ENERGY-EFFICIENT UAV TRAJECTORIES: SIMULATION VS EMULATION

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ABSTRACT

This paper uses an emulator to verify an energy-efficient trajectory for an unmanned aerial vehicle (UAV) acting as a portable access point (PAP) to serve a set of users. Specifically, we use the Common Open Research Emulator (CORE), and Extendable Mobile Ad-hoc Network Emulator (EMANE), which allow us to take theoretical assumptions regarding data transfer rates and transmission characteristics and test them in the virtualized wireless networking setting the two tools provide us. The optimal *fly-hover-communicate* trajectory that maximizes the system's energy efficiency is obtained using a circle-packing algorithm. The CORE-EMANE emulator results match the simulated results, thereby verifying the practicality of the obtained trajectory solution.

Index Terms— UAV Communication, Energy Efficiency, CORE, EMANE

1. INTRODUCTION

The viability of improving the energy efficiency of future cellular networks through various technologies, such as improving the coverage area and reducing the link power budgets, or by increasing the number of base station (BS) antennas[1] depends on the availability of a reliable power grid. This cannot be guaranteed in remote areas or disaster-hit areas. In those situations, Unmanned Aerial Vehicles (UAVs) can be used as radio access nodes, hereafter called Portable Access Points (PAPs), to provide coverage or enhance the network's capacity on demand and without any preinstalled power infrastructure. A PAP or a swarm of PAPs with an onboard fully charged battery unit will fly above the required service region. Given the fact that all commercial UAVs have a given payload capacity that also limits the battery size, it is crucial to design energy-efficiency trajectories for UAVs acting as PAPs for the following reasons: (a) achieve longer flight times; (b) improve payload capacity by reducing the energy required to fly; (c) reduce the environmental impact by reducing energy consumption. One significant advantage of using network emulators rather than just numerical simulations is that we can study the effects of all the protocol layers. This allows us to better evaluate any trajectory or user scheduling scheme, as protocol layers 2 and above and the physical layer may dramatically affect the data transfer rate and the system's overall performance.

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2. RELATED WORKS

A plethora of works considering the optimal placement of a PAP system is available in the literature. Most of them maximize/minimize quantities such as sum rate, coverage area, energy efficiency, etc. The tractable probabilistic line-of-sight (LoS)-non-LoS (NLoS) air-to-ground channel proposed in [2] was initially used by the researchers to maximize the coverage area [2]-[4] of hovering PAPs. The formulated problems are solved using the maximal weighted area and circle packing algorithms. The total downlink transmit power of a PAP is minimized in [5] and [6].

A major challenge in designing the trajectory was the infinite number of variables due to the continuous time domain. The authors in [8] introduced a time-segmentation approach to discretize the total mission time into steps of finite duration and used it to design an energy-efficient trajectory for a fixed-wing UAV. Since the number of variables in this approach increases with the mission time, the work in [7] introduced a path discretization approach in which the total trajectory of the UAV is segmented into small path segments of finite length. The authors then used this approach to design an energy-efficient trajectory for a rotary-wing UAV. Many researchers later used these approaches to design optimal trajectories for a UAV. A comprehensive summary of works considering energy-efficient UAV placement is available in [9].

The results presented in all the aforementioned works are based on numerical simulations done in MATLAB and Python, where no attempt was made to verify the obtained solution's viability using a network emulator. We use the CORE-EMANE emulator to verify the practicality of an energy-efficient fly-hover-communicate trajectory developed for a PAP to serve a set of ground users. Our main contributions are:(a) we formulate a mathematical problem to determine an energy-efficient trajectory that delivers a file of a given size to all the users by the end of the trajectory; (b) the exponentially complex is solved using a multi-level circle packing algorithm that gives the minimal set of hovering points (HPs) through which the PAP should traverse to complete the mission; (c) the practicality of the obtained solution is then verified using the CORE-EMANE emulator.

3. ENERGY-EFFICIENT TRAJECTORY DESIGN

In this work, we consider the planning phase of the PAP deployment through which an optimal trajectory is determined offline before the actual deployment.

