A landing spot approach for enhancing the performance of UAV-aided wireless networks

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***Abstract*—UAV-aided wireless networks allow ultra-flexible deployment of wireless resources when and where it matters. Despite their promise, such networks are severely hindered by the limited on-board battery budget. This paper introduces a novel yet simple approach to circumvent this problem, based on the concept of so-called *landing spots* (LSs). LSs allow to trade-off throughput for rest time. We also derive a dynamic program which optimally exploits any given LS setup for UAV trajectory design. Our study shows that LSs dramatically enhance the lifetime of flying radio access networks while only moderately affecting the throughput performance. In IoT data-harvesting settings, LSs substantially increase the total collected data payload for a given battery budget.**

I. Introduction

In traditional infrastructure based wireless networks, once the network is deployed the access points (APs) or base stations (BSs) are generally static. Even though the number of APs required and their locations are optimized in the network design phase, these networks can not cope with unplanned events such as failure of some APs (in a disaster hit scenario), or sudden temporal and geographical increase in traffic demands (in a crowded event scenario). Such unplanned events result in poor quality of service (QoS) to the users or even can cause a network failure. One way to alleviate this problem is the usage of unmanned aerial vehicles (UAVs) as flying APs or BSs. Thanks to recent progress in terms of performance, cost and weight, etc. UAVs carrying APs appears to be a promising technology for future wireless communication networks. Use of UAVs in a wireless network provides an additional degree of freedom in terms of mobility in the system design. The advantages include, dynamic network deployment, fast response to geographically varying traffic demands, the ability to favorably impact fading statistics by increasing line of sight probability, etc.

Interesting new problems arise from the study of flying APs. Among these, two important ones are static positioning and trajectory planning problems. In the static positioning problem, the locations of UAVs are determined in order to maximize the throughput or coverage to a population of ground users in a wireless network. Static positioning problems are studied in the context of UAV relaying [1], [2] and UAV BSs [3]–[6]. Note that the static positioning problem often ignores the potential service which can be offered to users while in-flight towards the chosen location or while returning from it to the UAV base. Trajectory planning problem arises when communication services to the ground users can be enabled at any point on the UAV's trajectory. Trajectory planning problems are studied in the context of relaying [7], information collection/dissemination [8]–[11]. See [12] for an extensive overview.

Despite the theoretical promise, the most noted practical limitation to the deployment of commercial UAV-aided networks appears to be the burden of carrying a small BS and a battery that is big enough to satisfy the power requirements of the BS and transmit for a meaningful mission duration. If uninterrupted service needs to be provided by such networks, this would require periodic replacement of the UAVs whose battery is about to exhaust leading to highly complex and costly fleet operation and management functions or restricting the UAVs to unpractical short mission durations (few tens of minutes by today's technology).

In this work, we capitalize on our early reported experimentation work with flying BSs [13] where we have observed that the power consumption due to flying is significantly higher than the power consumption of the on-board BS. This confirms the existence of an interesting trade-off between the throughput gain that stems from operating the UAV from an optimized location versus the power loss related to having to fly there. In other words, by saving flying energy we can save a lot in terms of network lifetime or the need of frequent replacement of UAVs in a wireless network. In this paper, we introduce a simple solution to this problem by exploiting the concept of UAV landing spots (LSs). A LS is a registered small piece of real estate (typically selected sets of authorized roof tops or dedicated pods) where a UAV is allowed to rest (akin to resting birds) while not interrupting transmission. Note that LSs may or may not be equipped with electric charging pods (here we assume they are not). Surprisingly, the concept of LSs for UAV-aided wireless network has never been studied before to the best of our knowledge.

In this paper, we investigate the role and benefits of LSs for the performance of UAV-aided networks. As application example, we consider an IoT-driven data collection scenario and we tackle the problem of UAV trajectory design under a typical energy consumption model and a finite battery budget. In that we generalize our previous path planning work which did not consider the use of LSs [10]. The gains related to

This work is supported by the European Research Council under the European Union's Horizon 2020 research and innovation program (Agreement no. 670896).

