Collecting Sensor Data from WSNs on the Ground by UAVs: Assessing Mismatches from Real-World Experiments and Their Corresponding Simulations

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***Abstract*—Communication approaches for autonomous robots in surveillance missions, remotely acting or collecting point-of-interest data, are widely researched. In this line of research, most works address the use of unmanned aerial vehicles because of the mobility flexibility of these vehicles to cover an area. However, these proposals are verified almost exclusively through network simulations. Simulations are efficient for speeding up experiments. In most cases, most experiments are simulated because of the difficulty of validating a proposal in the real world. Real-world experiences are doubly important because they provide much more robust validation to the proposals, real-world tests can be compared to simulated tests, and the gaps between the results can be used to enrich simulated environments that will be used for validations without real-world tests. In this line, this paper presents tests performed in simulated and real-world environments, compares the results of both experiments and presents how enhancement can be applied.**

***Index Terms*—UAV, drones, IoT, WSN, Simulation, Verification and Validation**

I. Introduction

Several studies have focused on data collection from wireless sensor networks (WSNs) on the ground by Unmanned Aerial Vehicles (UAVs) in past decades, leading to some specific solutions for environmental monitoring, security, precision agriculture, and several other applications [1]. UAVs are excellent examples of computing nodes with high mobility. Common to all these applications with UAVs is that the monitored or controlled geographic region is either difficult to access, very large, or hazardous, making overflying the only feasible way to collect data.

In parallel, the internet-of-things industry has propelled the miniaturization and increased the efficiency of systems-on-chip short-range low-power wireless communications, mesh-network technologies, and battery-operated sensors and actuators and thereby enabled the remote sensing and control of almost any instrument in any environment or physical space [2].

However, for UAVs, as long as node mobility is a key enabler of remote-sensing solutions, a number of problems still remain, such as intermittent wireless connectivity, radio interference, the choice of antenna, the effect of fading due to mobility, and handover issues. These call for research and development—along with field experiments—on several levels: intermittent wireless transmission, communication and coordination protocols, and system implementation and operation.

Exploiting multi-UAV systems can significantly enhance data-collection time, latency, fault tolerance, and network lifetime [1]. Proposed a distributed algorithm for UAV flight coordination and cooperative sensor data collection, DADCA [3], in which an arbitrary and dynamic set of UAVs can collaborate and self-organize to collect and transmit data from desired points of interest to a base station. In parallel, focusing on effective wireless communication in a ground-based mesh network, we have also proposed the mobility-aware mesh (MAM) routing protocol [4], an alternative protocol to the Bluetooth mesh standard, focusing on mobile sinks/collectors.

In this general context, it was proposed the ground-and-air dynamic sensor networks (GrADyS) project [5]. The GrADyS project aims to test the interaction and interoperability between dynamic mesh-network protocols, such as DADCA and MAM, to investigate the problems and explore the benefits of full air-to-ground mesh communication. Another critical aspect of the GrADyS project is the validation of air-to-ground interactions and protocols through network simulators and real-world "field experiments," i.e., the effective deployment of ground sensors and UAV fleets flying over an area to collect data.

Thus, a main project goal is to compare the performance results (throughput, latency, etc.) and the general behavior in similar scenarios run in simulated and real-world environments.

This article uses as background two previously published solutions within the scope of the GrADyS project, i.e., an open-source framework for UAV swarm sim-

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ulations along with the OMNeT++/INET[1] simulator called GrADyS-SIM [6]. In this tiny and well-documented abstraction layer for OMNET++/INET, we ran selection tests of the approaches with the UAVs and sensors on the ground. With the simulations, we present real-world results and compare them. The emergence of differences does not decrease the use of simulations, as they are a notably agile and economical approach to verifying hypotheses and proposals.

However, this work explores how simple data collection from a WSN can lead to significant differences. In this way, we also ratify the importance of validation and prototyping, even in basic research endeavors.

This work's main contribution involves validation results of simulations using practical tests in real-world testbeds[2], which collect data from sensors on the ground. This work also implements and tests Clara et al.'s [7] proposal for a better radio simulation in this scope. This implementation reduces the gap between simulations and the real world. We compared the simulation and data-collection results and, in the process, identified divergences and explored the problems between simulating scenarios and carrying out field tests with WSNs and UAVs.