3.1. System Model

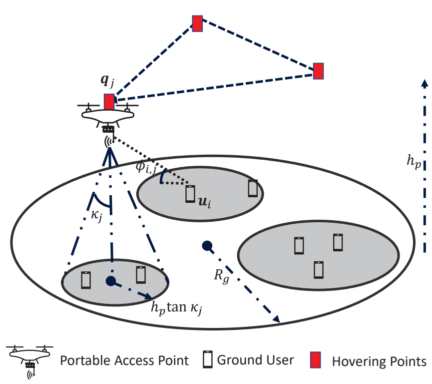


Fig. 1: System setup.

As shown in Fig. 1, a PAP is deployed to deliver a file of Q bits to ground users (GUs) located at $\mathbf{u}_i = (\mathbf{u}_{\mathrm{h},i}, 0) = (x_i, y_i, 0), \forall\, i \in \{1, 2, .., N\} \equiv \mathcal{U}$. The antennas of all users are assumed to be omnidirectional of unit gain. To do so, the PAP follows a simple fly-hover-communicate (FHC) protocol: the PAP flies from one hovering point (HP) q_i at a height h_p, to another, hovers for the time needed to exchange the data packets, then moves on to the next HP. The air-to-ground channel between the PAP and a GU considers the line-of-sight (LoS), and non-LoS (NLoS) channel links to model the probabilistic mean path loss between the PAP and the GU [3], given by [10]: $\overline{L}_{i,j} = \dfrac{d_{i,j}^2}{g_{\mathrm{o}}} \underbrace{\left[P_{\mathrm{l}}(\phi_{i,j})\left(\eta_{\mathrm{l}}^2 - \eta_{\mathrm{nl}}^2\right) + \eta_{\mathrm{nl}}^2\right]}_{L_{\mathrm{m}}(\phi_{i,j})}$, where $P_{\mathrm{l}}(\phi_{i,j}) = 1/\left\{1 + a\exp\left[-b(\phi_{i,j} - a)\right]\right\}$ represents the LoS probability between the PAP hovering at $\mathbf{q}_j = (\mathbf{q}_{\mathrm{h},j}, h_{\mathrm{p}})$ and the i^{th} GU located at a distance of $r_{i,j} = \|\mathbf{q}_{\mathrm{h},j} - \mathbf{u}_{\mathrm{h},i}\|$ from the center of the PAP coverage area, corresponding to an elevation angle of $\phi_{i,j} = (180/\pi)\tan^{-1}(h_{\mathrm{p}}/r_{i,j})$ with the PAP hovering at an altitude h_{p}; the parameters a and b are directly linked to the environment variables such as the mean number of buildings, their height distribution, and the ratio of built-up land area to the total land area using the two variable surface fitting [3]; g_{o} is the channel gain at a reference distance of 1m; $d_{i,j} = \sqrt{r_{i,j}^2 + h_{\mathrm{p}}^2}$. η_{l} and η_{nl} are the mean values of the excess loss due to the man-made structures associated with the LoS and NLoS links, respectively.

Hence the corresponding achievable data rate of the i^{th} GU when the PAP is hovering at $\mathbf{q}_j$, in bits per second, is given by $S_{i,j} = B\log_2\left(1 + \dfrac{P_{\mathrm{t}}}{\sigma^2 \overline{L}_{i,j}}\right)$, where B is the bandwidth allocated to each GU; σ^2 and P_{t} are the variance of the zero-mean additive white Gaussian noise and the transmitted power allocated to a GU, respectively;

The geographical area covered by a single PAP hovering at an altitude h_p can be modeled as a circular region of radius $r_{\mathrm{p}} = h_{\mathrm{p}}\tan\kappa$, as shown in Fig. 1. 2κ can be modeled as either the half-power beamwidth of the directional antenna at the PAP or the function of minimum SNR required at the GU.

3.2. Problem Formulation

The global energy efficiency (GEE) of a PAP system is defined as the number of bits transmitted per Joule of energy consumed [10]. Considering the mission of the PAP, i.e., delivering a file to a set of GUs, the trajectory that maximizes the energy efficiency is the same as the one that minimizes the total flying time to deliver Q bits to all the GUs. The corresponding flying time minimization problem, with $\mathcal{H}$ being the set of hovering points, can be formulated as follows:

