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RESEARCH ARTICLE

Development of a Low-Cost UAV-Based System for Measuring Mobile Network Signal Power Using Open-Source Technologies

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ABSTRACT Measurement of mobile network signal power, among other features, is an activity of major importance in the telecommunications industry due to several features associated with it, such as network optimization, Quality of Service or infrastructure planning. Unfortunately, major issues happen when those measurements must be taken in unconventional terrains such as remote, mountainous or rural areas, as traditional methods to gather information (drive or walk testing, crowdsourced data, usage of static measurement stations) quickly become ineffective. By employing Unmanned Aerial Vehicles (UAVs) equipped with signal receivers, this manuscript presents development works that aim to provide a scalable and cost-effective solution for collecting and processing signal measurements. The performed activities aim to use a UAV combined with open-source systems and standardized protocols to obtain and process signal measurements, as well as state-of-the-art software infrastructure that will be used to store and display such data readings in an inexpensive, secure and user-friendly manner. This approach not only enhances the understanding of signal distribution in various environments but also supports the optimization of mobile network performance, ultimately benefiting both public and private sectors in their efforts to improve connectivity and service quality.

INDEX TERMS Cloud computing, databases, unmanned aerial vehicles, cellular networks.

I. INTRODUCTION

The measurement of mobile network signal power is a fundamental aspect of the telecommunications industry, playing a crucial role in ensuring reliable and high-quality service for users. Accurate signal measurements are essential for optimizing network performance, as they help operators identify areas with weak coverage and take corrective actions to enhance connectivity [1], [2]. This directly impacts the Quality of Service (QoS), influencing the clarity of voice calls and the speed of data transmission, which are vital for customer satisfaction. Furthermore, effective infrastructure planning relies on understanding signal distribution, allowing operators to strategically place new cell towers and allocate resources efficiently. Compliance with regulatory standards is another critical factor, as operators must demonstrate that they meet coverage and service quality requirements. In a competitive market, maintaining high signal strength is key to customer retention, as users are more likely to remain loyal to providers that deliver reliable service. Additionally, accurate measurements support emergency services by ensuring that first responders have the connectivity they need during crises. Markets also benefit from signal strength data, enabling operators to tailor their services to meet customer needs and preferences. As technology continues to evolve, particularly with the advent of 5G and the Internet of Things (IoT), the importance of precise signal measurements will only grow, ensuring that networks can meet future demands and maintain a competitive edge [3]. Overall, the measurement of mobile network signal power is integral to enhancing service quality,

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optimizing infrastructure, and supporting the telecommunications industry's ongoing development.

However, there is a major challenge in the telecommunications industry when having to take measurements from the environment where they are supposed to be taken: accurately measuring mobile network signal power in non-conventional environments. Traditional methods of signal measurement (drive and walk testing, static measurement stations, crowd-source data) often fall short in areas that are difficult to access, such as rural regions, industrial sites, and urban environments with complex topographies. These areas frequently experience inadequate coverage and poor signal quality, which can lead to a divide between the service providers' reported coverage maps and the actual user experience [4]. One of the primary issues is that existing measurement systems are typically designed for conventional urban settings, where infrastructure is more readily available and accessible. As a result, data collection in remote or underserved areas is often limited, leading to a lack of reliable information about signal strength and quality. This gap in data can hinder operators' ability to make informed decisions about network expansion and optimization, ultimately affecting service quality for users in these regions. It is important to also highlight the discrepancies between the signal strength values reported by telecommunications operators and those measured by means of independent measurement systems. These inconsistencies can create confusion and mistrust among consumers, who may rely on inaccurate coverage maps when choosing service providers. The lack of reliable data can also impede regulatory compliance, as operators may struggle to demonstrate that they meet the required service standards in all areas. To address these challenges, our manuscript puts forward the development of a low-cost, scalable system for measuring mobile network signal power using open-source systems and standardized protocols. This innovative approach aims to create a more comprehensive and accurate picture of mobile network performance, particularly in non-conventional environments. While mainly focused on obtaining information from Long Term Evolution (LTE) deployments, the solution can be extended to other technologies such as 5G and 6G. By leveraging advanced measurement techniques and technologies, the project seeks to provide valuable insights into signal coverage and quality, enabling operators to make data-driven decisions.

A. PAPER CONTRIBUTIONS

It is the authors´opinion that the presented manuscript makes several significant contributions to the application domain covered here, which can be described as "*inexpensive Unmanned Aerial Vehicles tailored for accurate mobile network measurement*." Such contributions are as follows:

1. **Development of a low-cost mobile network measurement system (Contribution 1, C1)**: The manuscript puts forward the creation of an affordable and scalable system for measuring mobile network signal power integrating the usage of UAVs, cloud computing and data processing tools. This system utilizes open-source technologies and standardized protocols, making it accessible for various stakeholders.
2. **Innovative Data Collection Approach (C2)**: The development of a system for collecting and processing mobile network power measurements using Unmanned Aerial Vehicles (UAVs) to operate in terrains such as rural, industrial, hard-to-reach and other isolated areas that are hard to collect data from in this application domain. While UAVs can fly in many environments applicable to very diverse use cases, the integration in a system that uses a UAV to collect information about signal features of mobile networks, the storage of such measurements in a cloud computing-based environment and its visualization via open-source tools like Grafana constitutes a significant novelty by itself. By specifically targeting areas that are often overlooked by traditional measurement systems—such as rural regions, industrial sites, and complex urban landscapes—the project aims to fill a significant gap in the existing telecommunications infrastructure assessment. This innovative approach not only improves the accuracy of signal measurements but also enables mapping of coverage in environments where terrestrial access is limited.
3. **Near real-time Data for Connectivity Assessment (C3)**: The presented research and development works not only emphasize the importance of obtaining data on signal reception and mobile coverage, but also provide a tangible methodology and infrastructure on how to use the collected information to become aware of the connectivity performance of a mobile network. This information is crucial for both business interests and social initiatives, as it can inform public and private organizations about the actual connectivity levels in various regions, particularly in underserved areas.
4. **Bridging the Gap Between Reported and Actual Coverage (C4)**: By providing a more accurate assessment of mobile network performance, the presented manuscript aims to reconcile discrepancies between the coverage maps reported by the operators and the actual user experience. This contribution is vital for building trust among consumers and ensuring that service providers meet regulatory standards.
5. **Support for Infrastructure Planning and Optimization (C5)**: The insights gained from the proposed measurement system can assist telecommunications operators in making informed decisions regarding network expansion and optimization, especially in areas where collecting accurate information would be either too hard or too expensive. This can lead to improved service quality and better resource allocation.
6. **Contribution to Regulatory Compliance (C6)**: By providing reliable data on signal strength and quality, and by comparing it with the data expected from each of the mobile network operators, the project supports

telecommunications operators in demonstrating compliance with regulatory requirements.

B. PAPER STRUCTURE

This paper is structured in the following manner: an introduction to the research made in this manuscript has already been provided as section I. Section II describes the related works covered in this regard, as well as their advantages and weaknesses in the context where this paper is taking place. Section III shows the design and implementation activities performed to develop a system that will cover the open issues that have been found in section II. Section IV displays the testing activities that have been performed to learn about the performance and the feasibility of the system. Section V includes the conclusions that have been reached and what future work can be done. An appendix shows the largest figures added to the manuscript for better visualization of the collected information. Bibliographical references close the manuscript.

II. RELATED WORKS

When existing related works are considered for their study, it can be found that there is significant literature with regards to UAV usage for telecommunication-related tasks.

A. STATE OF THE ART

Khan et al. [5] present a framework for using low-cost UAVs to efficiently cover and track moving targets. It introduces three mobility patterns: random waypoint, Manhattan grid and reference point group mobility. The paper proposes three algorithms—Predictive Fuzzy Algorithm (PFA), Predictive Incremental Fuzzy Algorithm (PIFA), and Local Incremental Fuzzy Algorithm (LIFA) to enhance coverage efficiency. The study utilizes a real-world testbed, Drone-Be-Gone (DbeG). This approach provides a cost-effective solution using a) low-cost UAVs, b) efficient algorithms for real-time target tracking, c) validation through practical implementation, and d) flexibility to adapt to various mobility patterns. However, the solution is limited to specific movement patterns and presents challenges for larger areas or complex environments.

