Energy-Optimized Path Planning for Moving Aerial Base Stations: A Non User-Oriented Framework

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Abstract— Utilization of moving aerial base stations (ABSs) has attracted a lot of attention in recent years. Accordingly, path planning to optimize a given utility function, and in particular, mechanical energy, has been the subject of many investigations. Most of the works in this area are user-oriented, i.e., the path planning is implemented for a given user location. In this paper, we propose a non user-oriented path planning scheme, based on a family of spiral shaped curves, that is efficient in terms of energy and can provide a fairly uniform coverage for all users within a cell. We show that the proposed spiral curves will result in considerable amount of saving in mechanical power consumption compared to the radial paths already proposed in the literature. We also compare the proposed framework to an existing user-oriented path planning scheme, proposed by R. Zhang et al., in terms of coverage and energy-efficiency.

Index Terms: Path planning, UAV, ABS, energy efficiency, coverage, user-oriented.

I. Introduction

Unmanned aerial vehicles (UAV) have attracted much attention in recent years. An important application of UAVs is their deployment as aerial base stations (ABS) which are used to provide communication coverage over a given region [?], [?]. In many cases, ABSs are deployed statically [?].Although managing a static ABS network may be more straightforward, there have been many scenarios in which moving ABSs are of much interest. A major advantage of moving ABSs over static ones is their smaller power and energy consumption. Given the limitations in battery technology, larger power consumption is directly translated into smaller flying time before the batteries are charged again [?].

While in static ABSs, the major challenge is optimal positioning [?], for moving ABSs, such a challenge is elevated to the problem of optimal path planning where different utility functions such as throughput, consumed power, or the traveling distance are optimized subject to different constraints [?], [?], [?], [?]. A number of works have considered the problem of path planning with respect to consumed power. It is important to note that power/energy consumption in an ABS is composed of 2 distinct parts: RF power used for data transmission and mechanical power used for hovering and/or moving in the air [?]. Many of the works which focus on path planning for energy minimization focus on minimizing the RF power and not the mechanical power [?], [?]. In practice, however, mechanical power is the dominant portion of the consumed power and in many cases, the RF power can be ignored with respect to the mechanical power [?]. This will also be the case in this paper.

One of the major challenges in mechanical energy optimization is the lack of a closed-form formulation that gives the consumed energy based on the traveled path as well as speed, and acceleration of the ABS for both fixed-wing and quad-copter UAVs. As such, most of path planning works were limited to direct line trajectories with fixed or sometimes slowly changing speeds (one-dimensional path planning). Please note that even if the magnitude of the UAV speed is fixed, any change of direction results in non-zero acceleration and thus, one needs to include the acceleration vector in energy calculations. In their seminal work [?], Zhang et al. provided a comprehensive closed-form formulation for the energy consumption of fixed-wing UAVs that included both velocity and acceleration vectors.

The work of [?], paved the way for other 2-dimensional path planning frameworks [?], [?], [?], [?], [?] for fixed wing UAVs and ABSs. In these works, instead of focusing on mechanical power optimization alone, the aim is to maximize energy efficiency (EE) which is defined as the user achievable rate divided by the consumed mechanical energy. The reason is that in many cases, the path that provides the lowest mechanical power, is far away from the user which results in low rates. On the other hand, the path that provides the highest rate usually requires high power (in the extreme case, the ABS has to hover above the user which requires infinite power for fixed-wing ABSs). Using the EE concept, one can provide a balance between power and rate.

Since EE is defined with respect to a given user, a major draw-back of the above-mentioned works is that they are user-oriented, i.e., the path planning is implemented for a given user location. In practice and to be fair to all users, one has to devise a path for the ABS to provide an acceptable service level to all users within a cell. This draw-back exists in most of the proposed path planing frameworks, not necessarily those focusing on EE.

