On the Energy Consumption of Rotary-Wing and Fixed-Wing UAVs in Flying Networks

Pedro Ribeiro, André Coelho, Rui Campos
INESC TEC and Faculdade de Engenharia, Universidade do Porto, Portugal
{pedro.m.ribeiro, andre.f.coelho, rui.l.campos}@inesctec.pt

***Abstract*—Unmanned Aerial Vehicles (UAVs) are increasingly employed to enable wireless communications, serving as communications nodes. In previous work, we proposed the Sustainable multi-UAV Performance-aware Placement (SUPPLY) algorithm, which focuses on the energy-efficient placement of multiple UAVs acting as Flying Access Points (FAPs). We also developed the Multi-UAV Energy Consumption (MUAVE) simulator to evaluate UAV energy consumption. However, MUAVE was designed to compute the energy consumption for rotary-wing UAVs only.**

In this paper, we propose eMUAVE, an enhanced version of the MUAVE simulator that enables the evaluation of the energy consumption for both rotary-wing and fixed-wing UAVs. We then use eMUAVE to evaluate the energy consumption of rotary-wing and fixed-wing UAVs in reference and random networking scenarios. The results show that rotary-wing UAVs are typically more energy-efficient than fixed-wing UAVs when following SUPPLY-defined trajectories.

***Index Terms*—Energy-aware, energy consumption, fixed-wing, flying networks, multi-UAV, rotary-wing, UAV trajectory**

I. Introduction

Unmanned Aerial Vehicles (UAVs) have had an increasing interest from the scientific community in recent years. Due to their capabilities, such as hovering and carrying cargo, UAVs serve multiple purposes. A promising application of UAV technology lies in its use in wireless communications as part of Non-Terrestrial Networks (NTNs). NTNs include Flying Networks (FNs) consisting of UAVs equipped with communications nodes, such as Wi-Fi Access Points and Cellular Base Stations. FNs can reinforce and ensure wireless coverage for Ground Users (GUs), especially during temporary events, such as disaster management scenarios and crowded events. Since UAVs mostly rely on onboard power sources requiring recharging, it is crucial to estimate and optimize the UAVs' energy consumption. In previous work, we proposed the Sustainable multi-UAV Performance-aware Placement (SUPPLY) algorithm [1]. SUPPLY defines energy-efficient trajectories for multiple UAVs acting as Flying Access Points (FAPs). To implement the SUPPLY algorithm and evaluate the energy consumption of an FN using SUPPLY, we developed a Python-based simulator named Multi-UAV Energy Consumption (MUAVE) simulator [2]. MUAVE computes the energy consumption of FAPs for trajectories defined by SUPPLY or any other algorithm implemented in the simulator. Originally, MUAVE was designed to evaluate only rotary-wing UAVs, limiting its calculations to this UAV type. This paper expands MUAVE to support fixed-wing UAVs and investigates their energy consumption as an alternative to rotary-wing UAVs.

This work is co-financed by Component 5 - Capitalization and Business Innovation, integrated in the Resilience Dimension of the Recovery and Resilience Plan within the scope of the Recovery and Resilience Mechanism (MRR) of the European Union (EU), framed in the Next Generation EU, for the period 2021-2026, within project Produtech-R3, with reference 60.

The main contributions of this paper are two-fold:

- **The enhanced MUAVE (eMUAVE) simulator**, available to the community, which supports the computation of energy consumption for both rotary-wing and fixed-wing UAVs, using state-of-the-art energy consumption models;
- **The evaluation of energy consumption for fixed-wing UAVs and comparison with rotary-wing UAVs** when following SUPPLY-defined trajectories.

II. Background

A. UAV Types

UAVs can be classified into two types based on their flying mechanism: rotary-wing and fixed-wing.

Rotary-wing UAVs are typically equipped with multiple rotors, each with a rotor blade that moves air downward to generate the lift required to keep the UAV airborne. Rotary-wing UAVs are able to hover, making them particularly useful in use cases requiring stable wireless coverage. This capability, combined with precise trajectory following, allows for the optimized positioning of communications nodes in an FN. Additionally, rotary-wing UAVs can perform vertical take-offs and landings without requiring a runway.