This paper is organized as follows: Section II details approaches to the problem; Section III presents the main related works; Section IV describes our approaches and test designs; Section V presents the results and discussion; and, finally, Section VI concludes the study.

II. Problem statement

Often, one cannot effectively implement environmental monitoring only through image analysis (taken from overflights), and the process also requires the periodic collection of data from hundreds or even thousands of sensors on or close to the ground, such as those placed near tree crops.

One can use these sensors to monitor the humidity level, temperature, slight tremors, or slight displacements of the soil that are barely detectable by humans. In such cases, the best approach is to spread sensor nodes—numbering in the hundreds or thousands—over the areas and use UAVs to periodically visit and collect data. However, since numerous of these sensor nodes might be present on the ground, a swarm of UAVs coordinating their itineraries is necessary. Moreover, several sensor nodes placed in certain spaces, e.g., among two large stones or under a bush, can hinder UAV visits and/or the vertical wireless transmission of data.

Therefore, this necessitates building a mesh network of sensor nodes and routing each node's sensory data in the directions of the visited mesh nodes. However, this highly dynamic routing and collection of data among mesh sensor nodes and a fleet of UAVs poses several challenges due to the inherent mobility of UAVs, wireless interference (e.g., between the vertical and the horizontal data transmission), intermittent visits, and the overall energy drain of the system. Notably, effective and collision-free wireless transmission must accompany the optimization of the individual movements of the UAVs so as to achieve the maximum data throughput with the minimum amount of flight movement. It is in this context that several works [1] [8] [9] have offered different approaches to tackle such problems. However, most have verified their proposals through simulations or, when possible, bench tests. This current work considers these issues in the context of field testing and compares the simulation results with accurate measurements using UAVs and ground sensors.

III. Related Works

Most related works, e.g., Akbar et al. [8], have focused on route optimizations or associated modeling, while many others have concentrated on clustering [1]. Some researchers, have proposed physical UAV architectures, and several others employing control structures have used testbeds to validate their controls in indoor environments with precise location systems, e.g., Kumar et al. [10], D'Andrea et al. [11], and Guerreiro et al. [12]. Few Sensor Networks works have verified their proposals and effectively validated them with real-world tests. Studies such as the one conducted by Popescu et al. [13] have involved several steps ranging from proposal, modeling, and simulation perspectives, though without the complete validation of the proposed components. Most works have focused on planning [9] and simulations [14]. Regardless of the communication protocol or even the control of the aircraft, the crucial factor to consider in increasing the exchange of messages is the time taken to lift the link between the points and the time it remains active. Theoretically, the lighter the protocol, the more efficient it is. To the best of our knowledge, the RosNETSIM [15] is the most related work putting efforts into joint robotics and communications environment. However, it focuses on the binding between Ros and other simulators, directly related to MAVSIMNET [3].

Some works have addressed protocols prioritizing this passage of a UAV. Simulations have significant value; however, real-world factors involve numerous variables that one can measure and use to enrich the simulation environment.

IV. Approach and experiments

We aim to present the differences in the data generated from simulations related to UAVs and WSNs with real-world experiments. Such differences are crucial for analyzing the validity of simulated proposals and contribut-

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[1] https://omnetpp.org/

[2] https://gradys.tumblr.com/

[3] https://github.com/Thlamz/MAVSIMNET/

ing to improving the quality of simulations. Our approach involved state-of-the-art simulations (re)implemented in the most reliable way possible. In the following subsections, we detail the different elements used in our experiments. We implemented a testbed with five UAVs with 10 sensors based on ESP32 and distributed in subsets across a total area of 60ha. This scenario is called the GrADyS Testbed.

A. *Simulation approach*

A broad spectrum of studies has verified their proposals in an ad hoc manner, creating the minimum necessary resources for their simulations. This makes it more challenging to reproduce the experiments from these works. Other works have striven to verify their proposals using solid simulation solutions. In the case of WSNs, researchers have long used OMNeT++/INET and NS3, with a significant range of network protocols already applied and enabling new implementations. Others have used frameworks such as ROS/Gazebo to aid in the simulation of autonomous vehicles. However, it would be more focused on hardware kinematics instead of communications along initiatives such as RosNETSIM [15] to enable a merge between environments.

