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Experimental Evaluation of a UAV-Mounted LEO Satellite Backhaul for Emergency Connectivity

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***Abstract*—Reliable connectivity is critical for Public Protection and Disaster Relief (PPDR) operations, especially in rural or compromised environments where terrestrial infrastructure is unavailable. In such scenarios, Non-Terrestrial Networks (NTNs), and specifically Unmanned Aerial Vehicles (UAVs), are promising candidates to provide on-demand and rapid connectivity on the ground, serving as aerial base stations. In this paper, we implement a setup in which a rotary-wing UAV, equipped with a Starlink Mini terminal, provides Internet connectivity to an emergency ground user in the absence of cellular coverage via Low Earth Orbit (LEO) satellites. The UAV functions as a Wi-Fi access point, while backhauling the ground traffic through the Starlink constellation. We evaluate the system via both network simulations in ns-3 and real-world flight experiments in a rural environment, in terms of throughput, latency, coverage, and energy consumption under static and dynamic flight conditions. Our results demonstrate that the system can maintain a stable uplink throughput of approximately 30 Mbps up to approximately 200 meters, and with minimal impact on the UAV battery lifetime. These findings demonstrate the feasibility of deploying commercial LEO satellite terminals on UAVs as a practical solution for emergency connectivity.**

***Index Terms*—Unmanned Aerial Vehicles (UAVs); Non-Terrestrial Networks (NTNs); Low Earth Orbit (LEO) satellites; Starlink; emergency communications; experimental analysis.**

I. INTRODUCTION

Communication networks play a crucial role in Public Protection and Disaster Relief (PPDR) operations, to protect lives and ensure public safety, enable first responders and authorities to rapidly coordinate emergency interventions, and allocate personnel and equipment efficiently. As the number and severity of natural disasters (e.g., fires, floods, earthquakes, tsunamis, volcano eruptions) increases globally, and as armed conflicts and humanitarian crises evolve in scale and complexity, robust PPDR systems are vital to maintain reliable communication during emergencies [1], [2].

In recent years, Non-Terrestrial Networks (NTNs) [3] based on aerial and spaceborne platforms have emerged as a key component of 6th generation (6G) wireless systems [4] to provide wide-area coverage beyond the limits of terrestrial cellular networks, e.g., in rural and/or remote areas, and rapidly restore connectivity in disaster areas where ground infrastructure is either absent or compromised [5]. In particular, Unmanned Aerial Vehicles (UAVs) such as drones can act as flexible, fast-to-deploy, plug-and-play aerial base stations and edge nodes [6], to dynamically provide access connectivity to ground nodes in hard-to-reach areas where first responders cannot easily operate [7], [8]. Another approach for PPDR is to rely on Low Earth Orbit (LEO) satellites. Unlike Geostationary Earth Orbit (GEO) satellites, LEO satellites operate much closer to the Earth, typically between 300 and 1 000 km, which enables similar latency and throughput as in terrestrial networks [9]. Notably, LEO satellites can provide direct Internet connectivity by either relaying data to ground gateways (transparent payload) or processing data onboard (regenerative payload), making them particularly attractive for emergency connectivity [10]. In this context, Starlink, serving more than 8 million customers as of November 2025, represents one of the most mature examples of satellite-based Internet solutions, providing service performance comparable to that of many 4G and 5G cellular operators, particularly in rural or underserved areas [11], [12].

The scientific community is also exploring the integration of LEO satellite terminals directly onto rotary-wing UAVs. Specifically, UAVs can serve as aerial access points for ground users, and ultimately relay data traffic through the LEO satellite network to the Internet. For instance, Almeida *et al.* [13] demonstrated a framework where a UAV equipped with object detection capabilities served as an aerial mobile 5G base station via Starlink. While the system was able to support direct-to-smartphone connectivity, the satellite antenna was not mounted on the drone itself but rather on the ground, so the UAV could only operate within the immediate vicinity of the ground station. Conversely, Jordan *et al.* [14] successfully deployed a Starlink system on an Ultra UAV (a large fixed-wing platform) for scientific data collection in Antarctica. Despite the mission's success, the authors noted that significant design iterations were required to reduce weight and power consumption for routine operations. Similarly, Liu *et al.* [15] tested Starlink onto a Unitree GO2 Robot Dog, providing valuable datasets for satellite communication, even though the dynamics, energy, and payload constraints of a wheeled robot are fundamentally different from those of a rotary-wing UAV.