Braunfelds et al. [6] talk about the performance of Long Term Evolution (LTE) mobile networks for UAVs, focusing on Key Performance Indicators (KPIs) such as Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), and Signal-to-Interference plus Noise Ratio (SINR) at various altitudes (40, 60, 90, and 110 meters) using a DJI M30 UAV. It highlights the demand for stable wireless connectivity in UAV applications, emphasizing the need for communication links beyond visual line-of-sight. Unfortunately, limitations are mentioned, such as potential unstable connections when measurements fall outside the defined KPIs. The main equipment for measurements is a mobile phone, which we have improved in our own works. Zulkifley et al. [7] investigate the feasibility and performance of an LTE-based control system for low-altitude small UAVs, focusing on parameters such as latency, handover, and signal strength at varying altitudes. It concludes that while LTE networks can provide the minimum requirements for UAV connectivity, improvements are necessary to enhance aerial coverage, reduce interference, and lower latency. Advantages of using LTE include the ability to achieve Beyond Visual Line-of-Sight (BVLoS) operations, real-time GPS tracking, and efficient data transmission from onboard sensors. Challenges remain, though, such as reduced signal quality and data rates at higher altitudes, and the need for pre-flight setup to ensure LTE coverage. Platzgummer et al. [8] present a UAV-Based Coverage Measurement Method for 5G, highlighting the use of UAVs to conduct systematic, automated, and repeatable measurements of KPIs. The study employs a hexacopter equipped with additional sensors to a) enhance measurement accuracy and cover large areas, b) maintain consistent flight paths and c) gather data that can verify 3D channel models and antenna patterns. However, the paper also notes the limitations of stock UAVs in meeting measurement requirements (whereas the UAV used in our case has been tailored for the purpose of this manuscript), potential challenges in maintaining stable flight under windy conditions, and the need for careful planning of flight routes to avoid interference issues. Measurements are taken only from a smartphone. Festag et al. [9] investigate end-to-end performance of UAV communications in 5G cellular networks, focusing on applications such as aerial inspection, surveillance, and monitoring. It presents results from a collection of measurements that evaluate link capacity, communication robustness through network slicing, and stability during long-distance flights. Findings indicate that 5G networks can provide reliable and low-latency communication, thus meeting the requirements for video and command & control data transmission. Advantages include improved signal quality and throughput, as well as the potential for dedicated resources through network slicing, enhancing service quality for UAVs. Challenges relate to connectivity outages in areas with low signal quality and the need for buffering video data. Säe et al. [10] describe the impact of UAVs operating as aerial User Equipment (UE) on public LTE networks in rural environments, focusing on KPIs such as Physical Resource Block (PRB) usage, Modulation and Coding Scheme (MCS) class, throughput, and transmission power. The study finds that while UAVs introduce some minor interferences, they do not significantly degrade the performance of ground-level UEs. The advantages of using UAVs as described in this studied manuscript include enhanced network utilization and the ability to maintain connectivity in areas where ground infrastructure may be limited. However, there are challenges too, such as potential interferences and the need for network optimization to accommodate aerial UEs. Um et al. [11] present a novel architecture for Real Time Kinematic GPS (RTK-GPS) aimed at enhancing system redundancy in multi-UAV operations. It addresses the limitations of existing systems, particularly in maintaining stable RTK-GPS data transmission during failures. The proposed architecture utilizes a wireless ad hoc network to connect UAVs with a Ground Control Station (GCS), allowing for RTCM message propagation without requiring internet connectivity. Advantages include improved accuracy and availability of positioning data, with experiments showing a reduction in error by about 30% and high availability rates (up to 99.98%) with multiple RTCM sources. The system reliance on redundancy, though, may introduce complexity in managing data sources, and potential GPS signal loss. Gu et al. [12] show a novel approach to dynamic measurement and data calibration for Aerial Internet-of-Things (Aerial-IoT) systems, focusing on sensors deployed on high-altitude platforms like UAVs and parachutes. It highlights the challenges posed by unstable environmental factors such as air pressure, temperature and wind, which can compromise sensor readings. The proposed Data Calibration model, named DC-NN, utilizes Neural Networks to establish complex relationships between measured data and environmental factors. Advantages of this approach include improved measurement reliability in dynamic conditions and the ability to adapt to various environmental influences. Disadvantages include the complexity of implementing neural networks and the potential difficulty in interpreting results due to the intricate calibration process. Seijo et al. [13] present a Portable Full Channel Sounder designed for industrial wireless applications, utilizing sub-nanosecond wireless time synchronization to enable accurate measurements of time-variant wireless channels without the need for external synchronization. The authors of this studied manuscript claim that this enables greater mobility and flexibility in measurement scenarios, making it suitable for applications in mobile robotics. Key advantages include compact design, cost-effectiveness and the ability to perform real-time raw channel impulse response measurements, which enhance the understanding of channel behavior. Unfortunately, the channel sounder has limitations, such as a small bandwidth and reliance on a single antenna, which may restrict its performance in certain environments. Shining Lin et al. [14] introduce the concept of Direction-of-Arrival (DoA) estimation in UAV communications using a Hybrid Optical-Electronic Neural Network (HOENN), combining a stacked intelligent metasurface (SIM)-based optical neural network with a digital fully connected layer. The optical component processes signals at the speed of light with low energy consumption, while the electronic layer refines the angular spectrum estimation. A hierarchical framework further improves efficiency by splitting the DoA space into coarse and fine subregions, reducing computational load and observation requirements. Key advantages include reduced hardware complexity, and improved accuracy compared to conventional beamforming (CBF) methods. The authors also describe some challenges such as energy loss across metasurface layers, and sensitivity to signal-to-noise ratio (SNR).

There are other pieces of work that, while not strictly related to the use case that is put forward in our manuscript, have in common several other features, such as the usage of UAVs in communication-related environments. For example, Lin et al. [15] discuss the connectivity of low-altitude UAVs within commercial LTE networks, presenting findings from field measurements and simulations. It highlights that existing terrestrial mobile networks can support initial UAV deployments, offering advantages such as widespread infrastructure and established technology. Challenges arise from mobility support, as UAVs often receive signals from the sidelobes of base station antennas, leading to weaker connections and increased radio link failures. Additionally, Mekki et al. [16] present a scalable monitoring framework for network slicing in 5G, addressing the need for efficient monitoring across diverse technological domains. It emphasizes the challenges of resource monitoring, including data isolation and scalability, as multiple network slices are expected to run concurrently. The proposed framework features a technology-agnostic data collection protocol and supports the lifecycle management of metrics collectors for each network slice. Advantages include its ability to handle a high number of slices in parallel and enhanced data management across different domains. Possible disadvantages include the complexity of implementation across varied technologies. Lastly, Kim et al. [17] depict a novel approach to enhance communications between sensors and UAVs using LTE networks. It emphasizes the importance of intermittent connectivity, particularly in outdoor environments where line-of-sight conditions are favorable, leading to shorter Round-Trip Times (RTT) compared to indoor scenarios. Advantages of this approach include improved data transmission efficiency and optimal UAV placement for enhanced network performance. Unfortunately, the heavy dependence on outdoor conditions may limit effectiveness in urban or indoor settings.

B. OPEN ISSUES

Overall, there is a plethora of solutions that make use of inexpensive UAVs to measure parameters from varied environments and technological deployments. Unfortunately, there are several open issues that prevent the existing solutions from performing in an optimal manner. Table 1 shows each of the solutions studied, along with their advantages and disadvantages. Note how the Open Issues that have been found are numbered from 1 to 12 (OI1-OI12).

C. OPEN ISSUES TO BE SOLVED

It is our opinion that the research and development works that are about to be presented solve the following open issues:

1. OI1 (limitation to specific mobility patterns): our solution makes use of a UAV that flies freely in a three-dimensional space. In fact, it is required that it performs such flights to ensure that accurate measurements are taken.
2. OI2 (challenges in scalability): our solution is fully scalable, as it can make use of several UAVs at the same time.
3. OI4 (lack of in depth-analysis of KPIs): our solution takes into account specific measured KPIs that define the information that has been collected.

TABLE 1. List of proposals with strengths and open issues.

Proposal	Strengths	Open issues
Khan et al. [5]	Cost-effective solution, algorithms for real-time target tracking, validation through a testbed, flexibility to adapt to various mobility patterns.	Limited to specific mobility patterns (OI1), potential challenges in scaling the solution (OI2), dependence on the accuracy of target mobility predictions (OI3).
Braunfelds et al. [6]	KPIs for UAV operations, usability for UAV-provided services.	Lack of in-depth analysis of existing KPIs, potential unstable connections (OI4). Usage of just a smartphone for measurements (OI5).
Zulkifley et al. [7]	Beyond Visual Line-of-Sight (BVLoS) operations, real-time GPS tracking, efficient data transmission from onboard sensors.	Reduced signal quality and data rates at higher altitudes (OI6), need for pre-flight setup to ensure LTE coverage (OI7).
Platzgummer et al. [8]	Efficiently cover large areas, maintain consistent flight paths, and gather data that can verify 3D channel models and antenna patterns.	Limitations of stock UAVs in meeting measurement requirements (OI8). Usage of just a smartphone for measurements (OI5).
Festag et al. [9]	Improved signal quality and throughput, dedicated resources through network slicing, enhancing service quality .	Connectivity outages (OI9), need for buffering video data due to limited UAV processing capacity (OI10).
Säe et al. [10]	Enhanced network utilization and the ability to maintain connectivity in areas where ground infrastructure may be limited.	Potential interference and the need for network optimization to accommodate aerial User Equipment (OI11). Usage of just a smartphone for measurements (OI5).
Um et al. [11]	Improved accuracy and availability of positioning data.	Reliance on redundancy, potential GPS signal loss (OI12).
Gu et al. [12]	Improved measurement reliability in dynamic conditions and the ability to adapt to various environmental influences.	Complexity of implementing neural networks and the potential difficulty in interpreting results (OI13).
Seijo et al. [13]	Compact design, cost-effectiveness, real-time raw channel impulse response measurements.	Channel sounder has limitations (small bandwidth and reliance on a single antenna, OI14).
Shining Lin et al. [14]	Lower hardware complexity and improved accuracy compared to CBF	Energy loss across metasurface layers and sensitivity to signal-to-noise ratio
Lin et al. [15]	Existing terrestrial mobile networks can support initial UAV deployments	UAVs have weaker connections and increased radio link failures (O15).
Mekki et al. [16]	Can handle 5G slices in parallel, support for cloud-native environments, and enhanced data management.	Complexity of implementation across varied technologies (OI16), need for robust security measures (OI17).
Kim et al. [17]	Improved data transmission efficiency and optimal UAV placement.	Too heavy reliance on outdoor conditions (OI18).