Fixed-wing UAVs have rigid wings, like airplanes, that generate lift as air passes through them. This flying mechanism requires constant UAV movement to generate lift, preventing it from hovering. Fixed-wing UAVs require runways for both take-off and landing, but they excel in flying at greater altitudes and faster speeds while remaining energy-efficient.

B. UAV Energy Consumption Models

UAVs, especially in FNs, typically rely on electric batteries. Given the limited energy capacity of their batteries, UAVs have limited endurance. As such, estimating and optimizing UAV energy consumption is crucial. In FNs, UAVs expend energy on two tasks: communications and propulsion. Since communications account for only a small fraction of the energy used, they are often excluded from energy consumption models. The scientific community has proposed energy consumption

ISBN: 978-3-903176-71-3

models that realistically replicate the power consumption of both UAV types.

Multiple works (e.g. [3], [4]) have proposed models for rotary-wing UAV energy consumption. In this work, we focus on the model already integrated into the MUAVE simulator, proposed in [4]. This model considers acceleration – an essential factor in energy consumption – distinguishing it from other models. It incorporates only centrifugal acceleration, based on the conclusion that tangential acceleration's impact on energy consumption is inherently accounted for through changes in velocity. For circular movements, the model simplifies into a secondary model, defined in (1), where $||v(t)|| = V$ and $a_c = \frac{V^2}{r}$, with V being the flying speed and r the circular radius. P_b and P_{ind} are constants representing *blade profile power* and *induced power*, respectively. U_{tip} is the rotor blade tip speed and v_0 is the mean rotor induced velocity. d_0 and s represent the fuselage drag ratio and rotor solidity, respectively. g is the gravitational acceleration, ρ stands for air density, and A denotes rotor disc area. As outlined in (1), for circular movements, the model defines the power consumption for any combination of flying speed and radius. Using optimization techniques, it is possible to determine the flying speed that minimizes power consumption for a given radius; this is exactly the approach used by SUPPLY.

$$
\begin{aligned}
P(V,r) = {} & \underbrace{P_b\left(1+\frac{3V^2}{U_{tip}^2}\right)}_{blade\,profile} \\
& + \underbrace{P_{ind}\sqrt{1+\frac{V^4}{r^2g^2}}\left(\sqrt{1+\frac{V^4}{r^2g^2}+\frac{V^4}{4v_0^4}}-\frac{V^2}{2v_0^2}\right)^{1/2}}_{induced} \\
& + \underbrace{\frac{1}{2}d_0\rho sAV^3}_{parasite}
\end{aligned} \tag{1}
$$

Fewer models have been proposed for fixed-wing UAVs. Paredes et al. [5] developed a model that predicts the power consumption of a fixed-wing UAV. The model incorporates several parameters, including non-dimensional coefficients representing the aerodynamic properties of UAV wings and propellers. In [6], the authors developed a theoretical model to calculate propulsion energy consumption for fixed-wing UAVs, considering acceleration. Like the model defined in (1), this model simplifies for circular movements. The simplified power consumption model is given by (2). Power consumption is a function of flying speed V and radius r, with parameters c_1 and c_2 reflecting UAV characteristics and environmental conditions such as weight, wing area, and air density. This is the model used in eMUAVE.

$$P(V,r) = \left(c_1 + \frac{c_2}{g^2r^2}\right)V^3 + \frac{c_2}{V} \tag{2}$$

III. Sustainable multi-UAV Performance-aware Placement Algorithm

SUPPLY [1] was developed for networking scenarios involving multiple GUs with varying QoS requirements, focusing on energy efficiency. SUPPLY optimizes UAV deployment in two phases. In the first phase, it clusters GUs to reduce the number of FAPs needed. The second phase defines an energy-efficient trajectory for each FAP. The algorithm correlates the Signal-to-Noise Ratio (SNR) between GUs and FAPs, with the data rate achieved with each Modulation and Coding Scheme (MCS) index [7].

