiver along with elevation angle. In addition to this, UAV undergoes rotation at this point due to *OM*. Due to this, the center of beam spot of the transmitter antenna mounted on UAV is displaced, and the antenna's beam does not point towards the receiver antenna.

Thus, the distance as well as elevation angle between transmitter and receiver change due to hovering inaccuracy of UAV. In [8], these mismatches were characterized using extensive field experiments using a rotatory-wing UAV. The detailed discussion on hovering inaccuracy is not included here due to lack of space, and can be found in [8]. In [8], the performance in terms of received power has not been analyzed, which is done here using the hovering inaccuracy measurement made in [8]. In addition, in this work, a generalized antenna model is taken into consideration for analysis.

Let d and Θ respectively denote the distance and elevation angle, between transmitter and receiver in presence of hovering inaccuracy. This distance is given as:

$$d(h) = \sqrt{u_1 h^2 + u_2 h + u_3} \tag{1}$$

where $u_1 = 1.015, u_2 = -0.1193, u_3 = 0.2588$.

The elevation angle is given as:

$$\Theta \sim \mathcal{N}\big(\mu_M(h), \sigma_M^2(h)\big) \tag{2}$$

where $\mathcal{N}$ denotes the Gaussian random variable. $\mu_M(h) = a_1 h^3 + a_2 h^2 + a_3 h + a_4$ with a_1=$-0.01371, a_2$=$0.1518, a_3$=$-0.5653, a_4$=0.7925, and $\sigma_M(h) = b_1 h^3 + b_2 h^2 + b_3 h + b_4$ with b_1 =$-0.000584, b_2$=$0.00523, b_3$=$-0.0209, b_4$ =0.06973.

III. RFET Performance Analysis

In real life deployment scenario, UAV visits each sensor node and transfers energy wirelessly to each of them one by one due to limited RFET range and the associated ground coverage area. During this RFET process, the ground-deployed sensor nodes experience the hovering inaccuracy of UAV. Here, the performance is analyzed for a single sensor node; the other field sensor nodes will also experience the effects of UAV hovering inaccuracy in the same way during their respective turns for charging.

The power received at a sensor node when UAV hovers at an altitude h is given as:

$$\begin{aligned} P^{rx}(h,n,\theta) &= P_{tx} \cdot G_{rx} \cdot g(n,\theta) \cdot \left(\frac{\lambda}{4\pi d_{tx-rx}}\right)^2 \\ &= P_{tx} \cdot G_0 \cdot g(n,\theta) \cdot \left(\frac{1}{d_{tx-rx}}\right)^2 \end{aligned} \tag{3}$$

where P_{tx} is the power transmitted by transmitter mounted on UAV, G_{rx} is the receiver antenna gain, d_{tx-rx} is the distance between transmitter and receiver, and λ is the wavelength of transmitted RF wave with $G_0 = G_{rx} \cdot \left(\frac{\lambda}{4\pi}\right)^2$.

$g(n,\theta)$ is the radiation pattern of transmitter antenna mounted on UAV, and is given as [9]:

$$g(n,\theta) = 2 \cdot (n+1) \cdot \cos^n(\theta) \tag{4}$$

where n is the antenna exponent and θ is the elevation angle between transmitter and receiver. The beam width (θ_{HPBW}) of this antenna is given as:

$$\theta_{HPBW} = \approx \sqrt{4\pi/2(n+1)}. \tag{5}$$

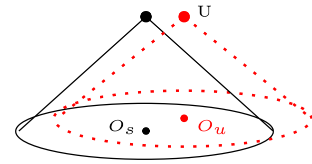

Fig. 1. Depiction of hovering inaccuracy of UAV-aided RFET.

We restrict the analysis to the integer set of values of n due to the ease of analytical tractability. Thus, $\cos^n\theta$ can be written in generalized form as follows:

$$\cos^n\theta = \begin{cases} \frac{1}{2^{n-1}}\Big[\sum\limits_{r=0}^{\frac{n}{2}-1}\binom{n}{r}\cos((n-2r)\theta)\Big] + \\ \frac{1}{2^n}\binom{n}{n/2}, & \text{if } n = \text{even} \\ \frac{1}{2^{n-1}}\Big[\sum\limits_{r=0}^{\frac{n-1}{2}}\binom{n}{r}\cos((n-2r)\theta)\Big], & \text{if } n = \text{odd}. \end{cases} \tag{6}$$

One can observe from (3) that, the received power depends upon the distance (d_{tx-rx}) and elevation angle (θ). Here, the received power with and without hovering inaccuracy have been studied to observe its impact on performance.

1) No Hovering Inaccuracy (Ideal): Here, UAV hovers just above the sensor node and does not undergo rotation; there is no hovering inaccuracy. The received power is given as:

$$\begin{aligned} P_1(h,n) &= P_{tx} \cdot G_0 \cdot g(n,\theta) \cdot \left(\frac{1}{d_{tx-rx}}\right)^2 \Bigg|_{\theta=0, d_{tx-rx}=h} \\ &= P_{tx} \cdot G_0 \cdot 2(n+1) \cdot \frac{1}{h^2}. \end{aligned} \tag{7}$$

Here, the center of beam spot of transmitter antenna will point towards the sensor node and the distance between transmitter and receiver is same as hovering altitude. Thus, $\theta = 0$ and $d_{tx-rx} = h$.

