An Indoor Experimental Testbed for 5G-based UAV Control and Communication

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***Abstract*—The integration of Unmanned Aerial Vehicles (UAVs) into next-generation mobile networks is widely recognized as a key enabler of disruptive applications, where aerial platforms may function either as network nodes or as advanced network users supporting a variety of services. Unfortunately, experimental testbeds in which UAVs perform tasks while communicating with ground infrastructure over Fifth-Generation (5G) networks remain scarce, primarily due to the challenges posed by legal restrictions on Beyond Line-of-Sight (BLoS) and autonomous operations. Motivated by this need, this work presents the design, implementation, and evaluation of a novel indoor experimental testbed for assessing the performance of UAV-based systems operating over 5G networks. The testbed features an autonomously controlled quadcopter equipped with a 5G modem, connected to a private 5G network implemented using Software-Defined Radio (SDR) technology and the OpenAirInterface (OAI) framework. To ensure a controlled environment, a motion capture system is used to provide absolute indoor positioning data, emulating Global Navigation Satellite System (GNSS) coordinates without relying on external satellites. A preliminary experimental campaign is conducted to evaluate the proposed system in terms of 5G network performance, radio link characteristics, and UAV platform energy consumption.**

***Index Terms*—Unmanned Aerial Vehicle, 5G Networks, Experimental Testbed**

I. Introduction

Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, have emerged as versatile platforms across a wide range of civil, industrial, and military applications [1], [2]. Due to their high mobility, UAVs are expected to play a pivotal role in providing adaptive coverage and enhanced connectivity in Fifth-Generation (5G) and beyond [3].

Inside a wireless ecosystem, UAVs can assume a dual role. As *network nodes*, UAVs can act as mobile base stations, relay points, or airborne edge computing units [4], contributing to enhanced coverage, improved network flexibility, and rapid deployment in both regular and emergency scenarios [3]. Specifically, in disaster recovery situations, UAVs equipped with communication payloads can be swiftly deployed to restore connectivity by replacing damaged infrastructure [5]. Nevertheless, their deployment is constrained by factors such as limited battery life, payload capacity, and vulnerability to adverse weather conditions [6]. In high-demand environments, such as stadiums or festivals, UAVs can serve as temporary base stations or relays to offload traffic from congested terrestrial networks, although managing interference and maintaining safe, secure flight operations near crowds remains a significant challenge [6]. In contrast, in remote or rural regions where fixed infrastructure is either unavailable or economically impractical, UAVs offer flexible, on-demand coverage solutions [5]. However, their deployment is often constrained by limited backhaul connectivity and operational costs. Beyond communication roles, UAVs can also act as airborne edge computing nodes [7], processing data closer to users or Internet of Things (IoT) devices to minimize latency in latency-sensitive applications [8]. Achieving this, however, necessitates a careful trade-off between computational demands and the UAVs' limited energy resources [9].

On the other hand, UAVs can also act as *connected users* (i.e., User Equipments (UEs)) within the network, unlocking emerging applications that depend on seamless mobile connectivity [10]. In logistics, UAVs facilitate autonomous parcel delivery across urban and rural areas, demanding precise navigation, real-time telemetry, and ultra-reliable, low-latency command-and-control links [11]. In safety and disaster response scenarios, UAVs capture and transmit high-definition video streams and sensor data, significantly enhancing situational awareness and supporting timely decision-making [12]. Additionally, in agriculture and infrastructure inspection, UAVs gather and upload extensive volumes of high-resolution images and sensor data for subsequent cloud-based processing and analysis [9], [13].

Although several experimental testbeds employing UAVs connected via Wi-Fi, Long Term Evolution (LTE), or 5G have been proposed in the literature [14]–[18], their deployment in outdoor environments is frequently constrained by stringent regulatory frameworks. For example, current European Union regulations impose rigorous restrictions on Beyond Visual Line-of-Sight (BVLoS) operations and autonomous UAV control in public airspace, hindering the validation of such systems in real outdoor contexts [19]. Conversely, indoor testbeds using UAVs often lack an absolute reference positioning system, posing significant safety risks as accurate localization is essential for secure and reliable autonomous flight [20].

