Development and Experimental Validation of a LoRa Wireless Sensor Network for Wildfire Surveillance

Francisco Santos, Daniel Silvestre, Rita Cunha

***Abstract*— This paper describes and evaluates a surveillance system based on Wireless Sensor Networks (WSNs) and Autonomous Vehicles (AVs). Firstly, the main wireless communication technologies are surveyed, resulting in the choice of the Long Range (LoRa) technology to support the communication of the sensor nodes. In order to better deal with the characteristics of the LoRa communication, a protocol is designed and tested in realistic experiments in both rural and urban settings, which allows researchers to have a comparison between manufacturer values and realistic ones. Given the intended objective of having the surveillance system applied to remote areas to detect malicious people entering private property or forest fires, autonomous vehicles are used to further enhance the detection capabilities. The overall system is implemented in ROS packages and documented for future use. In experiments at the Institute for Systems and Robotics (ISR) flying arena, the system achieved a good average tracking Root-Mean-Square-Error (RMSE) of 0.0381 m and inspected all events that crossed the motion detection sensors with a triggering delay of 133 ms.**

***Index Terms*— Wireless Sensor Network, LoRa, Unmanned Aerial Vehicle, Surveillance System**

I. INTRODUCTION

Since the past two decades, Wireless Sensor Networks (WSNs) have been gaining traction, partly due to the advancements made in the Micro-Electro-Mechanical Systems (MEMS) field which has both facilitated and motivated the development of new smart sensors characterized by their small size and low cost [1]. These networks usually consist of a large number of sensor nodes spread out across a geographic location with the goal of gathering sensor data. WSNs play a relevant role nowadays as they are widely used in fields like environment observation (e.g. pollution levels), agriculture (e.g. temperature, humidity and sunlight levels), disaster monitoring (e.g. water level in a river, wind speed and direction, amount of rain or snow) among others [2]. The power of these networks can be augmented by the introduction of autonomous vehicles (for instance, Unmanned Aerial Vehicles (UAVs)), allowing for cooperation between static and dynamic assets in numerous applications. Moreover, having a fleet of Unmanned Aerial Vehicles (UAVs) can benefit the task of passive surveillance where each vehicle can use an algorithm such as the one in [3] or [4] and search for the most problematic zones.

In the scope of forest fires prevention and fighting, the integration between the UAVs and WSN allows for a better understanding of the region in study through the use of a fire likelihood map updated with the information gathered by the aforementioned technologies. In this particular case, the WSN can be composed of nodes spread around the forest or perhaps it can also be composed of citizens interacting through a mobile application. The idea is to combine the information from users with the data from the UAV which is used to scan hard-to-reach areas or locations of increased interest in the construction of a map of potential fire ignitions. The map plays an important role when mobilizing assets to combat the fires and it also helps detecting fires in an early state where they are easily extinguished. Given the increase in forest fires in the last few years [5], it is clear why this example motivates the study of the aforementioned technologies [6].

The proposal is to develop a surveillance system using a WSN of motion detectors together with a UAV in order to provide surveillance for large areas. Moreover, the current proposal can be extended to a more general setting where the designer has access to a fleet of UAVs to cover both missions of passive surveillance (inspect sites with a high value in the uncertainty map) or active surveillance whenever there is an event generated by the WSN. The main contributions of this system to the literature can be summarized as follows:

- We develop a WSN protocol to be deployed on top of a Long Range (LoRa) network that improves the message drop rate and can accommodate cheaper modems;
- The proposed LoRa WSN is experimentally tested in both rural and urban settings and realistic metric values are presented and compared with the values found on manufacturer datasheets;
- A Robot Operating System (ROS) code for the integration of the WSN with an UAV is presented that can carry both reactive (in response to a sensor trigger) or proactive (according to a planned mission) surveillance.