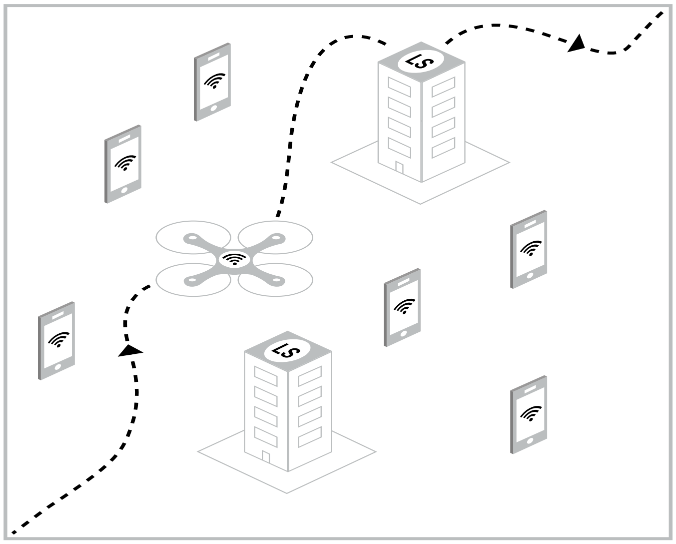

Figure 1. Information collection using a mobile AP with landing spots.

LSs are studied particularly in relation to the density of LSs available, and versus the system signal to noise ratio (SNR).

The rest of this paper is organized as follows: Section II presents the system model describing the UAV and communication model. In Section III, the dynamic optimization problem to maximize the weighted sum-rate is formulated and solved numerically using dynamic programming approach in Section IV. The average rate gain due to LSs is studied in Section V. In Section VI, we present the numerical results. Finally, Section VII concludes the paper.

II. System model

A wireless communication system where an AP serves K users is considered. The AP is mobile as it is mounted on an UAV, while the users are static and are located on the ground. The UAV's mission is aided by LSs. When the UAV stays on any of the LSs, power consumption is limited to RF and computation power of the on-board AP. We consider a 2-dimensional square $\mathcal{A} = [0, a] \times [0, a]$, such that the UAV, user positions and LSs fall within this region. The k-th user, $k \in \{1, \ldots, K\}$, is located at $(x_k^u, y_k^u) \in \mathcal{A}$. There are L LSs in total and their locations are given by the set

$$\mathfrak{L} = \left\{ \left(x_i^l, y_i^l\right),\ i = 1, \ldots, L,\ : \left(x_i^l, y_i^l\right) \in \mathcal{A} \right\}.$$

We assume that all LSs are of the same height h. An illustration of the system model is shown in Figure 1.

We first present the UAV mobility and power consumption model and then introduce the communication system model between AP and the ground users.

A. UAV Mobility Model

Let t_f represent the total mission duration. During the mission, $t \in [0, t_f]$, the UAV flies at a constant altitude of h and its position on the ground plane is given by the Cartesian coordinates $(x(t), y(t)) \in \mathcal{A}$. The UAV's mobility is modelled as

$$\dot{x}(t) = v(t) \cos \phi(t), \tag{1}$$

$$\dot{y}(t) = v(t) \sin \phi(t), \tag{2}$$

where $\dot{x}(t)$ and $\dot{y}(t)$ represents the time derivative of $x(t)$ and $y(t)$, $v(t)$ is the velocity, and $\phi(t)$ is the heading angle (in azimuth) of the UAV. The maximum velocity at which the UAV can travel is given by V, hence

$$v(t) \leq V. \tag{3}$$

The mission begins when the UAV starts from the origin at time $t = 0$, and ends when it reaches the final destination (a, a) at the end of the mission $t = t_f$. Therefore,

$$x(0) = 0,\ y(0) = 0, \tag{4}$$

$$x(t_f) = a,\ y(t_f) = a. \tag{5}$$

B. UAV Power Consumption Model

There are two components in the power consumption of UAV. Let $p_c(t)$ represent the power consumed by the AP that is mounted on the UAV (RF and computation related), and $p_f(t)$ represent the power required to maintain the UAV aloft. We assume that AP is always "on" during the mission time, and consumes constant power, i.e.,

$$p_c(t) = p_c, \forall t \in [0, t_f].$$

The power required to maintain the UAV aloft depends on its location. If the UAV is on any of the LSs, there is no power consumption due to flying, whereas it requires constant power p_f when flying i.e., not on any LS. Mathematically,

$$p_f(t) = \begin{cases} 0, & \forall t\ : (x(t), y(t)) \in \mathfrak{L}, \\ p_f, & \text{otherwise.} \end{cases} \tag{6}$$