4. OI5 (Usage of just a smartphone for measurements): our solution makes use of a more sophisticated piece of equipment.
5. OI8 (limitations of stock UAVs): our solution has a tailored UAV to use as the most optimal hardware possible for the purpose of taking measurements about mobile network signal features.
6. OI16 (Complexity of implementation): our solution integrates seamlessly several hardware and software components that result in increased usefulness and usability.

III. PROPOSED SOLUTION

A. PROBLEM DESCRIPTION AND PROPOSED SOLUTION

The primary problem addressed in our paper is the inaccurate and incomplete measurement of mobile network signal power in non-conventional environments, such as rural, mountainous, and industrial areas. As it has been explained in the two previous sections, traditional methods for signal measurement, such as drive testing, walk testing, and static measurement stations, are often ineffective in these environments due to accessibility issues and complex topographies. This leads to several critical challenges:

1. Inaccurate Coverage Maps: Telecommunications operators often report coverage maps that do not match the actual user experience, especially in hard-to-reach areas. This discrepancy can lead to consumer mistrust and regulatory non-compliance.
2. Limited Data Collection in Remote Areas: Existing measurement systems are typically designed for urban settings, where infrastructure is readily available. As a result, data collection in remote or underserved areas is often limited, leading to a lack of reliable information about signal strength and quality.

3. Inefficient Network Optimization: Without accurate data, operators cannot effectively optimize network performance, leading to poor service quality in certain areas. This is particularly problematic as the demand for reliable connectivity continues to grow, especially with the advent of 5G and IoT technologies.
4. High Costs of Traditional Methods: Traditional methods of signal measurement are often costly and time-consuming, especially when covering large or difficult- to-access areas. This makes it challenging for operators to conduct comprehensive network assessments.

Considering these issues, the need and desirability to create an inexpensive device capable of performing accurate measurements, as expressed in the introduction, becomes clear. The research and development works performed have culminated in three main subsystems that have been integrated with each other: a) the UAV and data acquisition system, b) a subsystem for data storage applications and graphical visualization interface and c) a subsystem used for interconnectivity of the former ones. The first one contains all the hardware and software resources required to collect mobile network data in a three-dimensional space, whereas the second one is used to store and visualize the collected information from the ground to infer knowledge from it. Lastly, the third one makes use of wireless communications and protocols that will keep the data flow between the UAV and the cloud working in a seamless manner. In addition to that, and as displayed in Figure 1, each of these subsystems requires further components, such as hardware and software parts for their computational performance, hardware and software components oriented towards UAV behavior and the necessary components for data collection and management. All these components are further extended later in this section of the manuscript.

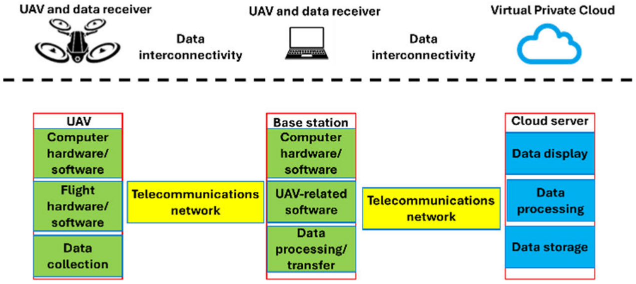


FIGURE 1. Three subsystems and their components.

B. BUILDING UP THE UAV

A UAV was built to have a device capable of taking the required measurements; this UAV can be regarded as a tailored tool capable of taking off, flying, collecting data and landing with ease. For the frame or "skeleton" of the UAV a F450 Frame with landing gear was chosen [18]. This frame made it possible to mount all the parts on it and ensure a degree of robustness to the UAV. The processing module of choice was a Raspberry Pi 3B+ [19]. It has a 64-bit SoC processor with a clock frequency of 1.4 GHz which makes it inexpensive and suitable for the purpose of running the required functionalities of the UAV. It also has a 1GB LPDDR2 SDRAM memory that works with wireless connectivity of 2.4GHz/5GHz IEEE 802.11b/g/n/ac Bluetooth 4.2, BLE (Bluetooth Low Energy), Gigabit Ethernet connectivity over USB 2.0 or several GPIO ports (General Purpose Input/Output), HDMI (High-Definition Multimedia Interface), CSI (Camera Serial Interface), Micro USB (Universal Serial Bus) and Power over Ethernet (PoE). All these connectivity possibilities that Raspberry Pi has, together with the great compatibility with operating systems and open-source projects, make it a very suitable choice for the UAV.

MaxPRO 2650 batteries were used as power source [20], specifically with 11.1V voltage and 2650mA intensity. LiPo (Lithium Polymer) batteries are the most used for UAVs, as they allow fast discharges, so UAVs can use large amounts of energy in a short time, besides being light and small compared to others. To charge the batteries, an iMAX B6 LiPro charger was used [21]. It has automatic charging speed control functions, which prevent overcharging. Additionally, it has charging functions and cell-balancing ones as well, either jointly or independently, and is adaptable to different types of batteries such as LiIon, LiPo and LiFe. A Set of 4 Emax 2213-935KV motors was used to propel the UAV [22]. These brushless motors are specially designed for 11 Volts LiPo voltage, so they are suitable for 2650mAh battery. They have a thrust of 860g per motor and 935KV (rpm/volt).

The Navio 2 controller was used as the navigation controller device [23]. It uses an APM (Advanced Power Management) version of Linux (ArduPilot) or it can also use a middleware to work with ROS (Robot Operating System). This controller has a high resolution MS5611 barometer, GPS (Global Positioning System) ublox M8N module compatible also with Galileo GNSS (Global Navigation Satellite System). This latter feature has come in as extremely handy for the development works, as Galileo is the GNSS that has been chosen for UAV navigational purposes [24].

Lastly, to use a Radio Controller, an FS-T6 programmable digital transmitter and 6-channel receiver in 2.4 GHz was chosen [25]. It has a very low power consumption and reaction time to ultra-fast signals with interference-free AFHDS (Automatic Frequency Hopping Digital System) technology. It has a bandwidth of 500 Hz, sensitivity of 1024, LCD (Liquid-Crystal Display), ppm/pcm security coding and supports up to 20 models with the same receiver.

C. IMPLEMENTATION OF A SIGNAL POWER DATA ACQUISITION SYSTEM

The implementation of the components used for data collection was performed by following an incremental prototyping perspective, so that there would be two rounds of development and data collection to make sure that, after having obtained information from the first prototype iteration, the prototype could be enhanced with a more sophisticated data collection system during the second iteration. This was the approach used for the data storage subsystem too, as it is described later in this manuscript how it was enhanced during the second iteration of its development.

During the first round of tests, a USB stick modem was used as the device that would collect information from the mobile network. The device of choice was the Huawei E3372 USB Stick Modem [26]. As it is Linux- and 4G-compatible it has been able to be used for the first round of testing activities. In this way some results and configurations could be extrapolated been of great use in the development of testing activities with the Sixfab Hat module. In terms of technical connection characteristics, the following stand out:

1. Communication standards:
    - FDD (Frequency Division Duplexing): DD800MHz/ 900MHz/ 1800MHz/ 1800MHz/ 2100MHz/ 2600MHz.
    - UMTS (Universal Mobile Telecommunications System): 900MHz/ 2100MHz.
    - Global System for Mobile Communications (GSM) bands: GSM 850/ GSM 900/ GSM 1800/GSM 1900.
2. Connection speed:
    - LTE FDD: Cat4 Downlink:150Mbps/Uplink:50Mbps.
    - UMTS: HSPA+ (High-Speed Packet Access): 42Mbps/ 5.76Mbps; 21Mbps/5.76Mbps; 14Mbps/ 5.76Mbps.
    - HSUPA (High Speed Upstream Packet Access): 7.2Mbps/5.76Mbps 2G: Enhanced Data Rates for GSM Evolution (EDGE) packet data service of up to 236.8kbps.

The appearance of the modem is as shown in Figure 2.

FIGURE 2. Huawei E3372 USB stick modem, as in [25].

After using this USB stick modem in combination with the UAV, it was proven that data could be retrieved from the flying UAV without any major problem. Consequently, the hardware and software upgrades for the second iteration of the implementation works were prepared. This time, a ''hat'' for Raspberry Pi making use of hardware communications components was utilized instead of the modem from the previous prototype. This device, namely the Sixfab hat with LTE capabilities [27] was used combined with the Telit LE910C4-EU modem [28]. They provided a module fully compatible with Raspberry Pi 3 and 4, low power consumption and fast connection speeds. Among its main features we can highlight the following ones:

- Compatibility with Raspberry via a 40-pin GPIO header.
- Mini PCIe (Peripheral Component Interconnect Express) socket compatible with LTE, UMTS/HSPA+ (High-Speed Packet Access) and GSM/GPRS (General Packet Radio Service)/EDGE coverage technologies in different frequencies and regions.
- Socket micro-SIM (Subscriber Identity Module).
- Possibility of use by USB with micro-USB port.
- Supports external 5V power supply per pin, via Raspberry 5V GPIO, micro-USB or optionally JST connector.
- Compatible with AT commands over UART (Universal Asynchronous Receiver-Transmitter) or USB.
- Operating temperatures between -25°C ~ 70°C.

On the other hand, the Telit LE910C4-EU module is compatible with the main frequency bands used by mobile operators and GNSS Galileo, as detailed in Table 2.

TABLE 2. Features of the data collection "hat" Telit LE910C4-EU.