The remainder of the paper is organized as follows. We review WSN technologies in Section II focusing on the main characteristics in terms of cost, range, battery power and throughput. Section III then presents the experimental

F. Santos is with Institute for Systems and Robotics, Instituto Superior Técnico, Lisbon, Portugal francisco.velez@tecnico.ulisboa.pt

D. Silvestre is with School of Science and Technology from the NOVA University of Lisbon (FCT/UNL), 2829-516 Caparica, Portugal, with COPELABS from the Lusófona University, and also with the Institute for Systems and Robotics, Instituto Superior Técnico, University of Lisbon. dsilvestre@isr.tecnico.ulisboa.pt

R. Cunha is with Institute for Systems and Robotics, LARSyS, Instituto Superior Técnico, University of Lisbon, Portugal rita@isr.tecnico.ulisboa.pt

This work was partially supported by the Portuguese Fundação para a Ciência e a Tecnologia (FCT) through Institute for Systems and Robotics (ISR), under Laboratory for Robotics and Engineering Systems (LARSyS) project UIDB/50009/2020, through project PCIF/MPG/0156/2019 FirePuma and through COPELABS, University Lusófona project UIDB/04111/2020.

results regarding the LoRa network in comparison to the expected from the manufacturer datasheet. In Section IV it is presented the proposal of integration using ROS for both the WSN and the UAV with the experimental validation in the flight arena being discussed in Section V. Lastly, in Section VI we highlight the main findings of this paper and offer some directions of future work.

II. WIRELESS SENSOR NETWORK

A. Survey on Wireless Communication Technologies

An initial point in the development of the system proposed in this paper is to analyze the main technologies used in wireless communication — Wireless Local Area Network (WLAN), Bluetooth, Cellular and Low Power Wide Area Network (LPWAN) [7], [8] — to showcase their weaknesses and strengths. Also, it should be noted that all the specifications mentioned correspond to the ones applied in Europe and all the technologies were reviewed according to their primary use cases.

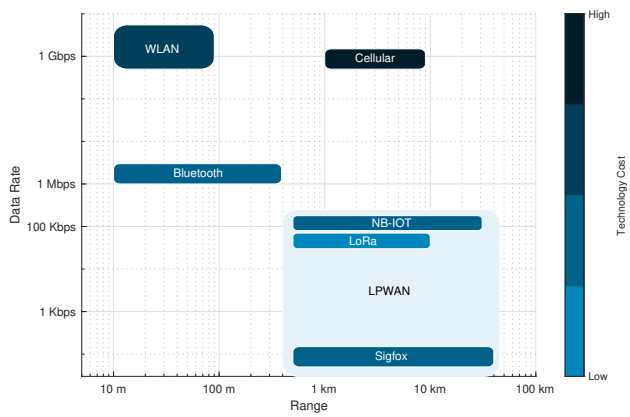

Fig. 1. Performance comparison regarding range, data rate and technology cost for WLAN, Bluetooth, Cellular and LPWAN.

Fig. 1 compares these technologies on the metrics of data rate, cost and range. Additionally, latency and battery life are also relevant characteristics. Concerning latency, LPWANs have the worst latency performance with a transmission delay that can range from seconds up to minutes [8]; for Cellular networks the latency values presented correspond to the ones for Long Term Evolution (LTE) and these usually range from 100 ms up to 6 s [9]; for WLAN the latency performance is safely the best with values in the millisecond range (usually less than 20 ms) [10]; finally, Bluetooth has a latency of around 20 ms to 200 ms [11]. With regards to battery life, LPWAN has the best performance with devices being able to last up to ten years without recharging [8]; devices using Cellular technology (LTE) can last from 2 to 4 years [9] while Bluetooth devices will last up to 2 years [12] and finally, devices using WLAN have the highest power consumption and will only last for up to 1 year [13].