$$\underset{\{\{\mathbf{q}_j\},\{T_{i,j}\},\{\beta_{i,j}\},\{T_j^{\mathrm{fly}}\},\{\alpha_j\}\}}{\text{minimize}} \sum_{j\in\mathcal{H}} \alpha_j T_j^{\mathrm{ho}} + \sum_{j=1}^{|\mathcal{H}|-1} T_j^{\mathrm{fl}} \quad (1)$$

$$\sum_{j\in\mathcal{H}} \beta_{i,j} T_{i,j} S_{i,j} \geq Q, \qquad \forall i \in \mathcal{U}, \quad (2)$$

$$\sum_{i\in\mathcal{U}} \beta_{i,j} T_{i,j} \leq T_j^{\mathrm{hover}}, \qquad \forall j \in \mathcal{H}, \quad (3)$$

$$h_{\mathrm{min}} \leq h_{\mathrm{p}} \leq h_{\mathrm{max}}, \quad (4)$$

$$\sum_{j\in\mathcal{H}} \beta_{i,j} = 1, \qquad \forall i \in \mathcal{U}, \quad (5)$$

$$\|\mathbf{q}_{\mathrm{h},j} - \beta_{i,j}\mathbf{u}_{h,i}\| \leq |h_{\mathrm{p}}|\tan\kappa, \quad , \forall j \in \mathcal{H}, \quad (6)$$

$$\frac{\|\mathbf{q}_{j+1} - \mathbf{q}_j\|}{T_j^{\mathrm{fl}}} \leq v_{\mathrm{max}}, \ \forall j \in \{1, ..., |\mathcal{H}| - 1\} \quad (7)$$

$$\sum_{j\in\mathcal{H}} \alpha_j T_j^{\mathrm{ho}} + \sum_{j=1}^{|\mathcal{H}|-1} T_j^{\mathrm{fl}} \leq T_{\mathrm{max}} \quad (8)$$

The objective function in (1) is the sum of the hovering time and flying time in which T_j^{ho} is the total time the PAP hovers at the j^{th} HP $\mathbf{q}_j$, and T_j^{fl} is the time required by the PAP to fly between j^{th} and $(j+1)^{\text{th}}$ HPs. A unity value to the binary indicator variable α_j indicates that the PAP is hovering at $\mathbf{q}_j$; $\beta_{i,j}$ indicates if the i^{th} GU covered by the j^{th} HP. (2) ensures that the file of size Q bits is transmitted to all the GUs by the end of the FHC trajectory through $|\mathcal{H}|$ HPs. While at an HP, the PAP follows a Time Division (TD) scheme to serve the GUs in the corresponding coverage region. (3) is the TD constraint in which $T_{i,j}$ is the time allocated to the i^{th} GU while the PAP is at the j^{th} HP. (4) is the altitude constraint in which h_{min} and h_{max} are the minimum and maximum permitted PAP altitudes. (5) expresses that the PAP should cover each GU while hovering at any of the $|\mathcal{H}|$ HPs. (6) is the coverage region constraint, whereas (7) restricts the maximum flying velocity to be less than or equal to v_{max}. (8) limits the total time used by the PAP to be less than the maximum available time T_{max}, which is available from the data sheet of the particular PAP used. The optimization problem is an exponentially complex mixed-integer non-linear (MINLP) problem.

3.3. Solving Methodology

Since the total hovering and flying time of the PAP can be reduced by reducing the number of HPs, a solution to (1) is a set of the minimum number of HPs, and the corresponding user scheduling ($\{T_{i,j}\}$) and association ($\{\beta_{i,j}\}$) policies. For a given set of GUs distributed along a circular geographical region of radius R_{g}, the problem of finding the optimal location of HPs is equivalent to packing PAP coverage circles of radius r_{p} over the bigger circle of radius R_{g}. We use the multi-level circle packing (MCP) algorithm proposed in Algorithm 2 of [10] to determine $\{\mathbf{q}_j\}$. In the first level, the algorithm places 5 circles of radius R_{g}/Λ following the 5-circle packing pattern so that the centers of the smaller circles lie on the vertices of a regular pentagon of side $2R_{\text{g}}/\Lambda$, where $\Lambda = 1.618$ is the golden ratio. In the next level, each of the smaller circles obtained in the previous level is covered by 5 smaller circles of radius $R_{\text{g}}/2\Lambda$. This continues until the circle's radius to be covered is less than or equal to the radius of the PAP coverage region r_{p}. Now the algorithm removes the circles that do not cover any users. The MCP algorithm is summarized in Algorithm 1. The FHC trajectory is the shortest path between $\{\mathbf{q}_j\}$. User association can be done as,

Algorithm 1: Multilevel circle packing (MCP) [10].