Even though the power consumption model used here doesn't take into account the parameters such as UAV velocity, acceleration, as modeled in [14], it allows us to capture the essential trade-off between throughput gain obtained by flying to optimal locations and energy savings arising from resting at LSs in its trajectory.

We consider that the UAV is equipped with a battery of capacity b_{max}. The power drawn from this battery is used for both communication and flying purposes. The energy in the battery during the mission time is denoted by $b(t)$,

$$b(t) \geq 0, \forall t \in [0, t_f], \tag{7}$$

and it evolves according to

$$\dot{b}(t) = -p_f(t) - p_c, \tag{8}$$

with

$$b(0) = b_{max}, \tag{9}$$

where $\dot{b}(t)$ represents the time derivative of $b(t)$. Since we are interested in obtaining the maximum information collected during the mission time with a given finite battery capacity, we consider scenarios where at the end of the mission UAV reaches its final destination with an empty battery

$$b(t_f) = 0. \tag{10}$$

C. Communication System Model

We consider an uplink orthogonal multiple access scenario where the communication links between the users and the AP are modelled as orthogonal point-to-point additive white Gaussian noise (AWGN) channels. As long as the AP is functioning i.e., the energy left in the battery is sufficient to power the AP, the information rate for the k-th user, $k \in \{1, \ldots, K\}$ is

$$R_k(t) = \log_2\left(1 + \mathrm{SNR}_k(t)\right), \tag{11}$$

where $\mathrm{SNR}_k(t)$ denotes the signal to noise ratio of k-th user at time t. Using the distance based path loss model, for the k-th user located at $(x_k^u, y_k^u) \in \mathcal{A}$,

$$\mathrm{SNR}_k(t) = \frac{P}{\sigma^2} d_k(t)^{-\alpha},$$

where the distance from the UAV

$$d_k(t) = \sqrt{h^2 + (x(t) - x_k^u)^2 + (y(t) - y_k^u)^2},$$

P is the transmission power of the k-th user, $\alpha \geq 2$ is the path loss exponent and σ^2 denotes the noise power. The instantaneous weighted sum-rate of the users is given by

$$C(t) \triangleq \sum_{k=1}^{K} w_k R_k(t),$$

with weights $w_k \geq 0$ and $\sum_{k=1}^{K} w_k = 1$.

III. Problem Formulation

The UAV starts at the initial location and has to reach the destination before running out of energy in the battery, and during the mission, the objective is to maximize the weighted sum-rate of the users. By treating the UAV as a deterministic dynamical system, we aim to find a control law i.e., trajectory that optimizes this objective. The optimal control problem is given by

$$\max_{\phi(t), v(t)} \int_{t=0}^{t_f} C(t)\, dt \tag{12}$$

subjected to

$$\begin{aligned}
&(1), (2), (7), (8) \text{ (State equations)}\\
&(3) \text{ (Input constraints)}\\
&(4), (9)\\
&(5), (10) \text{ (Boundary conditions)},
\end{aligned}$$

where $[x(t)\ y(t)\ b(t)]^{\mathrm{T}}$ are the states and $[v(t)\ \phi(t)]^{\mathrm{T}}$ are the input actions.

We assume that there exists at least one feasible solution to (12). This can be guaranteed by choosing b_{max}, p_c, p_f and V such that the UAV can at least travel from starting position to the destination along the minimum distance path i.e.,

$$b_{max} \geq t_m(p_c + p_f),$$

where $t_m = \sqrt{2}a/V$ is the minimum time required for the UAV to reach the destination without the help of any LS. Since $C(t)$ is not a concave functional of $v(t)$ and $\phi(t)$, (12) is a non-convex functional optimization problem which is difficult to solve in general.