For this application, a network that has long range capabilities (at least 1 km) and low power consumption (allowing for battery operated sensor devices) is required. Additionally, a low-cost technology is preferable to further motivate govern agencies in their adoption. Since only sensor data with low sample size (mostly binary values) and low sample rate needs to be transmitted, a network with high bandwidth capabilities is not necessary. Finally, regarding latency, a maximum value of 10 seconds is defined since when compared to the delay associated to the UAV time of flight, this value is negligible. Given this, LPWANs are the most promising technologies available. Within the LPWANs, LoRa was chosen due to a higher flexibility on the number of communications per device and given that it is several times more affordable than its rivals. Additionally, a LoRa gateway can easily be deployed in any area whereas Narrowband Internet of things (NB-IOT) requires LTE coverage to function, which may not be available at the deployment site for this project. Finally, a similar Chirp Spread Spectrum (CSS) modulation technology to the one used by LoRa had already been used by the US army to assist communications and surveillance due to its great properties of range and reliability (an application that is strongly related to this project) [14].

B. LoRa Technology

The LoRa physical layer is based on CSS modulation technology, which is commonly used for radio applications. With CSS modulation, wide band frequency impulses that can vary over time are used to transport the encoded data. The LoRa modulation process can be configured across different parameters: Carrier Frequency, Transmission Power, Bandwidth, Coding Rate (fraction between the number of raw bits over the number of encoded bits after Error Correction Code (ECC)), Spreading Factor, Implicit Header Mode (whether a header is included in the packet or not), Low Data Rate Optimization and Cyclic Redundancy Check.

1) Spreading Factor: The LoRa modulation is performed by representing each bit of payload information by multiple chips of information. The rate at which the spread information is sent is referred to as the symbol rate (R_S). The spreading factor represents the number of raw bits that can be encoded per symbol as well as the number of chips contained in each symbol (2^{SF}). As a consequence, increasing the spreading factor will increase the number of chips per symbol which results in smaller and even negative Signal-To-Noise Ratio (SNR) values at the receiver, increased sensitivity, link budget and range.

2) Time on Air: In order to evaluate the network performance regarding the delay times, it is important to first characterize the LoRa packet Time On Air (TOA). This value represents the time it takes to transmit a single LoRa packet. To calculate the TOA for this network, the *SX1276* modem datasheet [15] was consulted. The TOA depends on a number of radio parameters: the Spreading Factor (SF), the Bandwidth (BW), the use of Cyclic Redundancy Check (CRC), the Coding Rate (CR), the use of Implicit Header mode (IH) and the use of Low Data Rate Optimization (DE); as well as packet parameters like the preamble length

(N_{PREAMBLE}) and payload length (PL). In this way, the symbol rate and symbol time are defined as:

$$R_S = \frac{\text{BW}}{2^{\text{SP}}}\,, \tag{1a}$$

$$T_S = \frac{1}{R_S}\,. \tag{1b}$$

The preamble time can now be calculated as a function of the preamble length in symbols:

$$T_{\text{PREAMBLE}} = (N_{\text{PREAMBLE}} + 4.25) \times T_S\,. \tag{2}$$

To calculate the payload time, the number of symbols in the payload must first be calculated:

$$X = \frac{8\text{PL} - 4\text{SF} + 28 + 16\text{CRC} - 20\text{IH}}{4(\text{SF} - 2\text{DE})}\,, \tag{3a}$$

$$N_{\text{PAYLOAD}} = 8 + \max\left(\lceil X \rceil \times (\text{CR}+4), 0\right)\,, \tag{3b}$$

where the notation $\lceil\ \rceil$ is used as a round up operator that returns the minimum integer number that is larger than the argument. The payload time is therefore given by:

$$T_{\text{PAYLOAD}} = N_{\text{PAYLOAD}} \times T_S\,. \tag{4}$$

Finally, the total TOA can be calculated by:

$$T_{\text{PACKET}} = T_{\text{PREAMBLE}} + T_{\text{PAYLOAD}}\,. \tag{5}$$

In this case, the preamble size has the default value of 8 symbols and the payload length is of 18 bytes. Additionally, given the default settings for this network, the CRC parameter has a value of 1, the DE parameter is 0 as there is no low data rate optimization and the IH parameter is set to 1 to signal no use of an explicit header. The remaining parameters are dependent on the implementation and configuration of the network and must be decided according to the circumstances of each implementation.