To address these challenges, this paper introduces a novel indoor testbed specifically designed for the development and

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evaluation of 5G-enabled UAV systems. The proposed testbed features a quadcopter UAV platform equipped with a 5G modem, mainly acting as UE, which interfaces with a 5G network built using OpenAirInterface5G [21], [22] and implemented using Software Defined Radio (SDR) platforms. To emulate realistic navigation scenarios without relying on satellite infrastructure, the testbed integrates a high-precision motion capture system that maps indoor positions to synthetic Global Navigation Satellite System (GNSS) coordinates. An experimental campaign is conducted to validate the proposed testbed, focusing on key aspects such as network performance, radio link stability, and energy efficiency of the UAV platform.

II. Overview of Experimental UAV Testbeds in Wireless Networks

A variety of testbeds incorporating single or multiple UAVs into wireless communication systems have been proposed in the literature, aiming to explore their potential in both connectivity and autonomous operation.

In [14], the authors present a system for remote navigation and monitoring of a UAV swarm, leveraging a Wi-Fi mesh network for inter-UAV communication and LTE connectivity for linking with a ground control station. The system was experimentally validated in an outdoor environment using a Real-Time Kinematic (RTK) platform, which enabled centimetre-level positioning accuracy through GNSS augmentation. However, the lack of environmental control in the outdoor setting led the authors to restrict swarm scenario evaluations to a simulation environment. Moreover, the reliance on a commercial Internet Service Provider (ISP)-provided mobile connection prevents exploration of deeper integration between UAVs and the underlying network infrastructure.

In [15], a multi-UAVs testbed based on the Robot Operating System (ROS) framework is presented, aimed at ensuring uninterrupted service delivery. The proposed approach was validated through an experimental campaign focused on demonstrating the ability to maintain continuous coverage by dynamically alternating UAVs at the service location, replacing depleted units with fully charged ones. Outdoor positioning was achieved using GNSS receivers, while communication relied on a Wi-Fi-based network, which inherently limits the system operational range due to coverage constraints.

The study in [16] is the first to introduce the concept of *Rebots*, namely relay robots deployed as aerial nodes to extend wireless network coverage. A Rebot functions by relaying data to a designated Base Station (BS) over a wireless link, while also leveraging channel measurements to support its own geographical positioning. The proposed testbed is built on the OpenAirInterface LTE platform, and experimental results demonstrate the effectiveness of Rebots in dynamically and efficiently enhancing network reach through airborne relaying.

The potential for integrating a 5G Node B (gNB) within a UAV platform is examined in [17] and [18]. The former considers a commercial UAV carrying an onboard computer running a full 5G architecture, i.e. gNB and Core Network (CN), and providing wireless access through a small-size SDR. Experimental evaluations are carried out in an outdoor environment enclosed by a safety net, enabling the use of GNSS-based positioning. Building on this setup, the authors propose a UAV-BS platform with a similar configuration, designed to assess the performance of three traffic-aware positioning algorithms. A dedicated middleware supports this evaluation by computing the optimal UAV placement based on user traffic demand and real-time channel quality metrics.

Finally, the study in [20] investigates the performance and key capabilities of a 5G system in which a UAV operates as a UE, autonomously controlled by a script executed on another node within the same 5G network. Given the indoor nature of the experimental setup, the UAV relies on onboard sensors, such as Light Detection and Ranging (LiDAR), for navigation and environmental perception in the absence of GNSS signals.

III. Proposed In-Lab 5G-enabled UAV Testbed

This section presents the overall architecture of the proposed testbed, designed to evaluate UAV-based autonomous missions supported by a 5G network. The system, deployed at the *RESTART iTNT-NS* laboratory of the Polytechnic University of Bari (Italy), consists of three main components, as shown in Fig. 1: i) a bounded indoor *Flying Area*, equipped with a motion capture system (Vicon) for high-precision tracking of physical objects; ii) a powerful workstation serving as *Ground Station* and featuring a Wi-Fi network interface, the full 5G protocol stack, and a SDR; iii) a proof-of-concept *UAV*, integrating all components required to establish a 5G connection with the ground station and to interact with the motion capture system. In the following, we provide a detailed description of each involved component.