Features	Values
World region	EMEA (Europe, Middle East, Africa).
Connection speed	Uplink up to 50 Mbps Downlink up to 150 Mbps.
Frequency bands	4G bands: B1, B3, B7, B8, B20, B28A. 3G bands: B1, B3, B8. 2G bands: B3, B8.
Compatible geopositioning systems	GPS, Galileo, Glonass, Bei-dou, QZSS

Sixfab LTE Connection Hat (Figure 3) is compatible with all bands used in Spain (the country where the experiments took place), so tests can be performed with different operators. It complies with R&TTE "*European Directive 1999/5/EC on radio equipment and telecommunications terminal equipment and the mutual recognition of their conformity*." Additionally, compliance with REACH standards ensure that the module complies with the regulation for the collection and assessment of information on the properties and hazards of chemical substances. Finally, compliance with Restriction of certain Hazardous Substances (RoHS) ensures its safe usability in electrical and electronic equipment.

From a technical point of view, compatibility with UNIX-based operating systems, tested by the manufacturer of the Telit modem and users on the Internet, make possible the correct operation with Rasbperry Pi. It has also been verified that the different modules used have their own compatibility list such as NetworkManager and ModemManager.

FIGURE 3. Sixfab LTE connection hat appearance as in [26].

D. SOFTWARE COMPONENTS FOR THE UAV

For ground control of the UAV, the ArduPilot Mission Planner software [29] was installed. This software is used on a ground computer so it can be used as a Ground Control Station (GCS). It supports all ArduPilot variants such as helicopters, hexacopters or any UAV. It is mainly designed for mission management, planning and telemetry monitoring of the aircraft. Some of its main characteristics are the following:

1. Waypoint/flight zone fence/rally point entries with graphical interface intuitive and easy to use "drag and drop" interface using Google Maps / Bing / Open Street maps/ customized Web Map Services (WMS).
2. Select mission commands from the drop-down menus.
3. Download mission log files for further analysis.
4. Configuration of autopilot settings with user-friendly Graphical User Interface.
5. Interface with a flight simulator, in which a Software-In-The-Loop (SITL) UAV simulator can be created.
6. Run in-house SITL simulations of many frame types for all ArduPilot vehicles.

E. SOFTWARE FOR DATA COLLECTION, STORAGE AND GRAPHICAL USER INTERFACE

Once data have been collected by the UAV, it is still required to have them stored for its latter analysis and display. To fulfil this purpose, a collection of software components was required, as there were several functionalities that had to be covered with regards to data monitoring and storage. Therefore, the Prometheus + AlertManager + Grafana stack has been set (see Figure 4). Each of these software programs are useful in providing the required functionalities.

Prometheus is an open-source monitoring and alerting toolkit designed for reliability and scalability in systems and service monitoring that is particularly well-suited for monitoring dynamic cloud environments and microservice architectures, which comes in handy for our development works [30]. It is a system composed of several open-source monitoring and alerting tools originally developed by SoundCloud based on the GO programming language. The Prometheus project is part of the Cloud Native Computing Foundation since 2016, being the second largest project after Kubernetes. Prometheus collects metrics and data by storing them in a Time Series Database (TSDB). The metrics can be of various types and only depend on the nature of the application being monitored. Prometheus works based on metrics extraction. That is to say, it is based on a "pull" model so it is the main server that sends HTTP requests called *scrapes* to the endpoints (access points) with statically defined exporters or by dynamic systems (service_discovery). Under this system, each call reads the metrics defined in the endpoints referred to as "/metrics" to obtain the current state of the metrics and saves those values in the database. The main functionalities offered by Prometheus are as follows:

1. Multi-dimensional data model of time series data consisting of metrics with key/value pairs.
2. PromQL as a flexible query language.
3. No dependence on distributed storage.
4. Temporary data collection occurs through *pull* requests over Hypertext Transfer Protocol (HTTP).
5. Support for intermediate gateways for *push* data collection.
6. Targets can be automatically detected with Service Discovery or by static configuration.
7. Support for multiple rendering modes and dashboards.

In addition to that, the main architecture of Prometheus consists of several differentiated parts that play a role in the fulfilled development works:

1. **Server:** this is where all the data and metrics are stored by "scraping" to the different endpoints defined in the configuration.
2. **Client libraries and predefined exporters** such as "node_exporter."
3. **Special or developer-defined exports** such as HAProxy, StatsD, Graphite, etc.
4. **GUI (Graphical User Interface):** includes a basic graphical interface for querying and checking alerts or target status.
5. **AlertManager:** this is a component of the Prometheus monitoring system that is responsible for managing alerts generated by Prometheus and constitutes an important software tool in our development works. Indeed, it plays

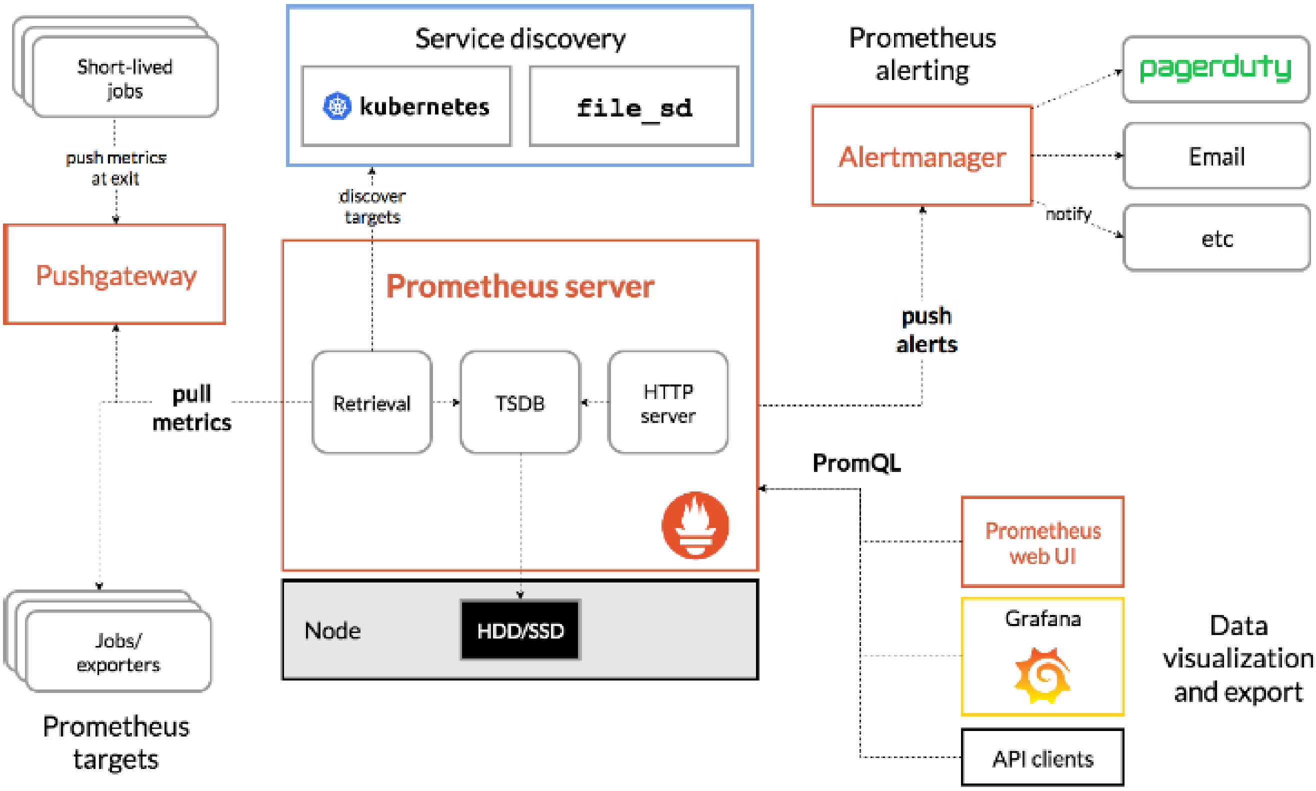


FIGURE 4. **Prometheus full architecture, as shown in [28].**

a major role in the alerting process by handling notifications, deduplicating alerts, grouping them, and routing them to the appropriate notification channels [31].

Lastly, Grafana is an open-source platform for data visualization and monitoring that allows users to create interactive and customizable dashboards. It is widely used in conjunction with various data sources, including time series databases like the one provided by Prometheus. Grafana provides a powerful and flexible interface for visualizing metrics, logs, and other data, so it has been regarded as the most suitable tool to be used in our development works [32]. It can be regarded as a multiplatform interactive visualization and analysis application for metrics. This is an "Open Source" application under AGPLv3 license, so a Contributor License Agreement (CLA) must be signed to contribute to the project.

Due to an extensive community of more than 600 developers, it has become one of the references in its application domain for monitoring stacks, being used together with TSDB systems such as influxDV, Prometheus, Graphite or platform monitoring systems such as Sensu, Icinga, Zabbix, or other data sources. Due to its popularity, it has been implemented to be natively compatible with standardized data sources such as Mysql, PostgreSQL, ElasticSearch, among others; or with end providers such as Cloudwatch, Azure Monitor, Google Cloud Monitoring, etc. The main advantages it offers for our implementation are:

1. Data unification.
2. Simplified data visualization.
3. Interactive panels that can be used by any end user.
4. Flexibility and versatility.