Compared to prior work, in this paper we implement a setup in which a Starlink Mini is directly mounted onto a commercial rotary-wing X8-1000 Pro RTK UAV. Specifically, a ground user connects to the UAV via Wi-Fi, while Internet access is provided through the Starlink constellation. We test this system via real-world experiments in a rural area near Catania with no cellular coverage, measuring throughput, latency, coverage, and energy consumption under static and dynamic flight conditions. Our results demonstrate that the

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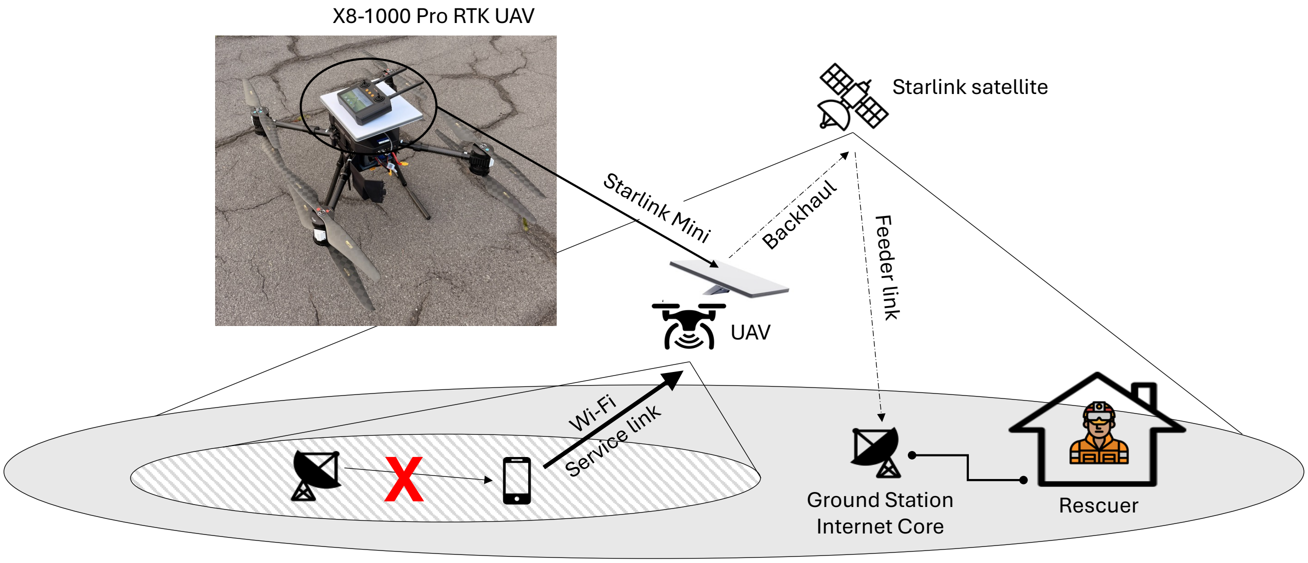

Fig. 1: A disaster-relief PPDR scenario in which a rotary-wing UAV drone, mounting a Starlink Mini antenna terminal, relays data traffic from a ground user via Wi-Fi to the rescuer through a Starlink satellite backhaul link.

drone can support the weight of the Starlink antenna, reducing the flight time by only about 8%. Moreover, we measure a stable uplink throughput of approximately 30 Mbps over a range of 200 meters, thereby demonstrating that this setup provides a stable and robust backhaul connectivity solution for PPDR. Our experimental results have been validated by laboratory simulations using `ns3-NTN`, an open-source ns-3 module that simulates full-stack satellite communication based on the 3rd Generation Partnership Project (3GPP) specifications [16].

The paper is organized as follows. Sec. II describes our scenario and motivations, Sec. III presents the experimental and simulation setups, Sec. IV presents our test results, and Sec. V concludes the paper with suggestions for future work.