A. Hardware Components

The flying area, shown on the right side of Fig. 1, is an indoor zone enclosed by safety nets and equipped with a rubberized floor. This setup was specifically chosen to minimize damage in the event of a malfunction, as the nets can safely catch the UAVs during unintended impacts. The flight zone is surrounded by a Vicon motion capture system composed of 18 Vicon Vero cameras. These cameras emit stroboscopic infrared light to detect the reflective markers placed on rigid bodies. With the aid of Vicon Tracker software, custom marker configurations can be set up and tracked in real time, enabling precise localization within the flying area [23].

The ground station, reported in the middle of Fig. 1, is implemented using a high-performance workstation running Ubuntu 24.04 LTS. It is equipped with an AMD Ryzen Threadripper PRO 5965WX processor, 128 GB of DDR4 RAM, and an NVIDIA GeForce RTX 4070 Ti GPU. To serve as the RF front-end of the gNB in the private 5G network, a USRP X410 SDR is employed. The workstation connects to the USRP via a 4xSFP28-to-QSFP28 network cable, supporting data rates of up to 100 Gbps. This high-throughput link ensures the low-latency performance required for real-time 5G operations.

The UAV platform is a fully customized quadcopter, shown on the left side of Fig. 1, specifically designed to support both

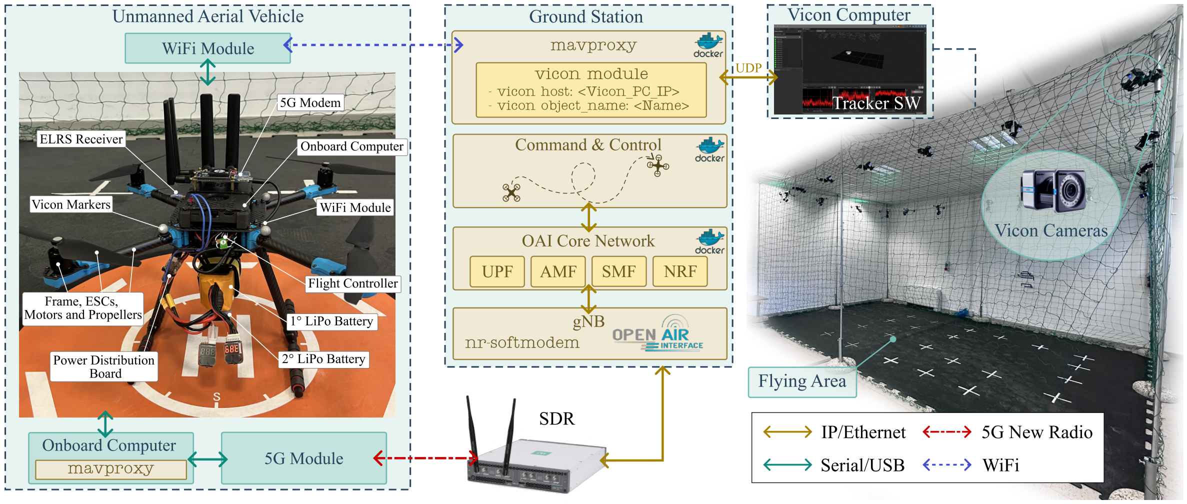

Fig. 1. Comprehensive representation of the proposed 5G-based indoor UAV testbed, including the main software and hardware components.