This paper carrying out all simulations related to telecommunications using GrADyS-SIM [6][4], an open-source OMNeT++/INET set of classes, a framework, for simulating cooperating swarms of UAVs on a joint mission in a hypothetical landscape that communicate through radio frequency. The framework was created to aid and verify the communication, coordination, and context-awareness protocols under development in the GrADyS project. GrADyS-SIM uses the OMNeT++ simulation library and its INET model suite, allowing for the addition of modified/customized versions of some simulated components, network configurations, and vehicle coordination systems to develop new coordination protocols and test them with the framework.

The framework simulates UAV movement, as dictated by a file containing some MAVLink instructions, where different network situations can affect it on the fly. The coordination protocol of the UAV swarm emerges from individual interactions between UAVs and aims to optimize sensory data collection over an area. It also allows the simulation of some types of failures to test the protocol's adaptability. Every node in the simulation is highly configurable, ensuring the rapid testing of different network topographies, coordination protocols, and node hardware configurations, among other factors. The project and documentation are available on Github[5], with lots of details about how to use it straightforward, customize or get some specifics parts of the code.

B. *Real World approach for the WSN and for the UAV*

To construct the WSN field, we used 10 units of a device based on the Espressif ESP32 system[6], the feature-rich MCU with integrated Wi-Fi and Bluetooth connectivity for a wide range of applications. We configured ESP32 to use only Wi-Fi radio communication simulating a seismic sensor. Every time it received a keep-alive message from a UAV, it responded with a message with the requested data. Defining the location of sensors on the ground itself presents a challenge in the real world. Although a simulated environment allows one to create several maps automatically and perform simulations, the process is less versatile in the real world. We selected 10 points that, to the best of our knowledge, blend the real-world impacts of sensors on the ground. The selected power was 11 dBm, ensuring that the sensors were unable to communicate at a distance of 50 m when placed on the ground. We arranged the sensors roughly in the shape of a capital "S" with a distance of approximately 60 m between each and ensured no communication between nodes at the WSN.

The UAV model was a custom-made multirotor with four motors (a quadcopter) and an AUW of approximately 1.9 kg. The UAV had 140-W motors, 9-inch propellers, and a 5,000-mAh four-cell battery (14.8 V). It had a minimum flight time of 20 minutes, and the usual flight speed was 10 m/s; it could reach 15 m/s if necessary. The equipment is similar to the DJI Phantom 4[7]. In addition, the UAV had an ESP32 for data collection.

The URL https://gradys.tumblr.com/ depicts the sensors, UAVs, the map1, and the experimental scenes, including an aerial tour of the sensors.

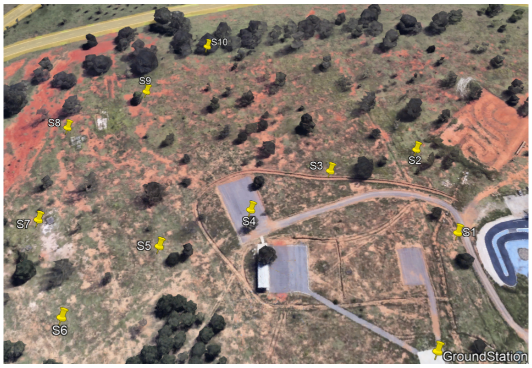

Figure 1: Sensors locations on the ground, accessible only by flying robots. GS stands for GroundStation and S1 to S10 are the Sensors locations from 1 to 10.

C. *Verification and Validation*

The proposed experiment involves a UAV flying over the entire area with the ten sensors, sending a 1-byte

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[4] https://youtu.be/Im6d5TEes4Y