SUPPLY determines the optimal FAP placement within an area defined by the intersection of the spheres centered on the GUs. The radii of the spheres are determined by the SNR values required to meet the capacity demand of each GU. Given that UAVs are more energy-efficient when flying at an optimal speed, SUPPLY selects the trajectory within the intersection area that minimizes the FAP energy consumption. It considers three possible trajectories: circular, inner-elliptic, and elliptic. The circular trajectory follows a circumference with a radius equal to the minimum distance from the centroid of the intersection area to its perimeter. The elliptic trajectories consist of two straight-line segments and two semicircles: the inner-elliptic trajectory lies within the circular trajectory's area, while the elliptic trajectory extends over the entire intersection area. For a detailed description of the SUPPLY algorithm, please refer to [1].

IV. Enhanced Multi-UAV Energy Consumption Simulator

The Enhanced Multi-UAV Energy Consumption (eMUAVE) simulator [8] implements the SUPPLY algorithm and computes the energy consumption for multi-UAV networks. eMUAVE, implemented in Python, builds upon MUAVE [2] and the UAV Power Simulator proposed in [9], which was designed for a single UAV acting as a flying gateway. eMUAVE includes all the original features of MUAVE while augmenting its capabilities to simulate energy consumption for fixed-wing UAVs. Moreover, it enables comparative analysis of the energy consumption per hour between the two types of UAVs when following the SUPPLY-defined trajectories for the same scenario; in the future, support for other trajectories can be added to the simulator.

eMUAVE considers a set of parameters related to network configurations, UAV specifications, and environmental characteristics. eMUAVE integrates the simplified power consumption model (1) to calculate the energy consumption of rotary-wing UAVs for a given trajectory, which can include both circular and straight-line flight segments. For fixed-wing UAVs, the simplified power consumption model given by (2) was selected. This model has been used in multiple state-of-the-art works and has also served as a baseline to develop more complex models for energy consumption in 3D trajectories. Additional factors were considered in the integration of this model, due to the flight dynamics and capabilities of fixed-wing UAVs. These UAVs require a minimum curve radius and impose a maximum value for centrifugal acceleration. The original model [6] proposes a maximum acceleration of 5 $\mathrm{m/s^2}$, a value adopted by later studies, which also considered a minimum radius of 5 m. In its current version, eMUAVE

ISBN: 978-3-903176-71-3

introduces the minimum radius constraint of 5 m. While acceleration is not directly limited, as in most state-of-the-art works, maintaining a radius of at least 5 m ensures that acceleration does not significantly exceed the limits considered in other state-of-the-art works. A limitation of this model is related to the parameters c_1 and c_2, used to simulate environmental and UAV characteristics. In [6], the authors assume $c_1 = 9.26 \times 10^{-4}$ and $c_2 = 2250$, resulting in a speed $V_{em} = 30\ m/s$, which leads to the minimum energy consumption and the corresponding minimum propulsion power consumption of $P_{em} = 100\,\mathrm{W}$ during straight-line flight. Equations to calculate these parameters are provided in [6]; however, the parameters used in those equations are not. Due to the inability to obtain environmental and UAV parameters to compute alternative c_1 and c_2 values, eMUAVE currently uses the same values. A fair comparison is achieved by considering rotary-wing UAVs with a comparable minimum propulsion power consumption of $P_{em} = 126\,\mathrm{W}$, as a result of the rotary-wing UAV parameters presented in Table I and in [3].

For each segment of the trajectories with a radius r, eMUAVE calculates the optimal UAV flying speed V, which minimizes power consumption, using optimization methods from the SciPy package [10]. For circular trajectories, a single value for speed and the corresponding power consumption is calculated. For elliptic trajectories, consisting of two straight-line segments and two semicircles, the speed is optimized separately for each segment to ensure the minimum power consumption. In order to calculate the energy consumption over a given period, the power consumption and the time in each segment of these trajectories are considered. For comparison purposes, eMUAVE is also able to calculate the hovering power consumption for rotary-wing UAVs ($V = 0\,\mathrm{m/s}$), as well as the optimal steady-state power consumption, achieved when the FAP moves in a straight line at the optimal speed. By implementing the SUPPLY algorithm, eMUAVE selects the trajectories that minimize power consumption for each FAP and UAV type. Finally, it generates graphical representations of energy consumption per hour. Additional outputs include graphical representations of the intersection areas and SUPPLY trajectories, text files with the FAPs' coordinates over time, and intermediate results such as calculated radii and power metrics.