5G-based communication and GNSS emulation. It is worth noting that the testbed is scalable and can support multiple UAVs simultaneously, as long as they possess equivalent connectivity capabilities, even if built on different hardware platforms. The quadcopter is assembled around the Holybro X500 V2 frame, which comes equipped with pre-installed motors, Electronic Speed Controls (ESCs), a power distribution board, and propellers. At the heart of the control system, there is a Pixhawk 6C flight controller, interfacing with onboard sensors and peripheral devices through serial connections. For flight control, we employ the ArduPilot Copter firmware, which supports the MAVLink protocol for real-time command, telemetry exchange, and integration with ground control systems [24]. To ensure manual fallback procedures (e.g., triggering `LAND` mode in case of a system failure), the quadcopter is equipped with an ExpressLRS (ELRS) receiver, which is paired with a compatible Radio Controller (RC). A SIM8262E-M2 5G modem connected via a high-speed USB 3.0 interface to a LattePanda 3 Delta single-board computer enables autonomous mission execution. The latter communicates with the flight controller via a serial connection to gather telemetry data and enforce control commands exploiting the `GUIDED` mode. Similarly, an ESP8266 Wi-Fi module interfaces with the flight controller via a serial connection, bridging virtual GNSS data between the motion capture system and the flight controller. Finally, two independent Lithium Polymer (LiPo) batteries power all the onboard hardware: one is dedicated to the onboard computer, and the other provides high current outputs to the motors. Although this choice may appear counterintuitive due to the added weight, as we will show in Sec. IV, the highly dynamic behaviour of the UAV leads to voltage fluctuations that could jeopardize the operation of the onboard computer.

B. Indoor Localization System

In typical outdoor UAV operations, geolocation is achieved using GNSS receivers. In their absence, such as in indoor environments, onboard sensors like accelerometers, gyroscopes, and LiDAR can provide situational awareness. However, these sensors are prone to measurement drift, potentially causing undetectable deviations in flight. To address this, the proposed testbed incorporates an indoor localization system, enabling safe and controlled prototype development. Once the development phase is complete and validated within the testbed, the emulation system can be replaced with a real GNSS receiver, allowing the UAV to transition to outdoor deployment.

Infrared data from the Vicon cameras is collected by a dedicated computer and processed in real time using the Vicon Tracker software, which continuously outputs high-precision pose estimates of the tracked object — in this case the UAV — via a UDP service. To relay this data to the UAV's flight controller, an instance of MAVProxy (with the Vicon module enabled) runs as a Docker container on the ground station. This module parses the Tracker's output and converts it into MAVLink-compatible messages (specifically, `GPS_INPUT`). These messages are injected into the MAVLink stream via MAVProxy and sent over Wi-Fi to the UAV using an onboard ESP8266 module configured as a Serial-to-Wi-Fi bridge. The flight controller receives the positioning data through its serial interface and integrates it into its internal estimation filter, effectively emulating conventional GNSS-based pose estimation. This setup provides the UAV with absolute positioning awareness within the indoor environment, enabling precise hovering, navigation, and control.

C. 5G-enabled UAV Command & Control

To set up a private 5G network, we used the OpenAirInterface5G software stack. Specifically, the 5G standalone architecture comprises an OpenAirInterface (OAI) 5G Core (5GC) and an OAI gNB, both of which are executed on the ground station. The 5GC is deployed using Docker; Access and Mobility Management Function (AMF), Session Management Function (SMF), Authentication Server Function (AUSF), Unified Data Management (UDM), Network Repository Function (NRF), and User Plane Function (UPF) run

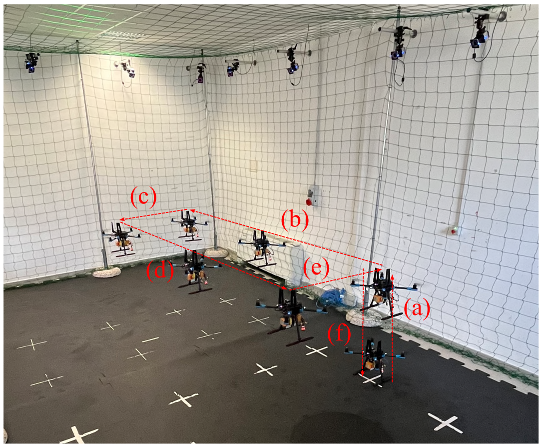

Fig. 2. Overlay of multiple UAV positions captured along an autonomous flight path.