- **Input**: R_{g}, r_{p}, $\{\mathbf{u}_i\}$;
- Find the set of PAP coverage circles ($\mathcal{H}_t$) using multi-level 5-circle packing: (35) and (36) of [10]
- Remove the circles with no GUs covered from the set to obtain $\mathcal{H}$ (constraint (5))
- Adjust the beamwidth of the PAP antenna to the farthest user in the coverage area: $\{\kappa_j\}$
- **Output**:$\{\mathbf{q}_j\}$: the set of HPs that cover at least one GU; $\{\mathcal{U}_j\}$: the set of GUs covered by each HPs.

$$\beta_{i,j} = \begin{cases} 1 & \text{if} \|\mathbf{q}_{\text{h},j} - \mathbf{u}_{h,i}\| \leq h_{\text{p}} \tan\kappa_j \\ 0 & \text{otherwise}, \end{cases} \tag{9}$$

thereby satisfying constraint (6). The GUs are scheduled according to (10):

$$T_{i,j} = \begin{cases} \frac{Q}{S_{i,j}} & \text{if } \beta_{i,j} = 1, \\ 0 & \text{otherwise}, \end{cases} \tag{10}$$

so that constraint (2) is satisfied; thus, the total time the PAP spends at each HP is estimated as $\sum_i T_{i,j}$ (constraint (3)). To minimize the flying time, the PAP flies at the maximum velocity v_{max} (constraint (7)).

4. THE CORE-EMANE EMULATOR

To support our claims of achievable data transmission under the conditions formulated in section 3, besides mathematical simulations, we have also used the tandem computer network and wireless ad-hoc research emulators CORE and EMANE for evaluation. This software solution relies on CORE to emulate the OSI model from layer 3 (network) and above, while EMANE handles the physical and data link layers [11] to produce a virtualized environment that mimics a real wireless data transfer scenario. Combined with CORE's built-in mobility functionality, we can generate a mobility script replicating the PAP movement path and hovering schedule derived from simulation, causing our emulated PAP to produce the same motions in CORE. One issue with this approach lies in the representation of space within CORE since its graphical environment operates on a two-dimensional plane, but, in the realm of flying drone-based communications, we are required to take altitude differences into account; however, since in the current setting we are only concerned with the distance between the PAP and each GU, and make no considerations for obstructions or other external interference, we can address this issue by creating a 2D space wherein the PAP node is kept stationary and all GUs are programmatically moved closer and farther from the PAP to maintain the same absolute distance value as they do in the three-dimensional scenario at every time moment.

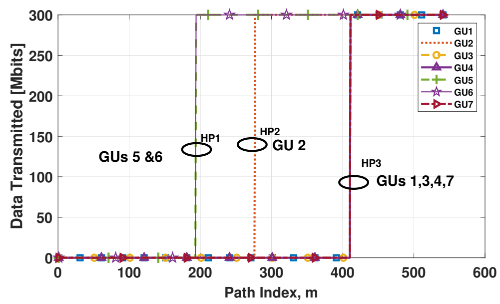
The functional design sequence to handle and process the simulation data in our tandem emulator solution is: (1) obtain CSV files of PAP and GU coordinates and the corresponding data transfer scheduling from simulation; (2) generate an ns-2[1] mobility script compatible with CORE and a bash script which, upon mobility start, coordinates the data transfer and network statistics collection between nodes; (3) the proper number of GUs is created in CORE as network-layer virtual nodes, and the physical and RF emulation parameters are set according to specifications; (4) the emulation and mobility scenario is executed, and the network test results are collected.