V. UAV Energy Consumption Evaluation

In order to assess energy consumption for rotary-wing and fixed-wing UAVs following the SUPPLY trajectories, a simulation-based evaluation was performed using eMUAVE. To define SUPPLY trajectories and compute energy consumption, eMUAVE was configured considering the UAV, environment, and network parameters presented in Table I.

A. Energy Evaluation Under Reference Networking Scenarios

The scenarios considered for energy consumption evaluation consist of a variable number of GUs with random heterogeneous QoS requirements, randomly distributed in an area of 100 × 100 meters. Two reference scenarios are considered herein, with 2 GUs and 5 GUs, respectively, as defined in Table II. These scenarios were selected due to the different sizes of the intersection areas, thus resulting in distinct trajectory radii.

TABLE I: Simulation parameters.

Parameter	Value
Rotary-wing UAV weight (W)	20 N
Rotor radius (R)	0.4 m
Blade angular velocity (Ω)	300 rad/s
Incremental correction factor to induced power (k)	0.1
Profile drag coefficient (δ)	0.012
Air density (ρ)	1.225 kg/m^3
Gravitational acceleration (g)	9.8 m/s^2
Rotor disc area (A)	0.503 m^2
Tip speed of the rotor blade (U_{tip})	120 m/s
Fuselage drag ratio (d_0)	0.6
Mean rotor induced velocity in hovering state (v_0)	4.03 m/s
Rotor solidity (s)	0.05
Blade profile power in hovering state (P_b)	79.86 W
Induced power in hovering state (P_{ind})	88.63 W
Fixed-wing parameter 1 (c_1)	9.26×10^{-4}
Fixed-wing parameter 2 (c_2)	2250
Fixed-wing minimum radius	5 m
Wi-Fi Standard	IEEE 802.11ac
Channel bandwidth	160 MHz
Channel frequency	5250 MHz
Guard interval	800 ns
Transmission power	20 dBm
Noise power	-85 dBm

TABLE II: GUs positions and offered load.

Networking Scenario	GUs Positions (x,y,z)	GUs Offered Load (Mbit/s)
2 GUs	(52,67,0), (59,96,0)	43, 76
5 GUs	(19,62,0), (85,46,0), (86,53,0), (2,9,0), (52,88,0)	36, 27, 19, 14, 23

The results for the energy consumption per hour are presented in Fig. 1. In the first scenario, SUPPLY selected the circular trajectory for both UAV types with a large radius ($r = 111\,\mathrm{m}$). Given the large radius, the energy consumption per hour was similar for rotary-wing and fixed-wing UAVs, with 455 kJ and 475 kJ, respectively.

For the second scenario, SUPPLY again selected the circular trajectory for both UAV types. With a smaller radius ($r = 58\,\mathrm{m}$), the energy consumption per hour was 458 kJ for rotary-wing UAVs and 615 kJ for fixed-wing UAVs, representing an increase of 34% for fixed-wing UAVs.

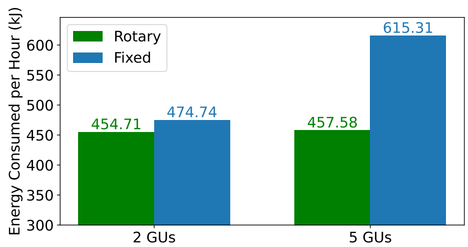

Fig. 1: Energy consumption per hour of rotary and fixed-wing UAVs for the reference scenarios.