[5] https://github.com/brunoolivieri/gradys-simulations

[6] https://www.espressif.com/en/products/socs/esp32

[7] https://www.dji.com/phantom-4

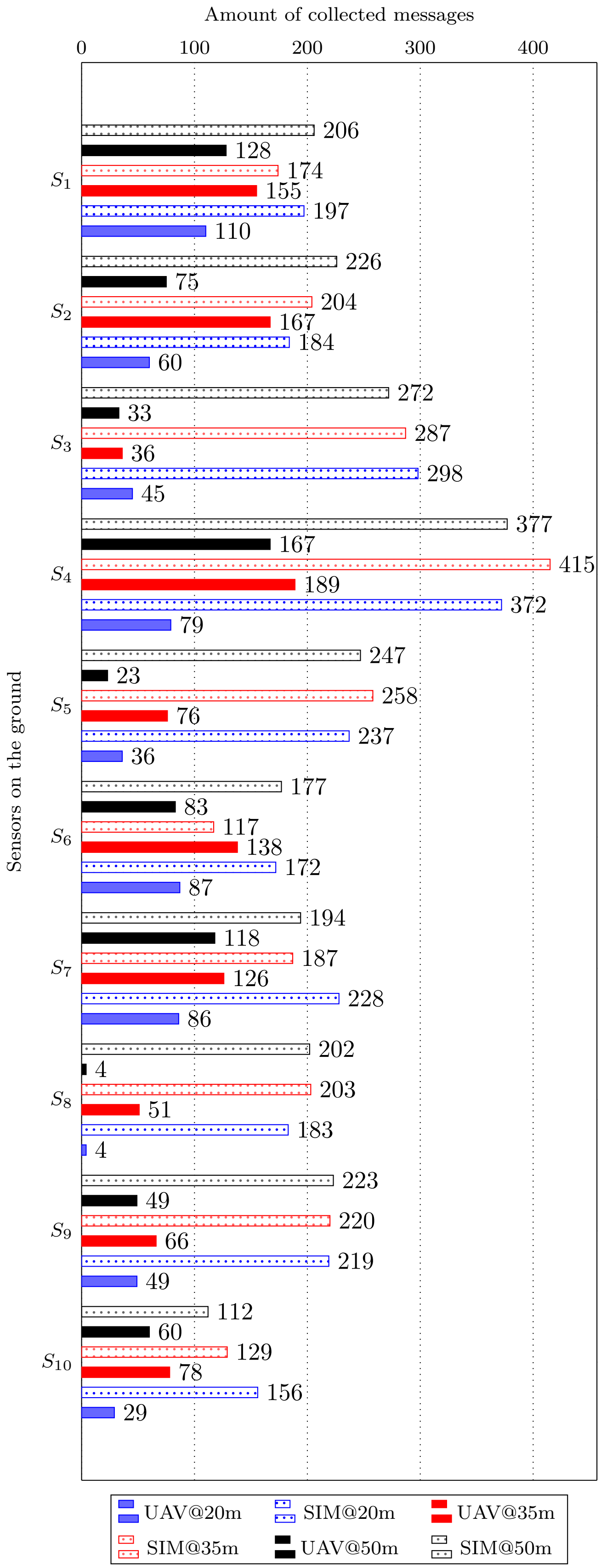

Figure 2: Amount of collected messages flying at 5m/s

keep-alive message every 200 ms. For each message that a sensor received, it responded with a message of also 1-byte. For each flight, the UAV traveled over each sensor, from sensor 1 to sensor ten and back in descending order to the ground station twice and counted the number of messages each sensor received. We repeated this process five times, and the numbers presented herein are averages of the five collections for real-world tests and simulations.

The UAV collects data by flying over the field with the sensors without the UAV stopping. The trajectory is the sum of the segments between the ten sensors provided, and the UAV goes back and forth between the GS and all points in a straight line. In the simulation, this round trip of the UAV is seen as several concatenated straight lines with a constant speed. In actual flights, there is wind and unwanted drag from the UAV that impacts collection, in addition to other problems with radio communication.

We used the same path and geographic coordinates in the simulations in GrADyS-SIM and the real UAVs, as well as the same dynamics of message exchange. We successfully tested several network protocols in the simulation. However, in real-world tests, protocols with more complex stacks, such as TCP and even UDP, are very inefficient and, in many cases, ineffective because the speed of the UAV makes it difficult or even impossible for links to form. We carried out the closest implementation for the simulation using the ESP-NOW protocol in the sensors while purely using 802.15.4 in the simulation. We conducted the experiments with the flying UAVs and simulations at heights of 20, 35, and 50 m and UAV speeds of 5m/s.