IV. Discrete Approximation

In this section, the optimization problem (12) is discretized to obtain numerical approximations of the optimal trajectories. The time period $[0, t_f]$ is divided into N equal length intervals of duration $\delta = t_f/N$, indexed by $i = 0, \ldots, N-1$. The value of N is chosen to be sufficiently large such that UAV's location, velocity, and heading angles can be considered to remain constant in an interval. In the i-th interval, (x_i, y_i), v_i, ϕ_i and b_i denote the UAV's position, velocity, heading angle and battery state. The rate of the k-th user in time interval i is

$$R_{i,k} = \begin{cases} 0, & \forall i\ : b_i < p_c\delta, \\ \log_2\left(1 + \frac{P}{\sigma^2} d_{i,k}^{-\alpha}\right), & \text{otherwise}, \end{cases} \tag{14}$$

where $d_{i,k} = \sqrt{h^2 + (x_i - x_k^u)^2 + (y_i - y_k^u)^2}$ and the first case represent the scenario where there is not enough energy left in the battery to power the AP. The power consumed due to flying in time interval i is

$$p_f(i) = \begin{cases} 0, & \forall i\ : (x_i, y_i) \in \mathfrak{L}, \\ p_f & \text{otherwise}. \end{cases}$$

A. Dynamic Programming

Then the discrete-time dynamic system is given by

$$\boldsymbol{s}_{i+1} = \boldsymbol{s}_i + f(i, \boldsymbol{s}_i, \boldsymbol{u}_i),\ i = 0, 1 \ldots, N-1 \tag{15}$$

where $\boldsymbol{s}_i = [x_i\ y_i\ b_i]^{\mathrm{T}}$ describes the state, and $\boldsymbol{u}_i = [v_i\ \phi_i]^{\mathrm{T}}$ specifies the control action i.e., velocity and heading angle, respectively, in the i-th time interval. The states are computed using

$$f(i, \boldsymbol{s}_i, \boldsymbol{u}_i) = \begin{bmatrix} v_i \cos\phi_i \\ v_i \sin\phi_i \\ -p_f(i) - p_c \end{bmatrix} \tag{16}$$

starting with the initial state $\boldsymbol{s}_0 = [0\ 0\ b_{max}]^{\mathrm{T}}$ and $b_i \geq 0, \forall i$.

For a given set of control actions $\pi = \{\boldsymbol{u}_0, \boldsymbol{u}_1, \ldots, \boldsymbol{u}_{N-1}\}$ the cost function is given by

$$J_\pi(\boldsymbol{s}_0) = J(\boldsymbol{s}_N) + \sum_{i=0}^{N-1} \sum_{k=1}^{K} w_k R_{i,k}, \tag{17}$$

where the terminal cost

$$J(\boldsymbol{s}_N) = \begin{cases} -\infty, & \text{if } \ \boldsymbol{s}_N \neq [a\ a\ 0]^{\mathrm{T}} \\ \sum\limits_{k=1}^{K} w_k R_{N,k}, & \text{otherwise} \end{cases} \tag{18}$$

and $R_{i,k}$ is defined in (14).

An optimal policy π^* that maximizes the cost is

$$\pi^* = \max_{\pi \in \Pi} J_\pi(\boldsymbol{s}_0), \tag{19}$$

where $\Pi = \{\boldsymbol{u}_i,\ i = 0, \ldots, N-1 \mid v_i \leq V, 0 \leq \phi \leq 360^o\}$. The optimization problem (19) can be solved by DP [15]. Given initial state $\boldsymbol{s}_0$, the optimal cost can be computed recursively using Bellman's equations by proceeding backwards in time by [15]

$$J(\boldsymbol{s}_i) = \max_{\boldsymbol{u}_i} \sum_{k=1}^{K} w_k R_{i,k} + J(\boldsymbol{s}_{i+1}),\ i = N-1, \ldots, 0, \tag{20}$$

where the terminal cost $J(\boldsymbol{s}_N)$ is given in (18). An optimal policy π^* solves (20). However, this solution is computationally expensive as the state space $\boldsymbol{s}_i \in \mathcal{A} \times [0, b_{max}]$ and for each state we have to find the optimal v_i and ϕ_i.