C. LoRa based WSN

In order to be able to use the more affordable *SX1276* modem, a network protocol was developed with the main focus on the ability for the base station to communicate with sensor devices bidirectionally. There is also an interest in decreasing the payload size and its corresponding TOA, which in turn saves power by decreasing the time that the modem is transmitting. In order to reference the devices, the following nomenclature will be used: n_i represents a node with id i and g_i represents a gateway with id i.

The proposed protocol defines three device types: **end-nodes** (able to be battery operated, can be equipped with a number of sensors and/or actuators), **range-extenders** (able to be battery operated, extend the range of the gateway) and **gateways** (responsible for the communication with the end-nodes and bridging the network to a base-station). Additionally, it must meet the following specifications: **Device addressing** - so communication can be made between the base station and a single node; **Data encryption** - so that the sensitive data in the payload is protected; **Bidirectional communication** - so that both Upload Link (UL) and Download Link (DL) messages are supported; **Message delivery acknowledgement and retransmission** - given the use of a public frequency spectrum susceptible to interference; **Detection of Transmission Errors** - using a CRC of the data to detect corrupted packets.

D. Hardware Equipment

The hardware equipment needed to deploy the WSN can be characterized by two main components: the processing unit and the radio transceiver. The processing unit is a Micro-Controller Unit (MCU) that can be the *ESP32* or *Arduino Uno* modules. These modules were selected given their high affordability and wide availability. Additionally, both modules are hugely popular, making them well characterized and tested platforms. As for the radio transceiver, the *SX1276* chip by *Semtech* was utilized [15]. The *Arduino Uno* was utilized as the gateway having the LoRa modem connected using the *Dragino LoRa Shield*. Alternatively, the *TTGO ESP32 SX1276* was utilized as the platform for the nodes.

III. EXPERIMENTAL VALIDATION AND RESULTS REGARDING THE WIRELESS SENSOR NETWORK

In order to evaluate the performance and ensure the correct functioning of the WSN, a network was established with a gateway (g_1) and 3 nodes (n_1, n_2 and n_3). The following metrics were tested: Received Signal Strength Indicator (RSSI), SNR, packet loss and packet delay. The sequence of steps consists in sending status request messages to the nodes sequentially and repeatedly. The nodes will respond to the gateway request by sending a corresponding status message. This allows the gateway to measure the RSSI and SNR values on the received messages and it allows the delay and packet loss to be calculated based on the corresponding sent and received messages. This process was repeated for several network configurations including different node and gateway locations and multiple physical layer configurations: $\text{SF} \in \{7, 9, 11\}$, $\text{BW} \in \{125\text{ KHz}, 250\text{ KHz}\}$ and $\text{CR} \in \{4/5, 4/8\}$.

A. Rural Experiment

In this test, the aim is to evaluate the performance of the network in rural conditions as well as to find the maximum range where communication is still possible. A location was selected where interference is minimal and where the nodes can be in line of sight of the gateway or with only some bushes or trees in the way while keeping a large distance to the gateway. To this extent, nodes n_1, n_2 and n_3 were placed at 438 m, 612 m and 956 m from the gateway, respectively. Additionally, 50 status request messages were sent to each node for each physical layer configuration.

Regarding Round-Trip Delay (RTD), Table I shows a comparison between the expected theoretical value and the average of the obtained results. As expected, the RTD follows the theoretical value as it depends mostly on the physical layer configuration. Also there is a difference of approximately 100 ms in the measured RTD and the theoretical one due to the processing times on the MCUs.

TABLE I

COMPARISON BETWEEN THE THEORETICAL RTD AND THE OBTAINED AVERAGE RTD ACROSS MULTIPLE PHYSICAL LAYER CONFIGURATIONS FOR THE RURAL EXPERIMENT.