D. Channel Modeling

The objective of channel modeling is to be able to predict the wireless channel signal strength at different points of the terrain, through the use of mathematical and computational models. In this context, one of the most known propagation loss mechanisms, that limits the communication range, is the Free-Space Loss (FSL), the same model used in the initials GrADyS-SIM simulations. This model considers only the signal in Line-Of-Sight (LOS) and abstracts any reflection effect or the presence of obstacles. The electromagnetic energy decays with the square of the distance.

Another propagation loss model, which presents more accurate results and was implemented in the GrADyS-SIM, is the Two-Ray model. This model is the simplest case of Ray Tracing [16], which considers only two ray paths: the LOS ray and the one ray that comes from ground reflection. Thus, in this scenario, there are no obstacles that cause other reflections or diffraction [17]. The mathematical formulation of the Two-Ray model is:

$$P_r = P_t \left[\frac{\lambda}{4\pi}\right]^2 \left[\frac{\sqrt{G_l}}{l} + \frac{\rho_s \Gamma \sqrt{G_r} e^{-j\Delta\phi}}{x+x'}\right]^2, \qquad (1)$$

where λ is the wavelength, G_l is the total antenna gain of the LOS path, ρ_s is the ground scattering coefficient, Γ is the Fresnel reflection coefficient of the ground, G_r is the total antenna gain of the reflected path, $\Delta\phi$ is the phase difference between the two received rays, l is the LOS path length, and $x + x'$ is the reflected path length.

V. RESULTS AND DISCUSSIONS

In Figure 2 the x-axis shows the number of messages that the UAVs were effectively able to collect while passing over the sensors at a UAV speed of 5m/s. The higher the number, the better and more efficient the collection of data. The y-axis lists the sensors (S_n), with six series shown for each of the 10 sensors: three series of real flights (solid-colored bars) and three simulated series (bars with no color fill) at three different heights (refer to figure legends). One can expect more data collection with a longer network link time. However, this is not trivial, and the UAV speed affects the data collection by changing the contact time between the UAV and a sensor. Although the height increases the distance between the sensors and the UAV, it also allows for a cleaner field of view for a longer period. Furthermore, vegetation greatly influences the view. The combination of these factors generates a combinatorial fan that future studies must address.

Figure 2 presents the individual measurements of the sensors' collected messages for a UAV flight speed of 5 m/s, for both the simulated and real-world cases. As expected, the actual measurements were significantly lower than the simulated ones due to real-world factors.

The most significant absolute and also proportional difference in a single sensor and collection occurs in the case of S_8, where the simulations involve approximately 50 times more messages collected compared with the real word at two of the UAV heights. However, analyzing the asymptotic behavior of each set of three series for each sensor is more noteworthy. For example, the simulated results of S_1 show a concave curve on the x-axis (206, 174, and 197 messages), indicating that the best UAV height to retrieve data is 20 m, followed by 50 m and finally 35 m. However, the field results of S_1 show a convex curve on the x-axis, indicating that the most efficient collection is at 35 m (155 messages), followed by 50 m (128 messages) and finally 20 m (110 messages). The situation where the field collection was more efficient at 35 m is repeated in eight of the 10 sensors in the field, while it occurs in only two sensors in the simulations.

Another noteworthy point is the homogeneity of the results. The differences between the number of collected messages at the different heights in the same sensor are much smaller in the simulations than in the field collections. In the field tests, due to environmental factors such as obstacles, one can easily notice large differences in the results, e.g., sensors S2 (up to 64%), S4 (up to 58%), S5 (up to 69%), and S8 (up to 92%). In the simulations, the largest difference between the collections at the different heights occurs in S6, reaching 33%. One can infer that the results of the simulations are significantly more linear and closer to each other than those of the field collections.

A. Accumulated results

Figure 3 summarizes the experimental results in a bar chart. We present four series for each of the three heights used in the experiments. The terms "UAV 5m/s" and "SIM 5m/s" indicate the number of accumulated messages from all the sensors in the field and the simulations, respectively, at a flight speed of 5 m/s. When grouped, one can notice that the simulations display very similar data, regardless of flight height. The maximum variation is 0.8% in the simulations, while, in the real flights, it reaches 41%. The data from the simulations tend to show that no relevant variation exists between the different collection heights, while the real-world collections show a relatively noticeable difference.