To obtain data, further modules and software components have been developed to obtain the desired metrics for monitoring the platform, which runs under a Linux operating system. To establish communication with the modem and establish the data connection, the ModemManager + NetworkManager stack has been used. ModemManager, on the one hand, is an open-source tool for Linux, used to establish communications with modem-like devices for configuration, status checking or connection management [33]. It is a "Dbus deamon" that provides a unified high-level Application Programming Interface (API) to communicate with modems regardless of the protocol used with the device, such as generic or specific AT and Qualcomm MSM Interface (QMI). It mainly uses the libqmi and libmbim libraries for communication over the QMI and the Broadband Model Mobile Interface (MBIM) protocol. The project is hosted on the Freedesktop.org website and contains its own documentation repository. It is not developed or managed by private entities or manufacturers, so compatibility with all modem models on the market is not guaranteed. Some manufacturers do contribute to the project by making their devices fully compatible with ModemManager. Although not 100% compatible, many devices allow the exposure of USB network interfaces with control channels such as Qualcomm with its proprietary QMI interface, which works most of the time with ModemManager, or the MBIM interface for USB-IF. On the other hand, NetworkManager is one of the main daemons on top of libudev and other Linux kernel interfaces and provides a high-level interface for configuring network connections, having become the standardized toolkit for Linux network configuration [34]. NetworkManager is integrated into most Linux desktop environments and has been designed to be fully automatic by default. It is also capable of managing the most important network connections and other network interfaces such as Ethernet, Wi-Fi or mobile broadband network interfaces. It is initialized as a system-based service in most distributions, and it will initialize the different services it requires such as WPA_Suplicant for Wi-Fi Protected Access (WPA) or the Point-to-Point Protocol Daemon (PPPD) for mobile broadband connections. It comes both with a desktop Graphical User Interface (GUI) that allows to manipulate and handle connections and has a Command Line Interface named NetworkManager Command Line Interface (NMCLI). The relations among the aforementioned components have been displayed in Figure 5.

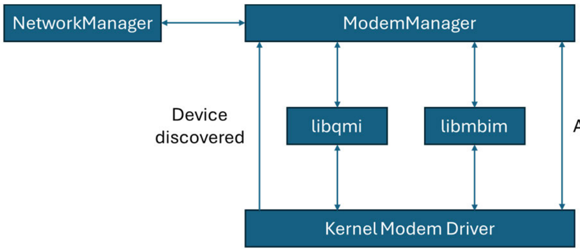


FIGURE 5. **Architecture diagram for data collection components.**

In the context of the monitoring and observability features displayed in the work done, an exporter is defined as a software component that collects metrics from an application, service or system and exposes them in a format that can be consumed by monitoring systems like Prometheus. Exporters act as intermediaries that gather data from various sources and make it available for visualization. Two types of exporters have been used for the development works performed: node_exporter and a custom_exporter.

Node_exporter is an exporter used for displaying the status of the server operating system and the UAV [35]. Node exporter is a hardware- and OS-oriented metrics exporter for Prometheus, which displays hardware and kernel data, exposed by *NIX kernels and based on GO. Some of the metrics exposed by node_exporter are detailed in Table 3.

As for the custom_exporter, it is a customized one that has been modified to obtain metrics of the modem status and connections of the UAV. The repository with modified metrics is hosted in a public GitHub repository. Considering the most important parameters that have been obtained, the metrics shown in Table 4 have been exported.

TABLE 3. **Metrics exposed by node_exporter.**

Features	Values
Memory	RAM total, RAM Used, RAM Cache, RAM Free.
Disk	Disk Space, IOPS, Mounts.
CPU	CPU Load, CPU Memory Disk.
Network	Network traffic, TCP flow, Connections.

This exporter is based on the GO client of ModemManager to create a basic exporter of modem and LTE connection status metrics for Prometheus. To obtain the signal metrics, ModemManager GO libraries have been used for the development of the custom exporter, and to obtain the GNSS data, they are parsed from National Marine Electronics Association (NMEA) messages. NMEA is one of the standard GNSS protocols and constitutes a serial communication protocol based on ASCII composed of different sentences, independent of each other, starting with the "$" sign and ending with a sequence of "<CR><LF> (carriage return and line feed). The first two characters identify the equipment; for receivers in GNSS-based deployments, such as the one used in the UAV, the prefix is GP, followed by a sequence of three letters that define the type of information being received. The following list describes some of these types of messages:

- $GPBOD - Bearing, origin to destination.
- $GPBWC - Bearing and distance to waypoint, great circle.
- $GPGGA - Global Positioning System Fix Data.
- GPGLL - Geographic position, latitude / longitude.
- GPGSA - Dilution of Precision (DOP) of GNSS and active satellites.
- GPGSV - GPS Satellites in view.
- GPHDT - Actual vessel heading in degrees.
- GPR00 - List of waypoints in currently active route.
- GPRMA - Recommended minimum specific Loran-C data.
- $GPRMB - Recommended minimum navigation info.
- $GPRMC - Recommended minimum specific GNSS data / Recommended minimum specific GPS/Transit data.
- GPRTE - Routes.
- GPTRF - Transit Fix Data.
- GPSTN - Multiple Data ID / Multiple Data ID.
- $GPWPL - Waypoint location.
- $GPXTE - Error / Cross-track error, Measured.
- $GPZDA - Date & Time.
- $GPVTG - Course and speed information relative to the ground.

When geolocation is activated, the receiver delivers the following data frames: GGA, GSV, GSA, GLL and RMC. Once the GGA message type is processed, the final parameters for

TABLE 4. Metrics exposed by custom_exporter.

MODEM METRICS	
Name	**Description**
modem_up	Defines whether the last modem query was successful or not.
modem_tac	Type Allocation Code (TAC) currently used by the modem.
modem_roaming	Defines whether the modem is roaming or not.
modem_registered	Defines whether the modem is registered or not.
modem_connected	Defines whether the modem is connected or not.
modem_operatorcode	Code of the operator currently used by the modem.
modem_lac	Location Area Code (LAC) currently used by the modem.
modem_cellid	Cell Identificator (CellId) connected.
GNSS METRICS	
Name	**Description**
modem_lat	Latitute
modem_lon	Longitude
modem_alt	Altitude
modem_rsrq	Reference Signal Received Quality
modem_rssi	Level of signal reported by the modem
modem_sinr	Signal-to-interference-plus-noise ratio
modem_snr	The LTE S/R ratio
SIGNAL METRICS	
Name	**Description**
modem_rsq	Reference Signal Received Quality
modem_rssi	Level of signal reported by the modem
modem_sinr	Signal-to-interference-plus-noise ratio
modem_snr	The LTE S/R ratio

sending position and geolocation metadata are obtained. The NMEA GGA Message type contains essential correction data that provides 3D location and accuracy data.

F. UAV CONNECTIVITY

In order to obtain metrics from a UAV connected to the Internet, a public endpoint must be used. In LTE connections the most common solution is either having incoming traffic blocked or to establish a Carrier-Grade Network Address Translation (CGNAT) connection. This is a technique used to employ the same public IPv4 address by associating several private IPv4 addresses to it. The purpose of this technique is to be able to connect several devices from several clients simultaneously using a single public IPv4 address and thus mitigate the shortage of IPv4 addresses. Some operators currently offer the possibility to connect via IPv4 directly to a mobile device, but they usually offer it in exchange for a fee and impose some restrictions on traffic. In our case, a Virtual Private Network (VPN) tunnel has been configured with Cloudflare for easy communication in the development works done. Cloudflare Tunnel is a tunnelling software that makes possible to encrypt and protect connections and application traffic in any type of infrastructure [36]. This service enables the implementation of a Zero Trust deployment, so all requests sent to these resources must first pass through all security filters. Applications are directly accessible only to authenticated users. The "cloudflared" tunnel daemon creates a direct encryption tunnel between the endpoint and the Cloudflare servers, which is automatically configured depending on the public hostnames assigned in Cloudflare. A secondary domain has been registered for the creation of the service endpoint galencoder.live. In this domain the different service access points have been configured so that connectivity can be guaranteed between the UAV and the other parts of the developed system:

1. https://dron-metricsmmcli.galencoder.live: this is an endpoint where the Prometheus server will look for the modem_exporter metrics within the default path "/metrics."
2. https://dron.galencoder.live: an endpoint where the Prometheus server will look for the "node_exporter" metrics of the UAV system in the default path "/metrics."
3. ssh-dron.galencoder.live: an auxiliary service endpoint to connect to the UAV by ssh in case of emergency or remote need.
4. ssh-web.galencoder.live: a Secure Shell (SSH) web endpoint to connect to the UAV without command line.

Since both SSH methods have pre-validation of user authentication by whitelisting in Cloudflare, only certain email addresses have been configured to be able to access these services.