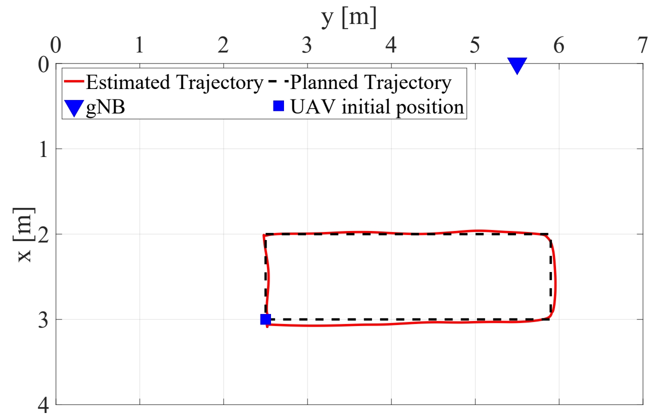

Fig. 3. 2D plot of the estimated trajectory executed by the UAV, compared with the planned trajectory, including the positions of the gNB and the UAV's initial position.

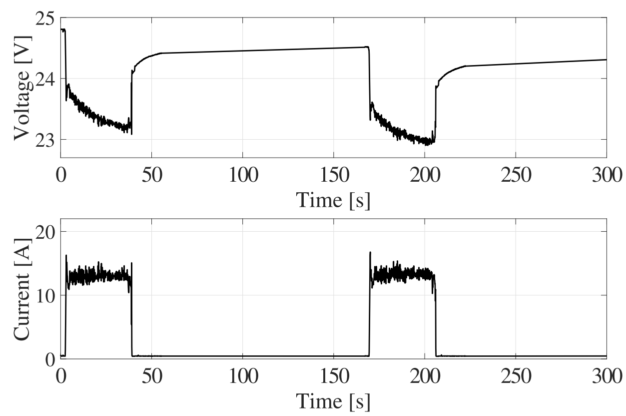

Fig. 4. Evolution of the battery voltage and output current over two consecutive missions, provided by the UAV flight controller logs.

in isolated containers to ensure modularity and scalability. The gNB is executed through the `nr-softmodem` command and can be configured via specific configuration files or command-line flags at runtime. This offers complete control over all the essential parameters required to establish end-to-end connectivity. The USRP X410 SDR is employed for the RF frontend, configuring all the necessary parameters while executing the gNB software. Using a programmable SIM card, the UAV's embedded 5G modem can register with this network by exchanging all the necessary identifiers and cryptographic parameters (e.g., IMSI, key, MCC/MNC). We point out that, to reduce computational effort, a Linux Operating System (OS) without a Graphical User Interface (GUI) is installed on the onboard computer. All the modem-related procedures are handled using the `mmcli` software suite.

When the overall system is running, it is possible to establish a network connection between the UAV companion computer and the `oai-ext-dn` container provided by OAI, which mimics an external data network node. On the onboard computer, an instance of MAVProxy — a bridging software based on the MAVLink protocol — is executed. MAVProxy allows the flight controller (connected via a serial port) to exchange MAVLink packets, including telemetry, position updates, and control messages, with another node over the 5G network. On the ground station, the Command & Control node is built using the `oai-ext-dn` container images. Specifically, it runs mission planning Python scripts created using the DroneKit and Pymavlink libraries. These scripts manage key flight operations, including switching the UAV's mode to `GUIDED`, executing automated take-off and landing procedures, and commanding movement along the x, y, and z axes to reach designated positions.

IV. Experimental Results

This section presents an experimental campaign conducted to evaluate the proposed testbed, validate its functionality, and derive key insights. All measurements were carried out within the indoor flying area, which measures $7 \times 4 \times 3\,\mathrm{m}$. The reference coordinate system is placed at the corner closest to the viewpoint of Fig. 1, with the x-axis aligned along the shorter side and the y-axis along the longer side of the area. The UAV centre of gravity is initially located at $[3\ 2.5\ 0.2]\ \mathrm{m}$, while the gNB lays on a desk overlooking the flying area at $[0\ 5.5\ 0.5]\ \mathrm{m}$. The latter is configured to work in the New Radio (NR) band *n77*, with a carrier frequency of $3995\,\mathrm{MHz}$ (allocated by the Italian government), and a Time Division Duplex (TDD) scheme. The Sub Carrier Spacing (SCS) is set to $30\,\mathrm{kHz}$, and the 5G network performance is evaluated under different bandwidths by varying the number of Physical Resource Blocks (PRBs).