For the UAV moving at 5 m/s, one can verify that the least favorable result noticeably occurs at a height of 20 m, where obstacles can cover more of the sensors. Regarding the naive simulation, one can expect that the best data collection occurs mainly at a greater signal strength and link time between points. However, the adopted signal decay model does not demonstrate significant sensitivity. The variation in the UAV flight speed shows a directly proportional impact (approximately twice the amount of data collected at half speed). This suggests that the signal decay model in the simulations was not sufficiently reliable to yield similar results.

Concerning the real-world tests, one can observe that the variation in UAV height has a smaller impact than the obstacles in the field. Thus, a combination of all the present factors shows that the collection at the height of 35 m at 5m/s is the most efficient of the five series of real flights.

B. Improving the simulations

It is reasonable to expect that simulations will show different results from field tests. However, proportion and equivalence in real experiments and simulations must be pursued and verified. In this line, with the results of the simulation and field tests, options to improve the simulation were analyzed. As example, the wireless connectivity of a Ground-and-Air Sensor Network was widely analyzed obtaining more realistic results [7].

This work presents a Two-Ray model, which in summary, presents greater conformity between the simulation and the real world. It is materialized and made available as a simple C++ class that can be inserted into the OMNET++/INET[8] environment.

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[8] https://github.com/Santiago852/ProjectGradys-IME/tree/main/src

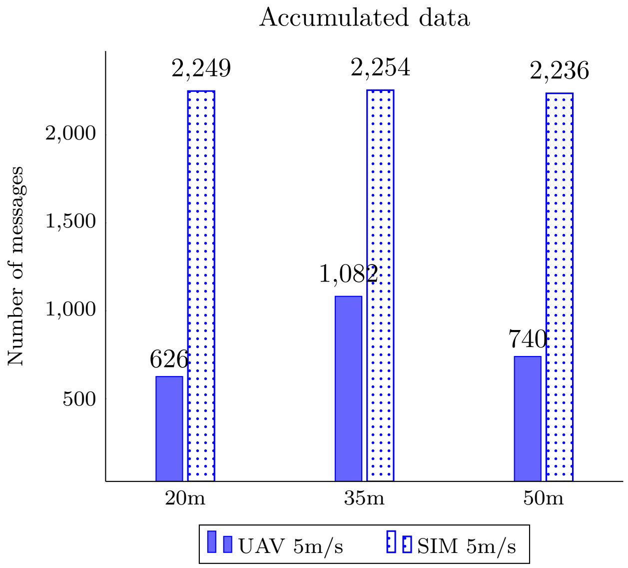

Figure 3: Accumulated messages per experiment.

In order to understand how to improve the GrADyS-SIM simulations, it is necessary to analyze the propagation channel and estimate the Received Signal Strength (RSS). Therefore, two simulations were performed in the MatLab program to analyze the received signal power (Pr) in the ground sensors considering both propagation models, explained in subsection IV-D. The simulation parameters are shown in Table I.

Parameter	Description	Value
$\lambda/2$	Dipole antenna lenght	Half-wave
f	Signal frequency	2.412 GHz
P_{TX}	Transmitter power	-2.2 dBm
S_{RX}	Receiver sensitivity	-85 dBm
G_{max}	Maximum antenna gain	1.97 dB
d	Link horizontal distance	0 - 350 m
ε_r	Relative permittivity soil	1.7
σ	Conductivity soil	0 mS/m
Δ_h	Std deviation of the ground heights	0.001 cm

Table I: Parameters of simulations

Figure 4 shows the results of the simulations for each UAV flight height (20m: blue curves, 35m: red curves, 50m: black curves) in the maximum horizontal coverage range (0-347.2m). The dashed curves are the results of the first simulations when it was considered the Free-Space Loss (FSL) model and isotropic antennas, which are theoretical antennas that irradiate the same power in every direction. The full curves are the results of the second batch of simulations, where the Two-Ray model with realistic soil and half-wave dipole antennas polarized vertically are considered.