The work of [?] provides a non user-oriented framework by replacing the user rate or EE with the concept of coverage for a typical user. Through a stochastic geometry approach, [?] proposes a family of trajectories and speed profiles such that if according to which the ABSs move, a pretty uniform coverage is guaranteed for any arbitrary user in any location of the cell. A major draw-back of [?] is that no analysis was provided to assess the proposed

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paths in terms of mechanical energy consumption. As such, only trivial and/or shortest curves of the proposed family of curves were utilized [?], e.g., the UAV's simply traveled on the radius of the cell, as there was no incentive to use other more complicated curves of the proposed family, e.g, spiral curves.

Our aim in this paper is to propose a non user-oriented path planning scheme that is efficient in terms of energy. At the same time, we are addressing the concerns that led to using EE as the function to be optimized instead of energy, through a different concept which is based on service coverage. To do so, we take advantage of the framework in [?] to free the planned paths from serving a specific user location by assuming that the ABSs are constrained to travel on certain family of curves called spiral trajectories[1]. This will ensure that all locations on the cell receive a more uniform service coverage. Then, we come up with the best curve out of this family with the most efficient energy consumption. The optimal path now only depends on the UAV specs and not a specific user location.

By focusing on the results of [?], we compare the proposed framework with the user-oriented one in [?] in terms of coverage and EE for any location on the cell. As it is predictable, the coverage and EE are provided more fairly in our case compared to the framework of [?] which is optimized to give the best EE (and as a result coverage) to the users around the cell origin. The difference is specially significant when users at the cell edge are considered.

It is important to note that the proposed scheme can simply be extended to any UAV and not only ABS trajectory design. The reason we are highlighting the ABS application is because the concepts of coverage and energy efficiency are more applicable to telecom. applications. However, we could consider a scenario where our aim is to monitor an area. In this case, we can still use these concept.

This paper is organized as follows: Section II introduces the system model and as well as some preliminary formulations. In Section III, we propose the optimization problem and its solution. Section IV presents the numerical results and Section V concludes the paper.

II. PRELIMINARIES AND SYSTEM MODEL

A. Spiral Trajectories

The family of curves below represent a spiral family trajectory:

$$Q(s) = \left[\rho^s kcos(\zeta s), \rho^s ksin(\zeta s)\right], \qquad s \in [0,1], \tag{1}$$

where ρ is the radius of cell and k and ζ are constants that determine the shape of the curve. In particular, by setting $\zeta = 0$, $k = 1$, we come up with a set of curves, each are a radius of the cell. This is referred to as the radial trajectory, which is the most intuitive path of this family.

Each ABS starts flying from the cell center toward the cell edge over $Q(s)$ in τ seconds. When it reaches the cell edge, it returns to the origin on the same path and continues on curve $-Q(s)$ to reach the other side of the edge before it returns to the origin and this action repeats continuously.

The instantaneous locations of ABSs along the flying on the spiral trajectory can be obtained by setting $s = \sqrt[2k]{\frac{t}{\tau}}$ in (1):

$$Q(t) = (x(t), y(t)) = \left[\rho\sqrt{\frac{t}{\tau}}\cos(\zeta \sqrt[2k]{\frac{t}{\tau}}), \rho\sqrt{\frac{t}{\tau}}\sin(\zeta \sqrt[2k]{\frac{t}{\tau}})\right]. \tag{2}$$

The velocity and acceleration vectors of the ABSs are defined respectively as follows:

$$V(t) = (x'(t), y'(t)), \tag{3}$$

$$A(t) = (x''(t), y''(t)). \tag{4}$$

Note that in Radial trajectory, when going from center to the cell edge or vice versa, there is no change of direction, and acceleration is non-zero only when there is a change in the absolute value of velocity, $||V(t)||$. However, in general, even if $||V(t)||$ is fixed, $A(t)$ might be non-zero as moving on a 2-dimensional spiral curve needs constant change of direction.