G. SYSTEM HOLLISTIC ARCHITECTURE

Overall, the final architecture of the complete system with its different subsystems has been displayed in Figure 6, where the main components can be distinguished:

1) VIRTUAL PRIVATE CLOUD SUBSYSTEM

The server for the monitoring has been set up at the provider Hetzner Cloud [37], using a CPX11 instance with 2vCPU AMD, 2 GB RAM, 4oGB disk and a maximum traffic of 20TB per month; it also has a public IPv4 assigned to it. To avoid latency we have chosen the data centre in Germany, which is where the closest data centre is from the development workplace. Prometheus has been installed using a subdomain of the galencoder.net project, leaving the address of the monitoring server as https://monitoring.galencoder.net:9090. HTTPS is the protocol used to encrypt web connections. An auth_basic has been configured for the administration and login of the Prometheus web interface. Finally, firewall rules are defined at the VPC (Virtual Private Cloud) level with the following "inbound rules:" a) opening only the essential ports at public level and b) enabling port 22 only from a range of local IP addresses to access the server and closing the rest of the ports. Within the Hetzner Cloud VPC, the server hosts Prometheus and Grafana for data monitoring and visualization, respectively. Prometheus operates under a subdomain of galencoder.net, providing a secure HTTPS endpoint for web access. This server uses firewall configurations to restrict open ports, ensuring that only essential services are accessible publicly. For instance, SSH (port 22) is limited to a specific IP range to prevent unauthorized access, while other unnecessary ports are closed for security. Prometheus serves as the core metric collection system, scraping data from multiple sources, including the UAV. It collects LTE connection metrics such as CellID, RSSI (Received Signal Strength Indicator), SNR (Signal-to-Noise Ratio), and SINR (Signal-to-Interference-plus-Noise Ratio). These metrics help analyse the connection quality, which is crucial for the UAV's mission. Grafana, installed on the same VPC and configured with Prometheus as the primary data source, provides a user-friendly dashboard for real-time visualization. Grafana's interface is accessible under another subdomain and uses AWS Route 53 for DNS management. Unlike Prometheus, Grafana's web service does not require additional authentication since user management is handled directly within Grafana.

2) THE UAV AND DATA RECEIVER SUBSYSTEM

Figure 5 displays the UAV as described in this section of our manuscript: it consists of a Raspberry Pi 3B+ mounted on a DJI F450 frame, equipped with LTE and GNSS modules. This setup includes a custom data acquisition module running a modified "modem_exporter," which fetches LTE signal parameters. The Raspberry Pi serves as the processing unit, managing both the custom exporter and Node Exporter to provide hardware metrics from the UAV itself. These metrics are crucial for monitoring system health and tracking signal strength during flights. The UAV relies on a Sixfab LTE HAT (Hardware Attached on Top) for network connectivity, utilizing Telit modems to connect to cellular networks. This configuration allows the Raspberry Pi to access LTE signals in real-time, logging metrics like RSSI, RSRQ, and interference ratios. GPS coordinates are also recorded.

3) DATA INTERCONNECTIVITY SUBSYSTEM

As it can be inferred from the previous subsections, it is of critical importance to have the main two subsystems (data collection via UAV and data storage via cloud infrastructure) working together in a seamless manner. The connection between the UAV and the Hetzner VPC server is secured and managed through public IP addresses and HTTPS protocols, ensuring data integrity and security. When metrics from the UAV custom exporter are sent directly to the Prometheus instance in the VPC, the UAV sends data to Prometheus using an API endpoint configured to accept *pull* requests. This setup is based on Prometheus scrape mechanism, where it periodically pulls data from the UAV exporters. Within Hetzner VPC, Prometheus is configured to scrape data from the UAV at regular intervals, such as every 10 seconds. This interval ensures that metrics are updated frequently enough for real-time monitoring without overwhelming the network or storage. Prometheus stores these metrics in a time-series database, enabling historical tracking, which is essential for identifying trends in LTE performance over time and for assessing potential performance degradation. HTTPS provides a secure layer, encrypting the data to prevent interception and unauthorized access. Grafana then accesses this stored data, displaying it on an intuitive interface for easy interpretation.

Additionally, the Hetzner VPC server is protected by firewall rules that restrict access to essential services only. Ports that are publicly accessible include those required for HTTPS connections (such as port 443 for secure web access). Other non-essential ports are kept closed to reduce the potential attack surface. Additionally, SSH access (port 22) is limited to specific IP ranges to secure remote management, allowing only administrators to log in from authorized locations. Lastly, Prometheus is configured to send alerts based on predefined thresholds, which notify administrators of potential issues, such as sudden drops in LTE signal strength or UAV system malfunctions. The dashboard is configured to display the metrics obtained from the UAV, as shown in Figure 7. The final panel is composed in two sections where we visualize the data with a refresh time of 5 seconds. The upper section shows the data of the LTE connection with the values of the metrics obtained such as CellID, RSSI, SNR, SINR or the OperatorCode. The lower section has several pieces of information: a) the TrackMap that shows the path of the UAV, b) the heatmap composed based on the measurements obtained from the LTE signal strength (RSSI) and c) a graph with the heights of the flight.

Although the RSSI readings may vary significantly between different devices, operators and measurement locations due to the particular features of each of these, it is taken as a reference that if the device receives a measured signal strength greater than -70dBm, it is in a good area of signal coverage and the higher the reading and closer to 0dBm is,

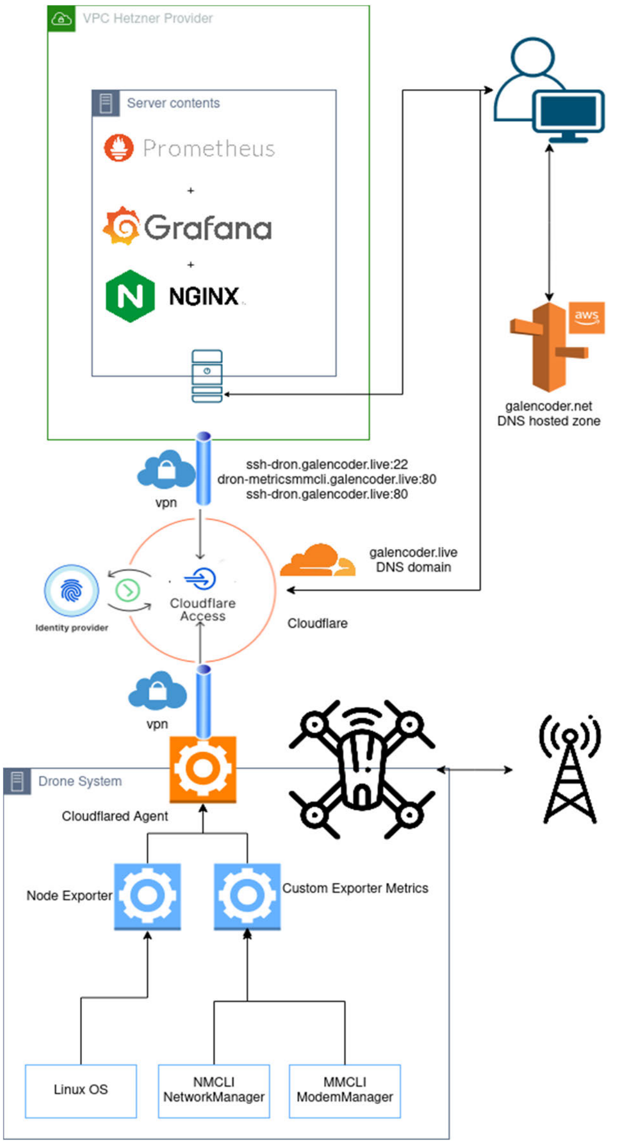


FIGURE 6. Architecture diagram for data collection components.

the greater the strength received, so its coverage would be significantly better the closer the read values get to the latter. Further criteria have been described in section IV.

IV. TESTING AND RESULTS

With the development of the solution already finished in its first stage, testing activities were carried out to check the feasibility of the proposed system.

A. PRELIMINARY TESTS

Since the UAV designed for the purpose of this manuscript was built from scratch (as it required several specific components for signal collection that are typically absent in commercial UAVs) it was required to have it tested first in a safe environment. An incremental approach was taken:

1. **Sole UAV, indoor flights**: the sole UAV was flown by a certified UAV pilot in a large indoor industrial facility where nobody would be at risk and no harm could be produced. This test provided results in a closed environment large enough to lift the UAV and verify its stability and proper communication with the laptop that was being used as the ground station.
2. **Sole UAV, outdoor flights:** at this point and after the first batch of indoor tests it was known that the built UAV was reliable enough to take off, hover, fly and land without any issues, so the same certified UAV pilot flew the UAV in an appropriate outdoor location. This was done taking precautions to avoid nearby populated areas, prohibited flight sites and locations likely to have people or animals wandering near the test area that would result in unwanted accidents, should the UAV be proven not to be suitable for outdoor flights. Nevertheless, the UAV was successfully tested as flightworthy in an outdoor environment.
3. **UAV with USB stick modem, outdoor flights:** testing activities were further expanded to having the UAV collecting information with the USB stick modem. While it was considered to use a smartphone to collect mobile network information, that stage was skipped in order to test USB modem data gathering on the grounds that, according to the reviewed literature, smartphones had already been used for that purpose, and we were looking to push beyond the existing state of the art.

Considering these preliminary tests and their results, Table 5 has been included in this manuscript to offer a holistic view of the actions performed and how they are related to the contributions described in the first section of this manuscript.

As depicted in the aforementioned table, there are several performance metrics that have been defined for each of the setups prepared for the preliminary tests, ranging from sustained flight for 5 minutes to the collection of RSSI information with the USB stick modem. In this latter case, it was checked that the highest received power reading was -80 dBm, whereas the lowest one was -111 dBm. Experiments performed involved flying in a three-dimensional trajectory determined by the certified pilot that was maneuvering the UAV. Results were satisfactory for each of the experiment iterations, which proved that the built UAV was aligned with the contributions mentioned in the first section.

B. DATA COLLECTION WITH FINAL SETUP

Lastly, flights and tests were performed with the final data collection system mounted and configured on the UAV (that is to say, the Sixfab LTE Connection Hat). This device worked with a SIM card installed to collect mobile network information from the operator that the SIM card itself was subscribed to. The appearance of the final setup used for UAV flight is depicted in Figure 8. It can be seen how the Sixfab hat used for mobile network measurements was mounted sandwiched between the Navio2 controller hardware (on top) and the Raspberry Pi used for UAV control and general functionalities (at the bottom).