As concerns the planned mission, the script used for all the experiments controls the UAV to follow the trajectory shown in Fig. 2, where multiple UAV positions, estimated by the Vicon localization system during the flight, are superimposed in a single image. Specifically, *(a)* the UAV initially takes off and reaches an elevation of $0.7\,\mathrm{m}$. Then it moves *(b)* leftward for $3.4\,\mathrm{m}$, *(c)* backward for $1\,\mathrm{m}$, *(d)* rightward for $3.4\,\mathrm{m}$, and *(e)* forward for $1\,\mathrm{m}$, therefore travelling along a rectangular trajectory at a fixed height. Finally, after hovering at the

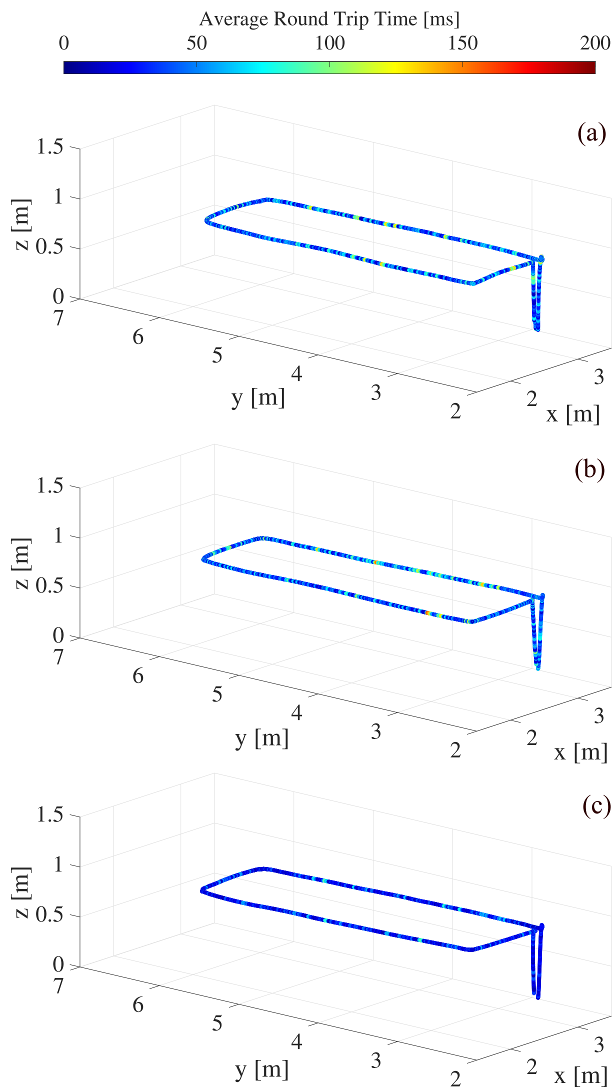

Fig. 5. Average Round Trip Time (RTT) along the estimated trajectory for different bandwidths, i.e. (a) 20 MHz, (b) 60 MHz, and (c) 100 MHz.

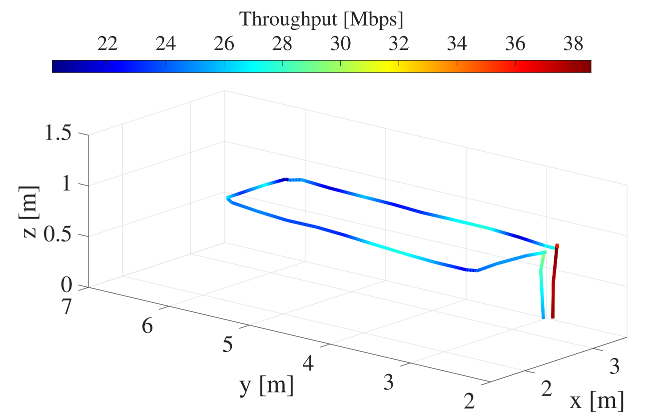

Fig. 6. Uplink throughput experienced along the estimated trajectory during the UAV flight, obtained based on the traffic generated by the `iperf3` tool.

starting position, *(f)* it lands, completing the mission. Fig. 3 presents the $0.90\,\mathrm{m}$ horizontal slice of the planned trajectory (dashed black curve) along with the position of the gNB. Here, we also report the average estimated trajectory travelled by the UAV during the mission, calculated by averaging five separate recordings captured by the Vicon system. As shown, the UAV's actual path closely follows the planned trajectory.