B. Energy Consumption Model

For a fixed-wing UAV moving on a 2-dimensional plane, the energy consumption depends on instantaneous velocity and acceleration as well as the weight. Increasing the velocity in general will result in less power consumption as it generates more lift force in fixed-wing UAVs. On the other hand, higher velocity will increase aerodynamic drag force, which may result in overall increase of power consumption.

In [?], a very useful formulation has been proposed that gives the consumed energy for a fixed-wing UAV that flies for τ seconds:

$$E = \tag{5}$$

$$\int_0^\tau c_1\|V(t)\|^3 + \frac{c_2}{\|V(t)\|}\left(1 + \frac{\|A(t)\|^2 - \frac{(A^T(t).V(t))^2}{\|V(t)\|^2}}{g^2}\right)dt$$

$$+ \frac{1}{2}m\left(\|V(\tau)\|^2 - \|V(0)\|^2\right), \tag{6}$$

where $V(t)$ and $A(t)$ denote the instantaneous velocity and acceleration vectors respectively, and c_1 and c_2 are defined as

$$c_1 \triangleq \frac{1}{2}\rho_a C_{D_0} S\ ,\ c_2 \triangleq \frac{2W^2}{(\pi e_0 \mathcal{A}_\mathcal{R})\rho_a S}. \tag{7}$$

In the above equations, $W = mg$ is the force of gravity, with m denoting the UAVs mass including all its payload, and g is the gravitational acceleration. Moreover, ρ_a is the

[1]There are other trajectories in [?] to serve our purpose. However, the closed-form formulation for them were not as straight-forward as the spiral curves, making the spiral curve more handy to be used.

air density in $\mathrm{kg/m^3}$, C_{D_0} is the zero-lift drag coefficient, S is a reference area (e.g., the wing area), e_0 is the Oswald efficiency, and $\mathcal{A}_{\mathcal{R}}$ is the aspect ratio of the wing.

In (6), we can divide E by τ to obtain the average consumed mechanical power P. Moreover, ignoring the part outside the integral (which numerically makes sense in many cases), the integrand is in fact the instantaneous power. This can be used to obtain the peak power, which is an important factor to decide if the UAV at hand can in fact serve to our purpose.

C. Energy Efficiency and Coverage

For a user at an arbitrary location in the cell, the coverage probability P_c is defined as the probability that the received signal to noise ratio (SNR) is above a certain threshold γ:

$$P_c = P(SNR_{Rx} > \gamma).$$

Threshold γ depends on the system specifications and in particular, the receiver ability to recover the data at smaller SNR values. For a given γ, a user (or a location in the cell) is called covered if P_c is greater than 0.

For an ABS consuming mechanical power of P and transmitting RF power of P_T at bandwidth of W (where P_T is negligible compared to P), the EE with respect to a user located at (X_u, Y_u) is defined as

$$EE = \frac{1}{E} \times \int_0^\tau B \log_2 \left(1 + \frac{\gamma_0}{H^2 + ((x(t) - X_u)^2 + (y(t) - Y_u)^2)} \right) dt, \tag{8}$$

where H is the flying height and $\gamma_0 = \beta_0 P_T / \sigma^2$ is the reference received signal-to-noise ratio (SNR) in which β_0 denotes the channel power at the reference distance $d_0 = 1$m and σ^2 is the white Gaussian noise power at the receiver.

As already mentioned in Section I and can be readily seen in above formulation, EE can only be defined with respect to a given user at coordinates (X_u, Y_u), making the optimization scheme user-oriented. As such, we can not focus on EE if we want a non user-oriented setting, where we want to provide an almost uniform quality of service to all users within the cell. However, we had to define EE in this section so that it can be used later to compare our result in terms of EE, as almost all existing literature optimize EE.