II. SCENARIO AND OBJECTIVES

A. Motivations

In a PPDR scenario, sudden natural or human-made events compromise traditional communication infrastructures, particularly power lines, fiber backhaul links, base stations, and core network nodes. Such disruptions are particularly severe in rural or otherwise underserved regions where network redundancy is limited. For example, the 6.2-magnitude earthquake that struck central Italy in August 2016 devastated towns such as Amatrice and Norcia, leaving them without telephone or Internet access for several days due to damaged power lines and telecommunication cables [17]. More recently, in May 2023, severe flooding and landslides in the Emilia-Romagna region of Italy resulted in Internet outages for more than 30,000 users in the affected areas [18], and impaired rescue operations.

In this scenario, UAVs may serve as mobile base stations from the sky [19], providing a reliable local network for PPDR operators and ground teams when terrestrial infrastructure is unavailable. Moreover, UAVs can carry sensing payloads such as optical, infrared, or thermal cameras to assist search-and-rescue (SAR) operations by detecting survivors or other points of interest in real time [20]. On top of this, UAVs can provide on-demand connectivity for other time-critical or infrastructure-limited applications, such as remote industrial inspections, environmental monitoring, and agricultural or forestry management, while collecting and transmitting relevant data in real time. However, UAVs generally require a reliable Line of Sight (LOS) connection link with a nearby terrestrial base station to relay the access ground traffic or local sensing data to the Internet, which is often unavailable in disaster scenarios [21].

Satellites can also provide robust, wide-area, and uninterrupted Internet connectivity during emergencies. For example, during recent weather disasters in Italy, Starlink satellites were reported to support an average Internet throughput of around 50 Mbps [17], up to three times faster than ground networks in disrupted zones. However, current architectures require user terminals to mount relatively large antenna panels (e.g., Starlink terminals) to connect to the satellites, which cannot be integrated into commercial user devices such as smartphones, thereby making direct-to-device standalone satellite connectivity difficult to achieve.

B. Our PPDR Scenario

To solve the issues of standalone UAV or satellite communication systems, we consider the PPDR scenario illustrated in Fig. 1. Specifically, we consider a multi-role rotary-wing UAV drone with both sensing and communication capabilities. In its communication role, it acts as a mobile aerial Wi-Fi gateway providing access connectivity to ground users located in disaster areas where terrestrial networks are unavailable. To establish a backhaul link to the Internet, otherwise unavailable, the UAV carries a Starlink Mini antenna terminal in the payload, which relays the ground traffic to a Starlink satellite. From there, data is transmitted to a ground station and

Fig. 2: Some of the authors of the paper with the X8-1000 Pro RTK UAV drone, mounting a Starlink Mini antenna terminal (left). An aerial overview of the experimental rural area near Catania (right).

ultimately routed to the Internet, to support PPDR operations in the rescue center.[1]

The primary goal of our research is to evaluate the operational limits and feasibility of an integrated UAV-satellite mobile gateway system as a practical solution to provide emergency Internet connectivity. We will demonstrate via field experiments and computer simulations that transporting a Starlink Mini antenna on a drone is possible in terms of payload weight and capacity, energy consumption, aerodynamics, and communication performance.

III. EXPERIMENTAL AND SIMULATION SETUP

In this section we describe our experimental (Sec. III-A) and simulation setup (Sec. III-B).

A. *Experimental Setup*

Our experimental setup, illustrated in Fig. 2, is conceptually designed as a rapidly deployable flying backhaul system for disaster areas where traditional terrestrial networks are damaged or offline. The architecture integrates a commercial off-the-shelf UAV with a LEO satellite antenna terminal to create a mobile relay node.

a) UAV: The aerial node is a DroneBase X8-1000 Pro RTK octocopter.[2] This platform was selected for its high payload capacity (up to 10 kg) and strong stability in adverse conditions, including resistance to high winds (up to 35 knots), which are essential requirements for maintaining reliable satellite alignment. Moreover, the drone utilizes a Dual-Antenna RTK GNSS module to achieve centimeter-level positioning accuracy, a critical capability for PPDR applications such as photogrammetry, mapping, and SAR missions. To ensure sufficient flight endurance, the propulsion system is powered by two high-voltage lithium-polymer (LiPoHV) batteries with a 6S configuration (22.8 V) and a capacity of 30 000 mAh each. This configuration enables competitive flight times of up to 50 minutes, even when operating at full payload capacity.