Note that the UAV's mission ends when it reaches the destination and there is no energy left in its battery. The mission duration depends on the battery capacity and the actions taken by the UAV during the mission. Therefore, t_f is a variable. However, for applying DP we choose $t_f = T$, where T is the maximum mission duration among all possible trajectories for a given battery capacity. This allows the DP to be only battery limited, and not constrained by the final time t_f. The maximum mission duration can be calculated with a trajectory where the UAV goes to the LS which is on the straight line connecting the starting and final locations, and is given by

$$T = \max\left\{\frac{b_{max}}{p_c + p_f}, \frac{b_{max}}{p_c} - \sqrt{2}a\frac{p_f}{Vp_c}\right\},$$

where the first term in the maximization corresponds to the case when there is no LS. Note that the definition of actual mission duration is still t_f and is counted as the first time instant when there is no energy left for communication and the UAV is at the destination.

V. LS Gain Analysis

In this section, we study the gain in average weighted sum-rate as a function of number of LSs. The average weighted sum-rate is given by

$$\mathrm{E}_{f_u, f_l}[C^*],$$

where the users and LSs distributions are denoted by f_u and f_l, respectively, C^* is obtained by solving (12) for a given realization of user and LS locations i.e.,

$$C^* = \max_{\phi(t), v(t)} \int_{t=0}^{t_f} C(t)\, dt.$$

We assume that the locations of users and LSs are independent and identically distributed (i.i.d.) uniform random variables over the 2-dimensional square $\mathcal{A}$.

Since there is no closed form expression for the solution of (12) it is hard to analyze the rate gain analytically as a function of LSs. Therefore, we resort to DP to obtain the gain numerically. However, before resorting to numerical methods, we obtain some intuition on the gain in a high SNR regime. Degrees of freedom (DoF) analysis often provides insights on a complex wireless network which is hard to analyze at finite SNR. It also serves as a good approximation when the system SNR is high.

A. DoF Analysis

The DoF of the considered network is defined as

$$\mathrm{DoF} \triangleq \lim_{P\to\infty} \frac{C^*}{\log_2 P} \triangleq \int_{t=0}^{t_f} \sum_{k=1}^{K} w_k \lim_{P\to\infty} \frac{R_k^*(t)}{\log_2 P}.$$

It can easily seen that the maximum DoF for this network is equal to the mission time

$$\mathrm{DoF} = t_f.$$

Therefore, a UAV trajectory that maximizes the mission time also maximizes the DoF of the network and serves as a good strategy when the system SNR is high. This value of t_f can be obtained by the trajectory where the UAV goes to the nearest LS on its way to the destination. The time spent in going to the nearest LS and then to the destination is given by

$$t_v = \frac{1}{V} \min_{i=1,\ldots,L} \left\{\sqrt{{x_i^l}^2 + {y_i^l}^2} + \sqrt{\left(x_i^l - a\right)^2 + \left(y_i^l - a\right)^2}\right\}.$$

In the remaining time UAV stays at the LS, and while at the LS power is consumed only for communication purposes. Mathematically,

$$\mathrm{DoF} = \max\left\{\frac{b_{max}}{p_c + p_f}, \frac{b_{max}}{p_c} - t_v\frac{p_f}{p_c}\right\}, \tag{21}$$

where the first term in the maximization corresponds to the case when there is no LS. The average DoF can be obtained by taking the expectation of (21) over the distribution of t_v, which in turn depends on the LSs distribution.

VI. Results

In this section, we numerically obtain the optimal trajectories of the UAV by applying DP, and also present the performance gain achieved from using LSs. We consider a square dimension a of 1000m. The UAV serves $K = 10$ uniformly distributed ground users, with weights $w_k = \frac{1}{K}, \forall k$. The path loss exponent is $\alpha = 2.3$ and the noise power is $\sigma^2 = 1$. The battery size is chosen to be 17.5W.h. The power consumed in flying $p_f = 400$W and it is independent of the velocity. The ratio between p_f and the power consumed for communication p_c is 10. The UAV flies at a constant altitude $h = 40$m and has a maximum velocity of $V = 17.7\frac{m}{s}$.