This setup was more complex than the previously used ones (just the UAV, UAV with the USB stick modem) but

TABLE 5. Main features of the preliminary tests.

Setup	Performance metrics	Experiment performed	Results	Connection to contributions
Sole UAV	Flight timespan, measured in minutes (5 minutes)	Indoor flights in a large enough location (i.e. industrial warehouse)	Indoor flightworthy UAV. Able to take off, hover, move and land with no issue	Contribution 1, Contribution 2
Sole UAV	Flight timespan (5 minutes), GPS metrics (latitude, longitude, altitude)	Outdoor flights in a completely rural, unpopulated location away from	Outdoor flightworthy UAV. Able to take off, hover, move and land with no issue	Contribution 1, Contribution 2, Contribution 6
UAV+ USB stick	Flight timespan, GPS metrics, Received Signal Strength Indicator (RSSI)	Outdoor flights in a rural environment. Collection of mobile network-related data.	Outdoor flightworthy UAV. Able to take off, hover, move, land and collect mobile network-related data	Contribution 1, Contribution 2, Contribution 3, Contribution 4, Contribution 5, Contribution 6

it allowed us a more detailed deployment and collection of measurement capabilities. Besides RSSI, RSRP (Reference Signal Received Power, indicates the average power of received reference signals), RSRQ (used in this context to measure the quality of the reference signal by combining RSRP and RSSI parameters), and SNR (Signal-to-Noise ratio, measures the strength of the received signal compared to the strength of the received noise) could be accurately measured. Other parameters such as GPS coordinates, altitude, SINR (Signal-to-Interference-plus-Noise Ratio, provides an indication of how clean the signal is) or the cell identification were measured as well. As the installation of this setup involved some major changes in the hardware used as part of the UAV, some test flights were performed to find out if the UAV was still robust and reliable as before to make sure that no unexpected events would take place. The UAV turned out to be as reliable as before. Since the measurements that were to be collected required a precise assessment to a) know whether the UAV was collecting actual, useful data, b) compare them to what would be considered to be good enough performance and c) compare them to the theorical data that can be openly provided by the operators, a number of thresholds was established to have an accurate view of the obtained results. Such thresholds have been represented in Table 6. In order to establish them, there are several sources that have been taken into consideration: a) the 3GPP (3rd Generation Partnership Project) Standards, which provide LTE specifications [38], b) the technical specifications provided in the documentation, like TS 36.214 [39] and c) other literature sources with LTE metrics, such as [40] and [41].

C. DATA COLLECTION FOR MOVISTAR

After these criteria were established, a number of flights was performed to obtain mobile network coverage data and to compare them with those provided by the mobile network providers. These flights were carried out both in isolated environments like town outskirts in rural areas and in urban areas with large enough open areas to ensure safety. Figure 9 (see Appendix section) shows the general appearance of one of those missions in the Grafana dashboard with the mobile operator *Movistar*, with several gauges offering information about the operator providing the network for the flight (it can be seen how the Operator Code is translated into *Telefónica Móviles España* in the Grafana screenshot in Figure 9a). As far as the readings of RSSI, RSRQ, SNR are concerned, they have been further explained here:

1. The minimum RSSI reading collected is -105 dBm and the maximum is -93 dBm (Figure 10, top). As will be seen in the results discussion section, if comparing the received data with those offered by the mobile network provider (Figure 9b) it can be observed that the data collected is suboptimal compared to the official one if the thresholds that we have set are taken into consideration.
2. The minimum RSRQ reading collected is -16dB, whereas the maximum reading is -10 dB (Figure 10, second graph from the top). Overall, these values can be considered good overall, even though the lower ones would be suboptimal too; such readings can be related to episodes of network congestion.
3. The minimum SNR reading collected is (Figure 10, second graph from the bottom) is -4 dB, whereas the maximum value collected is 10 dB. These values show that communications were ranging from fair to poor when these data were collected. While this could be related to the height where the data was collected, it shows a significant mismatch from what would be expected from a mobile network operator.
4. As for other readings collected, Figure 10 (bottom) also shows the altitude that the UAV flew. It can be seen how the UAV flew at an altitude of around 600 meters. Considering that the flights took place in the Calatayud town area, which has an average altitude of 536 meters [42], it can be inferred that the UAV flew between 52 meters and 69 meters above ground (as the lower altitude reading is 588 and the highest is 605). Rather than following a predefined pattern, and in order to avoid unnecessary

FIGURE 7. Modem exporter metrics dashboard in Grafana.

risks, the human certified UAV pilot that maneuver the UAV before was also guiding the UAV at this point. Information regarding coordinates (latitude 41.3, longitude -1.66, which have been also specified in the appendix as 41°18'00.0" North, 1°39'36.0" West), or the cell identifier were also obtained. These and further data have been included in the GitHub repository located at [43].

D. DATA COLLECTION FOR SIMYO

Another set of flying missions was performed in the same area with the same objective of measuring signal readings from mobile network providers. This time measurements were taken for the *Simyo* mobile operator. Therefore, a similar set of flights was performed to collect information about the network capabilities of this operator in the same area (see Figure 11a, located in the Appendix section) and, at the same time, taking into account the kind of information that was expected from the theoretical point of view (Figure 11b). Thus, the following readings where obtained:

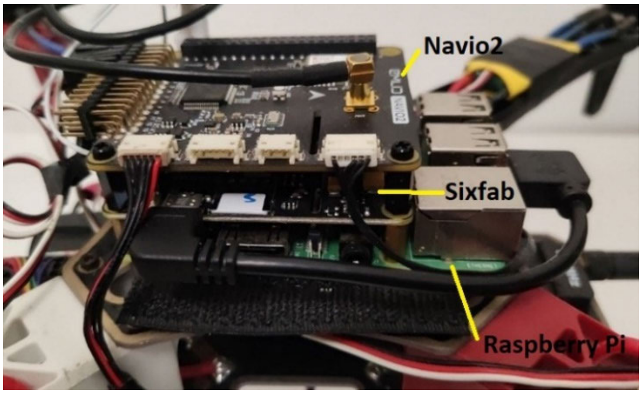


FIGURE 8. Navio 2+ Hat Sixfab + Raspberry Pi.

1. Focusing on the RSSI measurements collected for this latter mobile network provider, the minimum figure was -103 dBm and the maximum -90 dBm (Figure 12, top). While comparable to the figures obtained with Movistar -and generally speaking acceptable but lower than expected-, these are lower than the ones collected in the former case.
2. As far as RSRQ is concerned (Figure 12, second from the top), readings collected range from -10 dB (maximum

TABLE 6. Performance thresholds for LTE main measured parameters.

Signal quality	RSSI (dBm)	RSRQ (dB)	SNR (dB)	Performance impact
Excellent	>-65	>-9	>20	Fast LTE speeds, no interference, best performance
Good	-66 to -75	-10 to -15	13 to 20	Stable connection, good for streaming & calls
Weak	-76 to -85	-16 to -20	5 to 12	Slower speeds, buffering, moderate interference
Poor/Unusable	<-86	<-20	<5	Frequent disconnections, fallback to 3G or no service

value) and -15 dB (minimum measured value). These values are comparable to those obtained with Movistar but leave room for improvement in terms of performance.

3. As for SNR, the readings obtained are between 16 dB and 2 dB (Figure 12, second from the bottom). While these readings show average performance, they are better than the ones obtained from the Movistar network operator.
4. There are other readings that have been collected (SINR, cell identifier, operator identifier, coordinates); they have been placed in [43]. Altitude has been included in this manuscript (Figure 12, bottom). It ranges from 583 to 605 meters, so considering the average altitude of the surrounding area of 536 meters, it can be said that, on average, the UAV flew between 47 and 69 meters above ground.

In addition to these tests, low flights with the Simyo SIM card were taken in open park areas (coordinates 40°36’00.0”N 3°36’00.0”W) in Alcobendas [44] to further test the prototype capabilities in terms of flying and data collection.

Unlike Calatayud and its surroundings, Alcobendas is a far more urban-based area, located nearby other towns such as Madrid, Tres Cantos or San Sebastián de los Reyes, so it was deemed as relevant to take measurements in such an environment. Figure 12 shows the readings that were taken in terms of RSSI, RSRQ, SNR and altitude. The following information can be inferred from such readings:

1. RSSI minimum value was at -111 dBm, whereas the maximum one was at -80 dBm (Figure 13, top). This shows weak readings in terms of signal strength in this environment, with some drops below what would be the minimum acceptable for communications.
2. RSRQ was checked between -7 dB and -14 dB (Figure 13, second from the top). While it had some significant fluctuations that are comparable to the readings obtained with RSSI, the collected values remain highly usable and can be considered as excellent or good according to the criteria used.
3. SNR data ranges between 8.6 dB and 27.6 dB (Figure 13, second from the bottom). As it happened with RSRQ, and although there are significant fluctuations, SNR remains very favorable in almost every circumstance and poses no trouble for communications taking place.
4. There are other parameters that have been collected as well, such as UAV coordinates, cell identifier or altitude. In this latter case, the UAV could not be moved as freely as it had been done in rural areas, so collected values show that the UAV altitude fluctuated very little, from 711 to 712 meters (Figure 13, bottom). Considering that Alcobendas is 669 meters above sea level [45], it can be inferred that the UAV moved between 42 and 43 meters above the ground.