b) LEO satellite antenna terminal: The communication payload consists of a flat-panel Starlink Mini antenna.[3] This terminal was selected for its compact dimensions (298.5 × 259 × 38.5 mm), low weight (1.16 kg), and reduced power consumption (25-40 W), so it can be integrated within the drone's maximum takeoff weight constraints. The antenna is an Electronic Phased Array (EPA), which eliminates the need for mechanical steering, and permits to track multiple Starlink satellites simultaneously within a 110° field of view. Starlink Mini performs a dual function: it provides a backhaul link to the Starlink LEO satellite constellation, and simultaneously acts as a Wi-Fi access point broadcasting a local network for ground users. The Wi-Fi module is a Dual Band Wi-Fi 5 (802.11a/b/g/n/ac) router, supporting coverage to up to 128 connected devices, across an area of up to 112 m^2.

At its core, the Starlink constellation, operated by SpaceX, currently consists of around 9 000 LEO satellites, deployed across multiple orbital shells with different inclinations, at altitudes around 550-570 km. It enables near-global coverage, with an average downlink (uplink) speed of around 110 (15) Mbps and Round Trip Times (RTTs) below 40 ms [22]. The satellites operate primarily in the Ku-band at 10.7–12.7 GHz (downlink) and 14–14.5 GHz (uplink), and in the Ka-band at 17.8–18.6 GHz and 18.8–19.3 GHz (downlink) and 27.5–30 GHz (uplink), subject to regional authorisations [23].

c) Ground User Equipment (UE): The user segment consists of a Lenovo Yoga S730 laptop, which connects to the aerial node via standard Wi-Fi protocols.

B. *Simulation Setup*

To validate on-the-field flight measurements, we reproduced our target scenario in ns-3, a widely adopted and reliable

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[1] It is not publicly known whether Starlink satellites operate in a bent-pipe mode (i.e., connecting directly to ground gateways via transparent payloads) as in first-generation satellites, or they leverage regenerative payload techniques (which would make it possible to use inter-satellite links for traffic routing) as seen in second-generation satellites. For simplicity, in Fig. 1 we depict the former option.

[2] DroneBase Professional: https://dronebase.it/en/professional-drones/.

[3] Starlink Mini: https://starlink.com/specifications.

framework for end-to-end network simulation. Specifically, we use the `ns3-NTN` module [16],[4] an open-source extension of ns-3 that we developed to simulate full-stack satellite communication according to the 3GPP 5G NR-NTN Release 17+ specifications. This module implements the 3GPP NTN channel model based on [24], incorporating path loss, atmospheric absorption, scintillation, and frequency-dependent fading in the S-, L-, and Ka-bands. Moreover it includes antenna models for circular aperture, Very Small Aperture Terminal (VSAT), and Uniform Planar Array (UPA) configurations from [25], and an NTN-oriented Earth-Centered, Earth-Fixed (ECEF) Cartesian coordinate system. It also implements timing advance mechanisms [26] and customized Radio Resource Control (RRC) and Hybrid Automatic Repeat reQuest (HARQ) timers [25] for precise propagation delay computation. The accuracy of `ns3-NTN` has been validated against 3GPP calibration results in [10], [16], and currently appears as one of the most reliable and accessible software tools for NTN simulations.

In this work, the module has been further extended to simulate the multi-layer communication setup considered in this paper, specifically for Earth-UAV-satellite links.

IV. REAL-WORLD TESTS AND RESULTS

Experimental tests were conducted in a rural area near Catania (Sicily, Italy) with minimal radio frequency interference and quasi-perfect LOS between the UAV and the ground UE, as illustrated in Fig. 2 (right). All flight tests were performed under optimal weather conditions, characterized by clear skies and minimal cloud cover, to establish a performance baseline with negligible atmospheric attenuation or rain fade.