In this simulation, the possible UAV locations, the time, the battery levels and the actions are discretized. In the 2-dimensional square region $\mathcal{A}$ both x and y-coordinates are discretized with a step of 100m, which results in 121 unique geometric positions. The LSs are uniformly distributed over these positions. The discretization in time is $\delta = 8$s and the battery is discretized in steps of $\Delta b = 320$W.s. Possible control actions due to the geometric position limitations are:

$$\boldsymbol{u}_i \in \left\{ \begin{bmatrix} 0\frac{m}{s} \\ 0 \end{bmatrix}, \begin{bmatrix} 12.5\frac{m}{s} \\ \theta \end{bmatrix}, \begin{bmatrix} 17.7\frac{m}{s} \\ \theta + \frac{\pi}{4} \end{bmatrix} \right\}, \tag{22}$$

with $\theta \in \left\{0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}\right\}$.

Similar to classical mobile communication systems, the cell-edge SNR describes the radio link between the UAV at the center position $(x_i, y_i) = \left(\frac{a}{2}, \frac{a}{2}\right)$ and a user maximally far apart, hence $(x_k^u, y_k^u) \in \{(0,0), (0,a), (a,0), (a,a)\}$.

First, we analyze the optimal trajectory of the UAV with a LS. Figure 2 illustrates the optimal trajectories for an average cell-edge SNR of 0dB and 15dB. The optimal path depends on the average cell-edge SNR and will either passes through the optimal position where the weighted sum rate is maximum as observed for 0dB or to a landing spot for 15dB. Depending on the battery size, the UAV will stay in either one of those locations until the battery constraint forces it to fly to the final destination. As the time spent in a LS is more energy-efficient, the mission duration for 15dB (296s) is considerably larger than for 0dB (136s). High SNR allows the UAV to serve users with a relatively good rates (compared to low SNR scenario) from a LS in an energy-efficient manner leading to large mission duration.

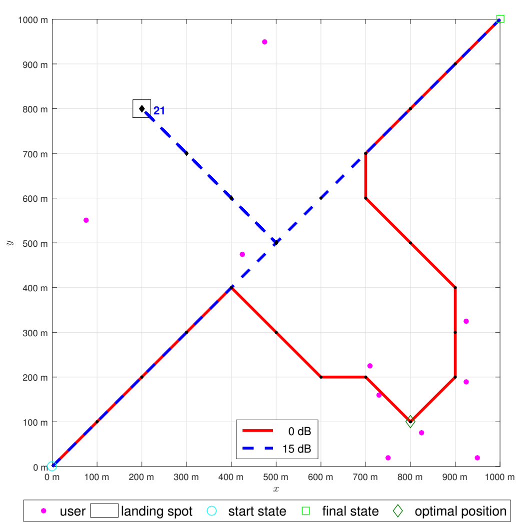

Figure 2. Optimal trajectories for an average cell-edge SNR of 0dB and 15dB with 10 users and one LS.

Second, we explore the advantage of installing LSs in terms of the overall collected data per UAV deployment. Figure 3 shows the relative collected data gain for different numbers of LSs compared to the base-line scenario without LSs. Small numbers of LSs grant already a large relative gain due to an extension of the mission duration shown in Figure 4. For a higher average cell-edge SNR the position of the LSs is less important, explaining the steeper slope in the beginning. The relative collected data gain converges for large numbers of LSs.

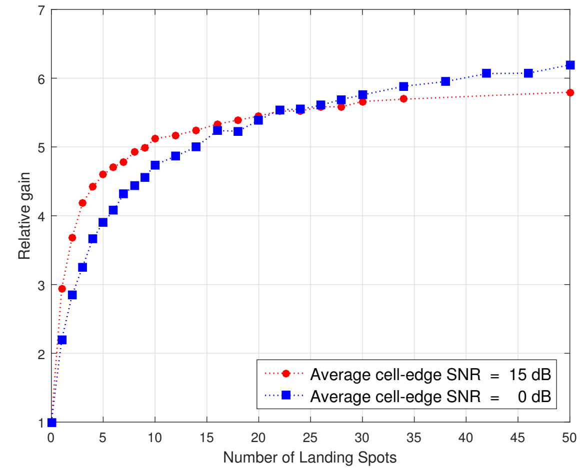

Figure 3. Relative collected data gain for different number of LSs.