2) In Presence of Hovering Inaccuracy: Here, UAV does not hover at the desired location (i.e., not just above the sensor node) and also undergoes rotation at this location. Thus, the sensor node experiences hovering inaccuracy in its charging process, which leads to change in elevation angle as well as alteration in distance between transmitter and receiver. Accordingly, the received power is given as:

$$P_2^{rx}(h,n,\theta) = P_{tx} \cdot G_0 \cdot g(n,\theta) \cdot \left(\frac{1}{d_{tx-rx}}\right)^2 \Bigg|_{\theta=\Theta,\ d_{tx-rx}=d(h)}.$$

The distance between transmitter and receiver is a function of height (cf. (1)), whereas the elevation angle follows Gaussian distribution (cf. (2)), mean and variation of which vary along altitude. Thus, in expected sense, it can be written as:

$$\begin{aligned} P_2(h,n) &= \mathbb{E}\big[P_2^{rx}(h,n,\theta)\big] \\ &= P_{tx} \cdot G_0 \cdot \left(\frac{1}{d(h)}\right)^2 \int_{-\infty}^{\infty} g(n,\theta) \cdot f_\Theta(\theta) \cdot d\theta. \end{aligned} \tag{8}$$

Remark 1: If X is a Gaussian random variable with mean μ and standard deviation σ, then its characteristic function $\Psi_X(\tau)$ can be given as: $\Psi_X(\tau) = \mathbb{E}[\exp(i\tau X)] = \exp(i\tau\mu - \frac{1}{2}\sigma^2\tau^2)$, where i denotes the imaginary number. Using this, it can be written as:

$$\mathbb{E}[\cos(\tau X)] = \cos(\mu\tau) \cdot \exp\left(-\frac{1}{2}\sigma^2\tau^2\right). \quad (9)$$

Using (9), (4), and (6); (8) can be written as:

$$P_2(h,n) = P_{tx} \cdot G_0 \cdot \frac{1}{d^2(h)} \cdot \begin{cases} F_1(h,n), & \text{if } n = \text{even} \\ F_2(h,n), & \text{if } n = \text{odd}. \end{cases} \quad (10)$$

where $F_1(h,n) = \frac{1}{2^{n-1}}\Big[\sum_{r=0}^{\frac{n}{2}-1}\binom{n}{r}\cos((n-2r)\mu_M)\cdot \exp\big(-\frac{1}{2}\sigma_M^2(n-2r)^2\big)\Big] + \frac{1}{2^n}\binom{n}{n/2}$

and $F_2(h,n) = \frac{1}{2^{n-1}}\Big[\sum_{r=0}^{\frac{n-1}{2}}\binom{n}{r}\cos((n-2r)\mu_M)\cdot \exp\big(-\frac{1}{2}\sigma_M^2(n-2r)^2\big)\Big]$.

IV. Results and Discussions

In this section, analysis done in the previous sections is numerically evaluated to observe the impact of hovering inaccuracy on the performance. The numerical values of different parameters considered here are as follows: $P_{tx} = 1$ W, $G_r = 2.1$, $\lambda = 0.32786$ cm (for frequency of 0.915 GHz).

The variation of received power in presence of hovering inaccuracy obtained from analysis (cf. (10)) and simulation against antenna exponent are shown in Fig. 2. The values obtained from simulation overlap with the analytical ones, which validates the closed-form expression. It may be noted that, the received power first increases then decreases. At lower value of n, the beam width of antenna is large (cf. (5)) with lesser gain (cf. (4)) and vice-versa. The sensor node cannot be covered for narrow beam width, due to finite coverage area of the beam on the ground. Therefore, the received power reduces significantly for higher n.

The deviation in received power, i.e., difference of power received without hovering inaccuracy (ideal case, cf. (7)) and with hovering inaccuracy (cf. (10)) against antenna exponent is shown in Fig. 3. One can observe that, the difference is significant and can not be ignored.

Remark 2: Hovering inaccuracy affects the performance significantly and its inclusion in UAV-aided system design is essential to avoid under-provisioning of resources.

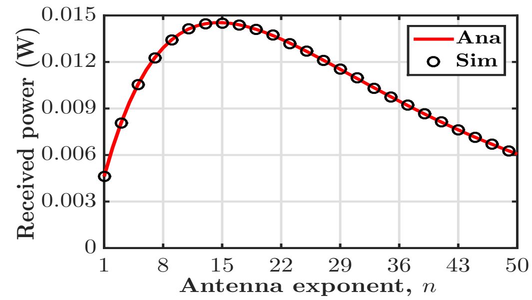

Fig. 2. Variation of received power against antenna exponent for $h = 1$ m.

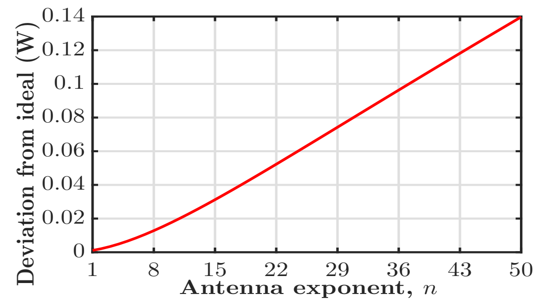

Fig. 3. Deviation in received power against antenna exponent for $h = 1$ m.

V. Concluding Remarks and Future Works

Hovering inaccuracy of UAV comprises of localization mismatch and orientation mismatch. In this work, the performance of UAV-aided RFET in presence of hovering inaccuracy has been analyzed. The closed-form expression for received power is obtained and validated through simulation. Compared to the ideal scenario, significant degradation in the performance is observed, which suggests the critical need for inclusion of hovering inaccuracy in system design.

Future work involves the optimal selection of system parameters, namely, transmit power, antenna exponent, and hovering altitude. Design of charging mechanism in presence of hovering inaccuracy is another important direction.

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