ISBN: 978-3-903176-71-3

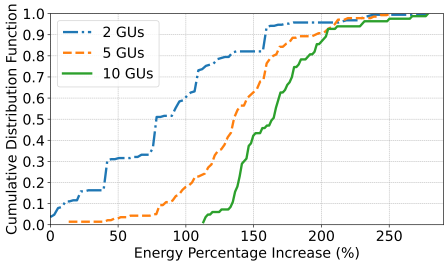

Fig. 2: Percentage increase in energy consumption per hour of fixed-wing UAVs compared to rotary-wing UAVs for each distinct number of GUs.

B. Energy Evaluation for Random Networking Scenarios

Considering randomly generated networking scenarios with a predefined number of GUs and interval for GUs' offered loads, we compared the energy consumption per hour of fixed-wing UAVs and rotary-wing UAVs. We also analyzed how the number of GUs in the network impacts the energy consumption. From the evaluation of reference networking scenarios, we observed that using fixed-wing UAVs generally led to higher energy consumption and that employing fixed-wing UAVs was not always feasible. As such, we focused on understanding: 1) the increase in energy consumption compared to rotary-wing UAVs and 2) the percentage of scenarios where the use of fixed-wing UAVs was not feasible. For this purpose, we generated 200 random scenarios for different numbers of GUs in the network: 2, 5, and 10. The GUs' offered load values were randomly selected from an interval between 0 and 500 Mbit/s divided by the number of GUs in the scenario. Fig. 2 shows the percentage increase in energy consumption per hour compared to rotary-wing UAVs for each number of GUs in the network. The 50^{th} percentile shows an energy increase of 75%, 134%, and 163% for scenarios with 2, 5, and 10 GUs, respectively. The results presented in Fig. 2 include only the networking scenarios where both UAV types could be employed. The scenarios with 2, 5, and 10 GUs showed that using fixed-wing UAVs was not feasible in 5%, 30%, and 59% of cases, respectively.

C. Discussion

We concluded that the SUPPLY algorithm achieves better energy consumption results with rotary-wing UAVs for the reference networking scenarios. Although fixed-wing UAVs can be employed in many scenarios, their use leads to significantly worse energy consumption results. Furthermore, due to the limitations introduced by their flying mechanism, fixed-wing UAVs can not always follow the trajectories defined by the SUPPLY algorithm. This becomes evident for smaller intersection areas. Additionally, the elliptic and inner-elliptic SUPPLY-defined trajectories are not suitable for fixed-wing UAVs, as they either result in higher power consumption or are impossible to employ due to the radius constraint. When considering smaller radii, the power consumption of fixed-wing UAVs increases significantly more than for rotary-wing UAVs. However, it is worth noting that for intersection areas with sufficiently large radii ($r > 100\,\mathrm{m}$), fixed-wing UAVs can achieve energy consumption results similar to rotary-wing UAVs.

The evaluation of random networking scenarios confirms that the SUPPLY algorithm generally achieves better energy consumption results with rotary-wing UAVs. Furthermore, increasing the number of GUs leads to an overall increase in energy consumption for both UAV types. As the number of GUs in the same area increases, SUPPLY tends to generate larger groups, resulting in smaller intersection areas. With a smaller area to place the FAP, SUPPLY defines trajectories characterized by shorter straight-line segments and smaller radii. This greatly impacts the energy consumption of fixed-wing UAVs. Additionally, the number of infeasible scenarios for fixed-wing UAVs increases with the number of GUs, as more trajectories fail to meet the radius constraint imposed by this UAV type.

VI. Conclusion

We proposed eMUAVE, a simulator capable of computing the energy consumption of rotary-wing and fixed-wing UAVs. eMUAVE enables the evaluation and comparison of the energy consumption for both UAV types when following trajectories defined by SUPPLY. Although fixed-wing UAVs can be used in most scenarios, energy consumption is typically higher than for rotary-wing UAVs. Also, fixed-wing UAVs can not hover and often can not follow the SUPPLY-defined trajectories. As such, rotary-wing UAVs are more suitable for FNs using SUPPLY. Future work may explore other networking scenarios suitable for fixed-wing UAVs, especially those where there is no need to follow trajectories with small radii.

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ISBN: 978-3-903176-71-3