We evaluate the system's performance in terms of throughput, RTT, signal stability, and energy consumption, using the iperf3 network testing tool. Field measurements were collected under both static and dynamic flight conditions, where the UAV was either in stationary hovering or in constant motion, at a constant height of 20 meters.

a) Static hovering: In Fig. 3 we evaluate the average downlink (DL) and uplink (UL) throughput when the UAV is in stationary hovering, gradually increasing the horizontal distance between the ground UE and the UAV up to 250 m. In these tests, we quantify the link degradation over distance to determine the maximum effective range of the system.

First, we observe that there is a close match between the experimental (solid bars) and simulation results with `ns3-NTN` (striped bars), which demonstrates the mutual accuracy of our simulator and experimental platform. For the DL case, the maximum throughput is around 90 Mbps within the 0-50 m range, corresponding to optimal link conditions, which is consistent with typical Starlink network performance reported in previous studies [22]. Then, the throughput starts to decrease as the horizontal distance between the ground UE and the UAV increases, dropping to around 30 Mbps in the 150-200 m range, and the link is completely lost beyond 200 m. This behavior highlights that, when the UE and the UAV are too far (more than 200 m in our results), the performance degrades both in UL and DL due to the failure of the Wi-Fi link, as expected. On the other hand, for shorter distances the Wi-Fi link works well, but a different behavior is observed in the two directions. Specifically, in the DL the throughput keeps increasing as the distance decreases, whereas in the UL it saturates at around 25-30 Mbps, showing that in this case the bottleneck is due to the limited Starlink capacity. Despite this difference, these results demonstrate that it is possible to establish effective DL and UL Internet connectivity to and from the ground via satellites, using a UAV both as a relay and as a backhaul node.

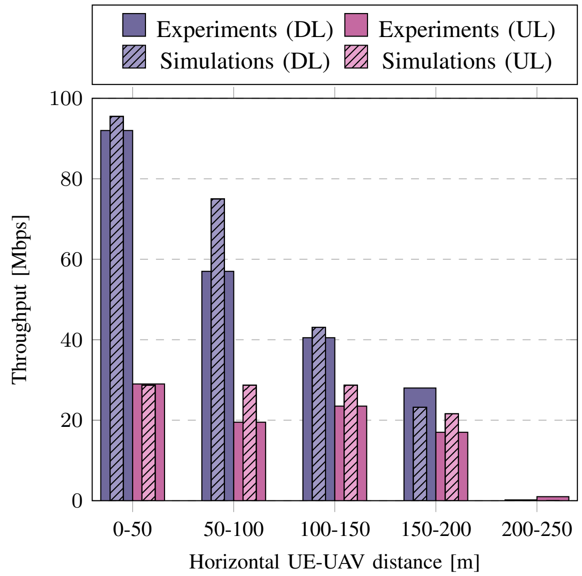

Fig. 3: Average DL and UL throughput in static hovering vs. the horizontal distance between the UE and the UAV. Solid bars are for real-world experiments, while striped bars are for ns-3 simulations.

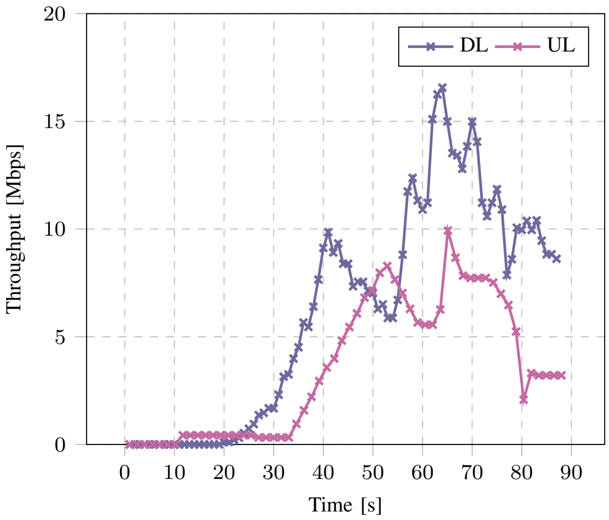

Fig. 4: Evolution of the DL and UL throughput during dynamic flight, as the UAV moves from an initial horizontal distance of 250 m toward the UE at a constant speed of approximately 2.5 m/s.

b) Dynamic mobility: In these tests we assess the resilience of the system during active flight, with the UAV in constant motion. In Fig. 4 we plot the DL and UL throughput

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[4] The source code of the module: https://gitlab.com/mattiasandri/ns-3-ntn.