III. The Path Planning Problem

For a given τ, we have to solve the following path planning problem:

$$\min_{Q(t)} E, \tag{9}$$

$$s.t.: \; Q(t) = \left(\rho \sqrt{\frac{t}{\tau}} \cos(\zeta \sqrt[2k]{\frac{t}{\tau}}), \rho \sqrt{\frac{t}{\tau}} \sin(\zeta \sqrt[2k]{\frac{t}{\tau}}) \right) \tag{10}$$

By replacing $Q(t)$ in (9) by (10), the optimization problem is simplified to

$$\min_{\tau, k, \zeta} E(\tau, k, \zeta). \tag{11}$$

Let

$$P(t, k, \zeta) = c_1 \|V(t)\|^3 + \frac{c_2}{\|V(t)\|} \left(1 + \frac{\|A(t)\|^2 - \frac{(A^T(t).V(t))^2}{\|V(t)\|^2}}{g^2} \right), \tag{12}$$

$$Z(\tau, k, \zeta) = \frac{1}{2} m \left(\|V(\tau)\|^2 - \|V(0)\|^2 \right). \tag{13}$$

Then we can rewrite the problem as

$$\min_{\tau, k, \zeta} \int_0^\tau P(t, k, \zeta) dt + Z(\tau, k, \zeta). \tag{14}$$

By replacing the first and second derivative of the curve $Q(t)$ in the above equations, we obtain the corresponding closed-form formulation[2] and by setting the partial derivatives to 0, we can obtain the extremum points for τ, k and ζ numerically. For the case of Radial trajectory, we set $k = 1$ and $\zeta = 0$ and only optimize τ.

Please note that since the optimal values only depend on the ABS specs as well as τ and ρ, and not the user location, they can be obtained off-line which is a major advantage compared to the user-oriented path planning scenarios.

IV. Simulation Results

A. Performance Comparison: Radial vs Optimized Spiral Path

For simulations, we consider 3 types of UAVs to act as ABS. A light one with weight $m_1 = 4.5$ kg and a heavier one with $m_2 = 63.5$ kg [?], and a third one with $m_3 = 10$ kg from [?]. We set the values of c_1 and c_2 according to [?] and [?]. We consider a cell of radius $\rho = 4000$m. For simulations, we assume that the ABS path does not start at the center, but in the vicinity of $\rho/10$ from the cell center. This is because in the proposed model in [?], the speed values close to center are too large which may result in impractical peak powers. That may indeed slightly reduce the coverage around the cell center which is unavoidable. Tables I and II show a summary of the simulation parameters used in this subsection and the next one.

In Table III, we have reported the optimized values for τ, ζ and k for the 3 cases. For each weight, we considered the optimal path scenario as well as the radial trajectory of [?] and reported the average consumed power, the weight-normalized average consumed power and the weight-normalized peak power. As can be seen, the optimal spiral paths improve the power consumption around 2 times compared to the radial path proposed in [?]. This translates into 2 times larger flying time before a battery recharge is necessary. In Fig. 1, we have plotted the optimal paths for the 3 ABSs. As can be seen, the paths are far away from the radial path and are obviously longer in length, yet, they require considerably less power.

[2] The obtained equation was too complex and lengthy to be reported here.

ρ	B	β_0	N_0	P_T	γ_0
4000 m	1 MHz	-50 dB	-170(dBm/Hz)	10 dBm	70 dB

TABLE I: Simulation parameters.

$m = 4.5$ Kg		$m = 63.5$ Kg		$m = 10$ Kg	
c_1	c_2	c_1	c_2	c_1	c_2
0.0041	159.0572	0.0274	19328	0.00092	2250

TABLE II: UAV's parameters

B. Performance Comparison: User-Oriented Path vs Non User-Oriented Path

In this part, we consider an ABS with the same specs as that of [?]. As in [?], we assume that the ABS is transmitting with $P_T = 10$ dBm at bandwidth of 1 MHz. We assume the power spectrum density of the noise at the receiver is -170dBm/Hz and the reference channel power is $\beta_0 = -50$dB.