The curves of the first simulations (dashed curves) show that the communication link between the UAV and the ground sensors is operational up to 209 m of horizon distance, for a flight height of 50 m (worst case), and up to 214 m, for a flight height of 20 m (best case). Beyond these coverage distances, the received power becomes less than the receiver sensitivity of -85 dBm. In the second simulation (solid curves), the communication link between the UAV and the ground sensors starts to work only in the initial horizontal distance of 8.4 m up to 347.2 m, for a flight height of 20 m. For flight heights of 35 m and 50 m, initial coverage distances are 22.8 m and 42.2 m and final coverage distances are 138.7 m and 168.8 m, respectively. This initial zone without coverage happens because of the type of antenna and the polarization admitted in this second simulation, which is in agreement with the vertical half-wave dipole diagram.

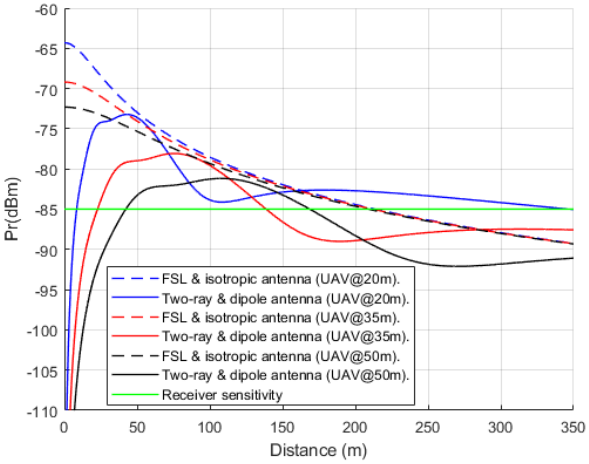

Figure 4: Received signal power.

Table II summarizes the results of the received power analysis, taking into account Figure 4. The average received powers, in the Two-Ray model, are lower than in the FSL model, so it is in compliance with the number of received messages, shown in Figure 5.

Propagation model	UAV height (m)	Horizontal coverage range (m)	Total coverage distance (m)	Average received power in coverage zone (dBm)
FSL	20	0 - 213.9	213.9	-77.50
	35	0 - 212.0	212.0	-78.32
	50	0 - 209.0	209.0	-79.08
Two-ray	20	8.4 - 347.2	338.8	-81.83
	35	22.8 - 138.7	115.9	-80.24
	50	42.2 - 168.8	126.6	-82.36

Table II: Received power analysis.

Figure 5 shows the previous results, adding the bars named ”SIM-IME 5m/s” for the new simulations. These results show greater proximity between the simulations and the results of actual flights. Therefore, this model was implemented in the GrADyS-SIM simulation. However, these results are still closer to the simulated initial ones than to the results of the real experiments.

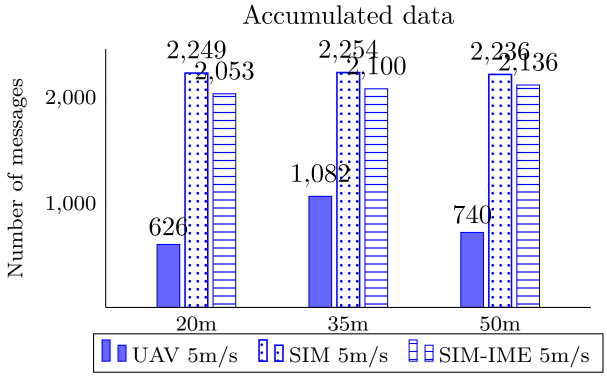

Figure 5: Accumulated messages per experiment with an extra simulation with a Two-Ray model added in INET. The bars named SIM-IME presents that.

For future works, other factors that would improve the accuracy could also be considered, such as the influence of other scattered rays due to non-specular reflection [18], which can reach the receiver with random directions and energies, due to the obstacles around the sensors.

VI. Conclusion

We performed simulations and carried out field tests to collect data from a WSN using a UAV and presented the observed similarities and differences. We did not aim to downplay the importance of using simulations. However, we explored their limits and presented them for the better use of simulations in bid verification. However, we also aimed to show the importance of field validations in obtaining more reliable results. We subsequently intend to present collections and tests with swarms of UAVs, new network protocols, and tools to improve the simulations with a more extensive set of network topologies on real-world tests.

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