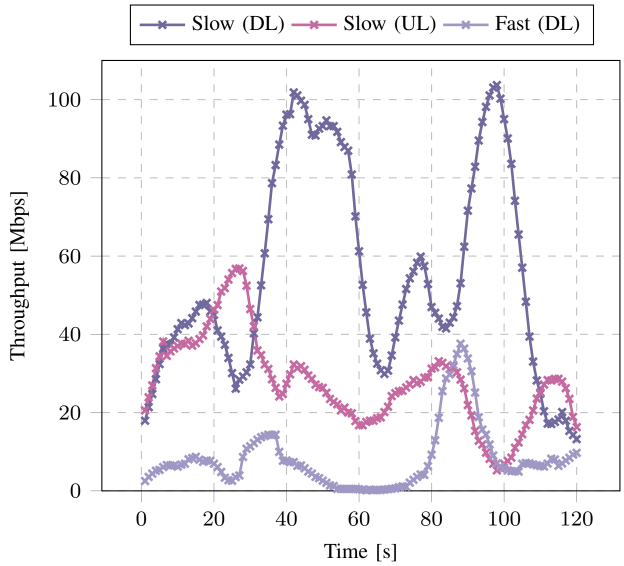

Fig. 5: Evolution of the DL and UL throughput under “Slow” (limited speed and modest orientation changes) and “Fast” (complex maneuvers at higher speed) mobility conditions.

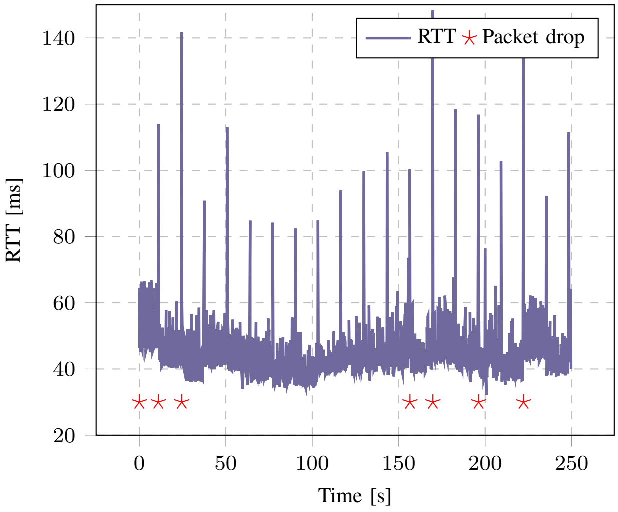

Fig. 6: Evolution of the RTT, with packet drop events.

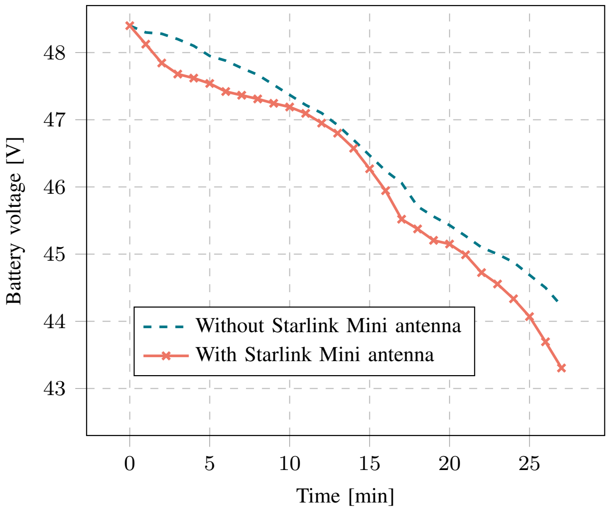

Fig. 7: Evolution of the battery voltage at the UAV, with and without the Starlink Mini antenna payload.

as the UAV moves from a horizontal distance of 250 m toward the UE at constant velocity. We recognize different regimes. At first, the throughput is nearly zero since the Wi-Fi link is unavailable beyond 200 m, confirming our results in Fig. 3. Then, as the UAV approaches the UE, the Wi-Fi link finally activates, and the DL (UL) throughput gradually increases up to around 18 (10) Mbps after around 65 s (when the distance to the drone is around 100 m). Nevertheless, we observe that the throughput is quite unstable. This behavior was also recorded in offline tests where the Starlink Mini antenna was mounted on the ground and connected to the UE via a wired Ethernet link. Therefore, we conclude that this instability is inherent to the satellite backhaul itself, and independent of the UAV mobility or the local Wi-Fi connection.