Figure 4 depicts the relation between the mission duration and the number of LSs. The use of a landing spot allows for a reduction in energy consumption increasing the mission duration in the battery limited system. For a higher average cell-edge SNR the larger transmit power leads to the LSs having a better instantaneous weighted sum rate. This increases the probability that the UAV chooses a LS over the optimal position (where weighted sum rate is maximum) or reduces the travel time to and from the optimal LS. The mission duration converges for large numbers of LSs.

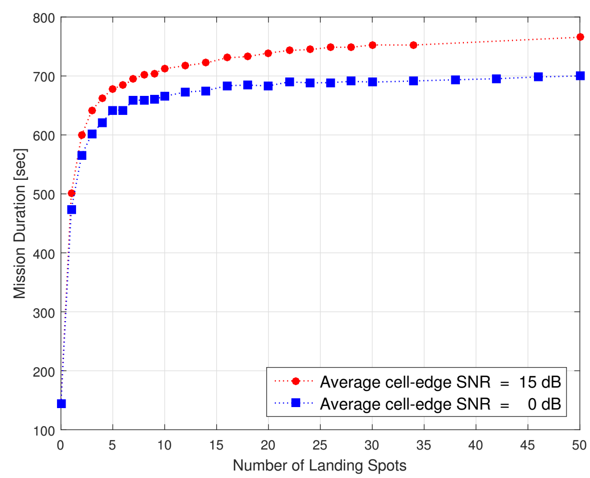

Figure 4. Average mission duration for different number of LSs.

Figure 5 shows the relation between the total collected data and the average cell-edge SNR for different numbers of LSs. The amount of collected data using a fixed number of LSs increases for higher average cell-edge SNRs. This slope steepens with the number of LSs and considerably outperforms the conventional collected data growth due to an SNR increase without LSs.

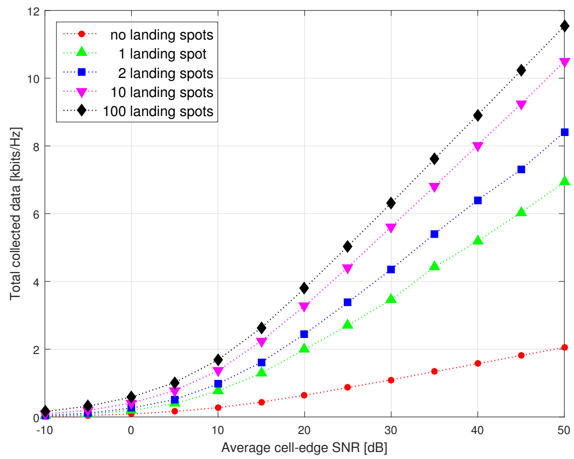

Figure 5. Average throughput for different SNRs and numbers of LSs.

VII. Conclusion

We have introduced a novel concept of LSs for helping the UAV-aided wireless networks. The problem of finding optimal trajectory of an UAV mounted AP that exploits the LSs and maximizes the weighted sum-rate is formulated. This dynamic optimization is solved numerically by using DP. Interestingly, the trajectory of the UAV and the exploitation of LSs highly depends on the system SNR. Then we have studied the gain in throughput as a function of number of LSs. Our study has shown that small number of LSs are enough to achieve substantial increase in the total collected data for a given battery capacity.

We have assumed that during the mission, whether the UAV is flying or resting on a LS, it has (line-of-sight) LOS links to all the ground users. However, in reality this assumption might not be true, and resting on a LS might result in (non-line-of-sight) NLOS links to some users, which results in a decrease in their throughput. We intend to address this problem in the future by including a distance based LOS probability in the system model. Another extension of this work is to investigate the scenario where the LSs have recharging capabilities. In this scenario it is interesting to see how frequently the UAV visits a LS and the amount of time it spends there.

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