E. RESULTS DISCUSSION

While expected signal strength maps suggested uniform coverage in certain areas, the actual measurements revealed significant variations, especially in urban environments with obstacles. The study found that RSSI, RSRQ, and SNR values fluctuated more than expected, indicating potential discrepancies in network planning. This comparison underscores the necessity of empirical signal mapping for network optimization. Significant performance gaps (Contribution 4, C4) were identified between predicted and measured network quality, particularly in areas expected to have strong coverage. Certain locations exhibited unexpectedly low signal power, suggesting issues with network optimization or local interference. Poor SNR values indicated a high presence of interference, potentially caused by co-channel transmissions or environmental obstacles. These findings suggest that traditional network coverage estimations may overestimate service reliability, leading to user dissatisfaction. In this way, it becomes clear that by using UAVs, mobile network operators can check the actual signal power in a specific area (contributions C1and C2) and, if not matching what has been claimed within some acceptable tolerances, take the required measures to guarantee it. Unlike ground-based surveys, the UAV approach provided aerial signal mapping, enabling a three-dimensional analysis of network coverage. The fact that all these readings were obtained in real-time (C3) and in locations where regular methods could not be used shows the usefulness of the solution that is put forward by the authors of this manuscript (Contributions C5 and C6), as it shows that three-dimensional data reading and collection tools are of major importance to prove that the coverage and network power values claim are being matched in real scenarios.

V. CONCLUSION AND FUTURE WORK

The work shown in this manuscript underscores the critical need for improved measurement systems capable of accurately assessing mobile network signal power in

General / Modem Metrics

Status Modem: Up

Cell ID: 128143892

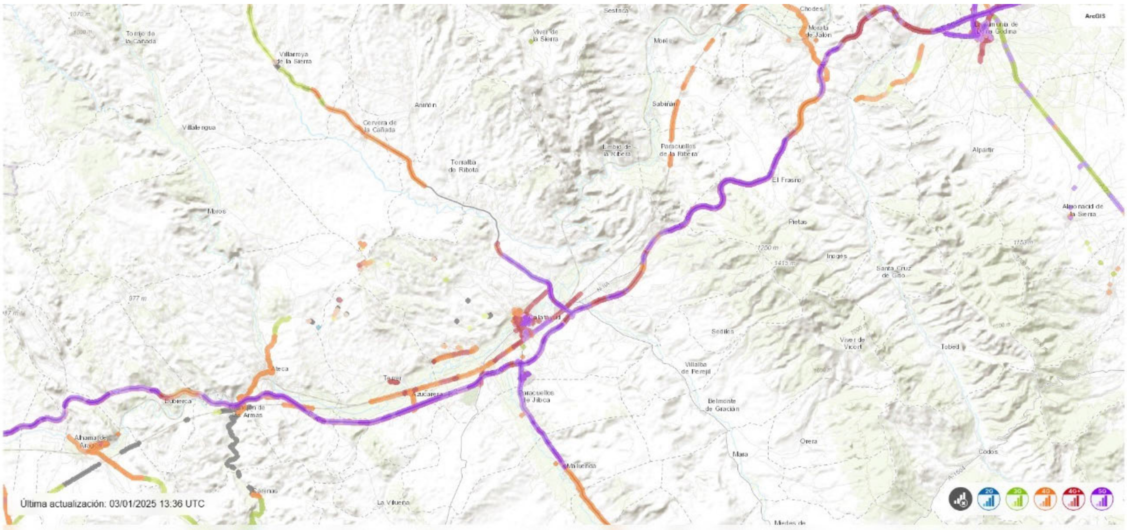
Operator Code: 21407

Operator Code: Telefónica Móviles España

LAC: 65534

TAC: 28642

9a)



Última actualización: 03/01/2025 13:36 UTC

9b)

FIGURE 9. Data dashboard for Movistar coverage in the countryside (9a) and theoretical Movistar coverage (9b) for the area around coordinates 41°18′00.0″N 1°39′36.0″W. 4G appears colored in orange and red.

```
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› Options Legend: Auto Format: Time series Step: auto Type: Both Exemplars: false

```
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```

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› Options Legend: Auto Format: Time series Step: auto Type: Both Exemplars: false

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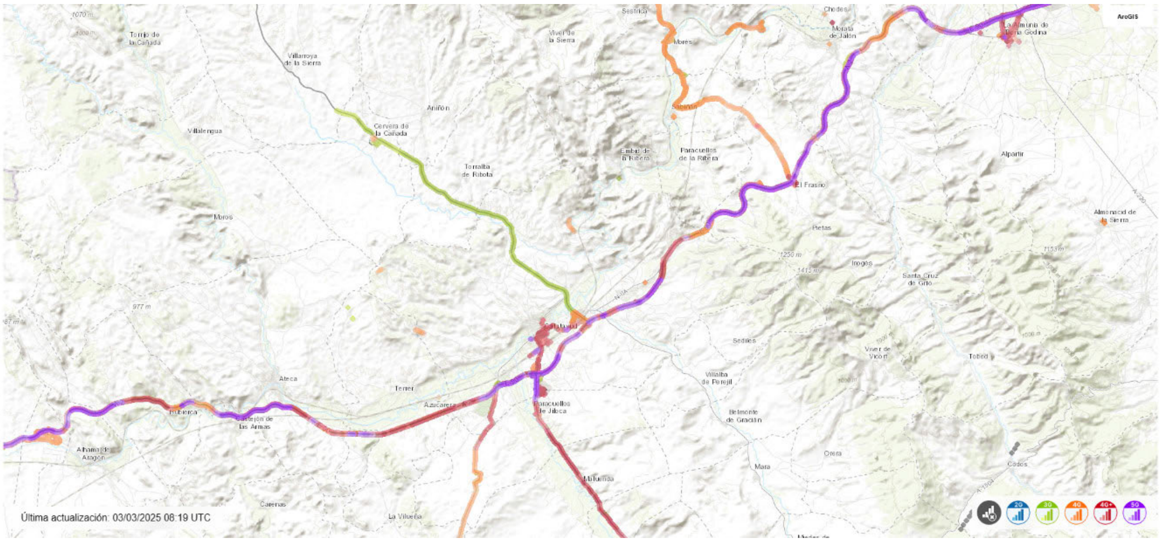
```

FIGURE 10. Collected Movistar data (RSSI, RSRQ, SNR, altitude) for an area around coordinates 41°18′00.0″N 1°39′36.0″W.

11a)



11b)

FIGURE 11. Data dashboard for Movistar coverage in the countryside (11a) and theoretical Movistar coverage (11b) for the area around coordinates 41°18′00.0″N 1°39′36.0″W. 4G appears colored in orange and red.

```
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```

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modem_alt{v_operator="simyo"}
Options  Legend: Auto  Format: Time series  Step: auto  Type: Both  Exemplars: false
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```

FIGURE 12. Collected Simyo data (RSSI, RSRQ, SNR, altitude) for an area around coordinates 41°18′00.0″N 1°39′36.0″W.

```
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```

› Options Legend: Auto Format: Time series Step: auto Type: Both Exemplars: false

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```
modem_rsrq
```

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```
modem_snr
```

› Options Legend: Auto Format: Time series Step: auto Type: Both Exemplars: false

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› Options Legend: Auto Format: Time series Step: auto Type: Both Exemplars: false

{__name__="modem_alt", icc="8934013372043244920", imei="351626104660755", imsi="214035849799491", instance="dron1-metricsmmcli.drones.ga:80", job="dron1-metricsmmcli", operator="ESPRT", operatorid="21403", rat="lte", v_operator="simyo"}

FIGURE 13. **Data dashboard for Simyo coverage in an urban area (Alcobendas, Spain) for an area around coordinates 40°36′00.0″N 3°36′00.0″W.**

non-conventional environments, where traditional methods often fall short. The effectiveness of UAVs equipped with signal receivers has been demonstrated as a viable solution for collecting data in hard-to-reach locations, thereby enhancing the accuracy and comprehensiveness of signal measurements. The work presented here aims to bridge the gap between reported coverage by telecommunications operators and the actual user experience, fostering trust among consumers and ensuring compliance with regulatory standards. Additionally, the proposed low-cost, open-source measurement system is scalable and accessible, allowing for broader participation in network assessment efforts, which can significantly impact infrastructure planning and optimization.

Future works could focus on expanding the range of environments and scenarios tested with the measurement system, including diverse geographical areas and various urban settings. Flights have been shorter and at relatively low altitudes when they have been carried out in urban areas; more flights could be made to obtain more data and to create a more detailed and accurate signal strength map. This could be done with a swarm of UAVs to save time; the limit in this case would be given by the Prometheus server but being in cloud its resources can be easily scaled, so it would not be much work if the swarm of UAVs is very large. Furthermore, integrating the system with emerging technologies such as 5G and the Internet of Things (IoT) will be essential to assess their performance and impact on network quality. Further studies could provide insights into changes in signal strength over time, while collaborations with additional telecommunications operators could validate findings and enhance practical applications. User-centric studies may further explore the relationship between accurate measurements and user satisfaction, informing the public about system enhancements. Lastly, research could be done on how the implications of improved measurement systems could influence regulatory frameworks, and developing advanced analytics could yield deeper insights into network performance.

APPENDIX

The figures referenced in Section IV have been placed as the main part of this section.

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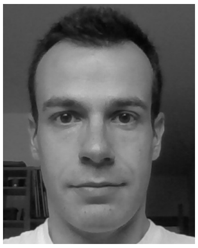

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