Then, in Fig. 5 we test the system under more dynamic conditions. The UAV either flies slowly with limited speed, at about 2 m/s, and modest orientation changes (“Slow”), or executes more complex maneuvers at higher speed, changing attitude and pitch angles (“Fast”). At high speed, we observe occasional link failures and throughput degradation, for example around 60 s. This is because the UAV dynamics may compromise the ability of the Starlink antenna to maintain precise alignment with the satellites. Conversely, at slow speed, both DL and UL links remain fully usable, despite some fluctuations, even without manual or mechanical antenna pointing, which confirms the robust operation of the proposed system.

c) Latency: Latency in NTN is predominately governed by the propagation delay due to the long distance between the ground and the satellites. In the case of Starlink, LEO constellations provide competitive RTTs compared to other satellite solutions, often below 50 ms, but need frequent handovers as satellites move rapidly with respect to the Earth.

In Fig. 6, we consider a static hovering scenario, and show the RTT of the network for a single packet (ping), measured from the time when data is generated at the ground UE to when it is received at the ground station via the UAV-satellite network, and in the reverse direction. Star marks indicate packet drop events. As expected, the RTT is generally lower than 50 ms, though with periodic, high-magnitude spikes up to 140 ms at regular intervals of approximately 13 s. This systematic timing is indicative of Starlink-specific constellation management protocols that trigger handovers and require time-consuming signaling procedures, e.g., for path re-routing and re-initialization. We mainly attribute these spikes to either intra-satellite inter-beam handovers, where the UE switches between different beams of the same satellite, or inter-satellite handovers, where the UE associates with a different satellite. Occasional packet drops are also recorded, suggesting that data loss may occur during handover.

d) Energy consumption: Finally, in Fig. 7 we evaluate the energy consumption at the UAV in terms of battery voltage levels both with and without the Starlink Mini antenna payload. We observe that the additional weight of the Starlink hardware has a minor impact on energy depletion. After 27 minutes of flight, the Starlink configuration showed a voltage drop of 0.9 V compared to the baseline. Given our operational range (48.5 V to 42 V representing 100% to 30% capacity), this corresponds to a 9% reduction in remaining state of charge at the 27-minute mark. This result demonstrates that the proposed PPDR system is not only able to effectively provide Internet connectivity, but also sustainable with respect to mission duration.

V. Conclusions and Future Works

In this paper we successfully demonstrated via field experiments near Catania (Italy) and ns-3 simulations a functional prototype in which a UAV drone, mounting a Starlink antenna terminal, rapidly provides Internet access and backhaul connectivity for PPDR operations in otherwise unserved areas. The throughput analysis revealed an asymmetric behavior; DL capacity is primarily constrained by the local Wi-Fi link, with signal degradation at a distance of around 150-200 m; conversely, the UL capacity is bottlenecked by the satellite backhaul link. Dynamic tests demonstrated that UAV velocity and maneuvering can, under certain circumstances, severely compromise the throughput, even though the system remains fully operational at moderate speeds, even with no mechanical antenna pointing. The system supports a low RTT of around 40–50 ms, but systematic periodic latency spikes and occasional packet drop events were observed every 13 seconds, likely due to satellite handovers. Finally, the Starlink payload consumes little energy onboard the UAV, and the flight time is reduced by only 8%.

As part of our future work, we will explore alternative terrestrial access technologies beyond Wi-Fi, such as 5G NR. We will also test a closed-loop PPDR scenario where a UAV collects opportunistic 5G NR UL control signals to localize UEs, and communicates with the ground station for SAR support via the proposed UAV-satellite backhaul architecture.

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