For comparison, we consider a spiral path, optimized solely based on the ABS specs on one hand (see the last row of Table III and green curve in Fig. 1), and the optimized circular path in [?] on the other hand, where the ABS turns around the cell center whose flying radius R and speed V are optimized to provide the best EE for a user in the center of the cell ($R = 158$m and $V = 25.67$ m/s). It is interesting to see that the average power consumption for both cases are pretty close: about 98.3 watts for the non user-oriented case and 119 watts for the user-oriented case.

Fig. 2 shows the fraction of covered points within the cell for both paths for different received SNR threshold values γ. As can be seen, for almost all thresholds, the non user-oriented path provides a full cell coverage while this is not the case for the user-oriented path. For example, for threshold value of 1.4dB, half of the cell area never gets any coverage.

To get a better insight on coverage, we keep the same threshold for γ as above (1.4dB) and in Fig. 3 we have provided the coverage heat map for the two cases.

These figures coincide with Fig. 2: for the user-oriented curve, a noticeable portion of the cell (half of the cell area in this case) never gets any coverage (dark blue color) while it gives coverage with probability close to 1 to users faraway from the cell edge; on the other hand, the non user-oriented curve provides a pretty uniform coverage for the whole cell (green to light blue colors) but the coverage probability is not as high as the one for the user-oriented curve. Both scenarios can have their relevant applications. The probability of coverage close to 1 is important for cell phone users, indeed, if we can afford the zero coverage probability for a major part of the cell. For applications such as sensor data collection or search and rescue missions, having a non-zero coverage, even though smaller than 1, is far more important. Needless to say that the coverage probability can be improved for the non user-orientated case by using more than 1 ABS moving on similar but rotated spiral curves.

To assess the EE for both scenarios, we again compare

m (Kg)	Curve	$\overline{P}$(Watts)	$\frac{\overline{P}}{m}$ (Watts/Kg)	$\frac{P_{peak}}{m}$ (Watts/Kg)	ζ	k	$T(s)$
63.5	Radial	2531.3	39.8	136.9	0	1	294
63.5	Spiral	1159.4	18.2	18.6	6.033π	0.933	1791
4.5	Radial	37.9	8.4	47.9	0	1	[illegible]
4.5	Spiral	19.8	4.4	4.9	2.81π	0.885	1801
10	Radial	301.5	30.1	33.8	0	1	301
10	Spiral	98.3	9.8	10.8	4.94π	0.79	1150

TABLE III: Average and normalized consumed power for radial and optimal spiral paths.

Fig. 1: The optimal spiral path for ABSs with different specs.

Fig. 2: Fraction of cell coverage area: user-oriented vs non user-oriented.

Fig. 3: (a) Coverage probability heat map for the user-oriented path, and (b) coverage probability heat map for the non user-oriented path.

the heat map for both paths. We use the very same assumptions as above and obtain EE for any point within the cell. As can be seen in Fig. 4, the EE is more uniform in the non user-oriented case. Indeed, the values of EE corresponding to the user-oriented case of [?] around the center are higher than our case. In particular, EE is reported to be 68 kbits/joule at the center for the user-oriented path while our curve can provide an EE as large as 15.5 kbits/joule in the center. On the other hand, while the EE at any point on the cell edge is about 5.9 kbits/joule for the user-oriented case, these values range from about 8.4 to 9.9 kbits/joule for our case, which shows about 40 to 70 percent improvement.

Fig. 4: (a) EE heat map for the user-oriented path, and (b) EE heat map for the non user-oriented path.

V. Conclusion

In this paper, we proposed a non user-oriented framework which can provide a fairly uniform coverage over the cell while it is also efficient in terms of power consumption. This efficiency in power is 2 compared to the intuitive radial trajectory proposed in [?]. The existing literature on ABS path planning, including the work of [?], try to optimize the path with respect to a given user while the proposed framework in this paper does not depend on the specific user location. Compared to [?], our work is superior in terms of guaranteeing the coverage for all parts of the cell for any reasonable SNR threshold. As far as EE is concerned, the work of [?] is superior around the cell center while our work provides a pretty robust EE across the cell including the cell edge.