The analysis begins by examining the behaviour of the UAV flight battery, with the voltage and current parameters being recorded by the flight controller during each mission. A 6S LiPo battery with a capacity of $6000\,\mathrm{mAh}$ and a fully charged voltage of approximately $25\,\mathrm{V}$ is used. Fig. 4 shows the battery voltage and current during two consecutive missions. Initially, the voltage reads around $24.75\,\mathrm{V}$, which drops to about $23.75\,\mathrm{V}$ immediately after take-off and continues to decline as the UAV mission progresses. During flight, the current draw fluctuates between $10\,\mathrm{A}$ and $15\,\mathrm{A}$, reflecting the significant energy required to sustain the UAV in the air. After landing, the voltage rises again as the battery cools down. Due to these rapid voltage variations, a dedicated battery was assigned to power the onboard computer, eliminating the need for additional hardware. In the subsequent mission, while the current draw remains similar, the voltage continues to decrease, indicating ongoing battery discharge.

Fig. 5 presents end-to-end Round Trip Time (RTT) measurements between the Command & Control node on the ground station and the UAV onboard computer, collected using the `ping` utility. The tests were conducted by varying the number of PRBs in the cell, resulting in different bandwidth configurations of $\{20, 60, 100\}$ MHz. The results are averaged over five independent missions for each bandwidth setting. As expected, increasing the bandwidth reduces the average latency, from approximately $46\,\mathrm{ms}$ at $20\,\mathrm{MHz}$ to around $28\,\mathrm{ms}$ at $100\,\mathrm{MHz}$. This improvement is likely due to the TDD scheme, where delays from time-domain resource allocation can be offset by a greater availability of frequency-domain resources. Moreover, a detailed examination of the RTT throughout the trajectory reveals reduced variability with increasing bandwidth, indicating a more stable network connection.

However, increasing bandwidth does not always translate into proportional performance gains. This is illustrated in Fig. 6, which shows the end-to-end uplink throughput measured during the mission using the `iperf3` tool. The traffic was generated via User Datagram Protocol (UDP) with a target bitrate of $100\,\mathrm{Mbps}$, while the ground station recorded the received data rate. At take-off, throughput approaches a peak value of $38.6\,\mathrm{Mbps}$. As the UAV proceeds with its mission and begins processing commands, throughput declines, averaging $26.67\,\mathrm{Mbps}$ over the entire flight. This reduction is likely due to the onboard computer (Lattepanda 3 Delta) processing and data handling limitations. The increased computational load during task execution strains system resources, reducing the bandwidth available for communication. Nonetheless, the achieved average throughput remains sufficient to support high-quality traffic such as real-time video streaming, a common UAV application.

V. Conclusions

This work introduced a novel indoor testbed for developing and experimentally validating 5G-enabled UAV systems, addressing key limitations of outdoor and indoor deployments. The testbed integrates a GNSS emulation system based on a high-precision motion capture system, and a fully functional 5G standalone network implemented with a SDR and OpenAirInterface5G, enabling realistic and repeatable experiments in a controlled environment. The experimental campaign demonstrated the testbed's ability to support autonomous UAV navigation, assess energy consumption, and evaluate network performance under different bandwidth configurations. The results highlight that increased bandwidth reduces latency and improves stability. They also reveal the impact of onboard processing constraints on throughput. Overall, the proposed platform provides a reliable, flexible environment for testing advanced drone communication and control strategies, paving the way for future research on UAV autonomous operation and 5G network integration. In particular, the evaluation of novel autonomous algorithms that exploit 5G physical layer information can be undertaken by modifying the Command & Control node. Furthermore, the companion computer capabilities can be enhanced to assess edge computing architectures and the impact on flight autonomy, as well as analysing AI-driven communication management towards 6G. Future work will include evaluating multi-UAV scenarios, which can be easily supported by running multiple instances of the Command & Control node, as well as investigating the feasibility of exploiting the mmWave frequency bands for UAV control, by adopting specific on-board modems and up/down converters to extend the gNB spectrum range.

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