[1]https://www.nsnam.org/

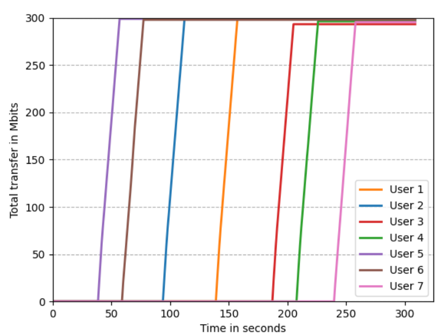
5. RESULTS AND DISCUSSION

The simulation parameters are $g_{\text{o}} = 1.42 \times 10^{-4}$, $B = 10^6$ Hz, $h_{\text{p}} = 50$ m, $Q = 300$ Mbits,$R_{\text{g}} = 350$ m, $(h_{\text{min}}, h_{\text{max}}) = (10\text{ m}, 120\,\text{m})$, $P_{\text{t}} = 0.2$ W, $\sigma^2 = 10^{-}14$ W, $\kappa = 1.2$ rad.

We consider a set of 7 GUs distributed over a circular region of radius 350 m. The MCP algorithm takes these inputs and finds the set of PAP coverage circles that cover the entire region. Among these circles, the ones with at least one GU are selected. This gives a set of 3 HPs. The shortest path between the HPs is determined by solving it as a traveling salesman problem (TSP). Moreover, we consider that the trajectory starts and ends at the same geographical location, at coordinates $(0, 0)$ in the horizontal plane. The continuous trajectory is discretized into path segments of length 1 m. Each path segment is represented using a number referred to as path index, m, represented in Fig. 2 (a). Now the GUs are associated with the corresponding HPs according to (9). Each GU is scheduled for a time determined using (10).



(a) Simulation: Data transfer scheduling.



(b) Emulation: Data transfer scheduling.

Fig. 2: Simulated and emulated results.

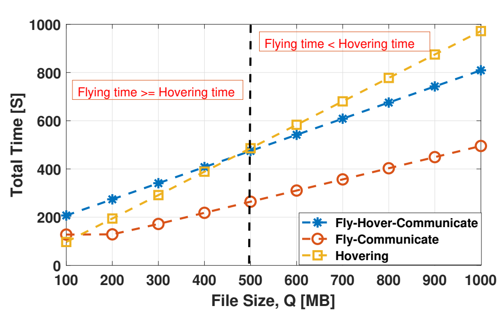


Fig.3: Mission time Vs File size.

Fig. 2(a) shows the scheduling of the GUs at different segments of the PAP trajectory. As seen in the figure, the plots overlap since the PAP, while in HPs 1 and 3, serves more than one GU following the TD scheme. The plot shows that each GU is associated with the nearest HP and is scheduled according to their proximity to the PAP (constraints (5) and (6)). At the end of the trajectory, all the GUs were delivered with a file of size 300 Mbits (constraint (2)). The number of HPs determined using the multi-level circle packing algorithm is more heavily dependent on the area of the serving region than the number of users. For instance, any number of users distributed over $R_{\text{g}} = \Lambda r_{\text{p}}$ can be covered by 5 HPs. The number of HPs required following the approach in [8] scales with the number of users. Thus, our approach is scalable to any number of users distributed over any geographical area.

Fig. 2(b) shows the corresponding emulated results. When executing the simulated scenario in CORE-EMANE, we used the EMANE RF-Pipe radio model with the following parameters: bandwidth 1 MB, carrier frequency 2.4 GHz, 23 dBm transmission power, and the two-ray radio propagation model. Data transmission was emulated with the iperf3 network measurement tool [12] that was used in its UDP mode for (a) transferring the target data amount from the PAP to each GU as allotted in their respective hovering period and (b) logging the results. The emulation aims to prove a minimum data rate (in this case, 18 Mbps) for which the calculated optimum trajectory and user schedule can complete the mission, i.e., the file delivery to all the users. The figure shows the achieved data transfer between the PAP and each GU matches the results from Fig. 2(a) but with better precision since we can represent it as a function of time rather than simply reporting on the cumulative total data transfer achieved per HP index.

Fig. 3 compares the total mission time following the FHC protocol with the hovering (the PAP hovers at the center of the geographical region) and fly-communicate protocol in which the PAP can communicate with users while flying. Interestingly, the hovering case outperforms the FHC protocol when the file size is small since the time wasted during flying is comparable to the data transmission time. The fly-communicate trajectory needs less time than the other schemes since the flying time is also utilized for communication. But the scheme assumes the file transferring to a user can be paused and restarted at a later segment of the trajectory. Since this requires the users to follow a torrent-like protocol, we conclude the FHC is the easily implementable trajectory solution.

6. REFERENCES

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