Physical Layer Configuration	Theoretical RTD	Average RTD
CR=4/5, BW=125 KHz, SF=7	92.68 ms	185.58 ms
CR=4/5, BW=125 KHz, SF=9	329.72 ms	457.45 ms
CR=4/5, BW=125 KHz, SF=11	1318.92 ms	1425.90 ms
CR=4/5, BW=250 KHz, SF=7	46.34 ms	133.50 ms
CR=4/8, BW=125 KHz, SF=7	123.40 ms	222.55 ms

In Fig. 2, it is shown that the tested physical layer configurations barely affect the strength of the received signal. This is expected as the RSSI value is determined only by the transmitted signal output power (the power at which the the LoRa modem transmits the modulated signal), the antenna gain of the transmitter and receiver and by the gain loss due to the medium. As all these parameters are constant on each test, the RSSI value is expected to remain constant as result. Due to these same reasons, the plot clearly shows a decrease in the RSSI value as the distance to the gateway increases. This happens due to the medium gain loss and is more noticeable when there is no line of sight between the nodes and the gateway.

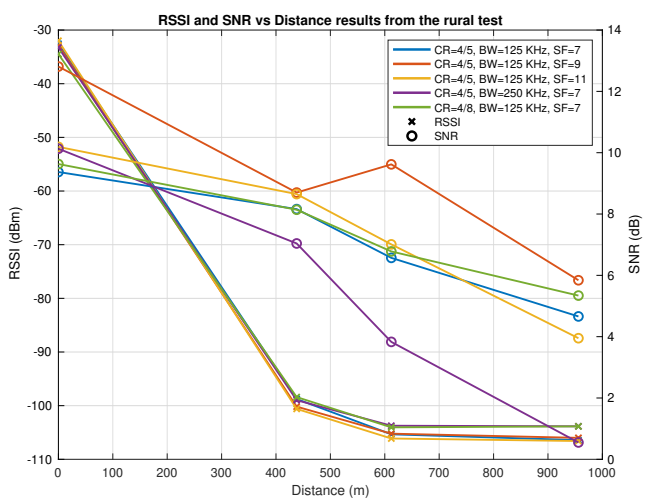

Fig. 2. Results obtained from the field test. RSSI and SNR over distance across multiple physical layer configurations.

When it comes to SNR values, the results shown in Fig. 2 describe how the SNR value varies over distance and across physical layer configurations. As expected, as the distance increases the amount of noise that the signal is subjected to also increases and the SNR decreases as a result. However, in this case the SNR value never goes below 0, showing that there is little to no noise on this rural environment, as there are no obstacles or other signals being transmitted causing interference. Regarding physical layer configurations, all of them follow the same trend of worse SNR values over distance.

TABLE II

NODE LOCATIONS FOR THE URBAN EXPERIMENT.

	A	B	C	D	E
Distance (m)	171	73	193	110	34
Has line of sight to the gateway	Yes	No	No	No	No

In summary, the rural experiment showed communication to be possible with a range close to 1km while still maintaining a relatively strong signal. This points to the possibility of even larger distances being covered by the WSN. Additionally, an overall message loss of 1.33% was obtained given that out of the 50 messages per 3 nodes and per 5 physical layer configurations (750 in total) only 10 messages were dropped. Also in this subject, it should be noticed that the implemented packet retransmission capability plays an important role in reducing the message loss as often the retransmissions were successful as denoted by a smaller packet loss rate, demonstrating an improved robustness of the network. When comparing the various tested physical layer configurations, interesting results were obtained: increasing the spreading factor actually leads to an increase in packet loss, which was not expected (the benefits of increasing the spreading factor may be more visible at larger communication distances); additionally, changing the coding rate and bandwidth had little effect on packet loss. In this way, the configuration which best suits a rural environment is: a bandwidth of $\mathrm{BW} = 125$ KHz, a coding rate of $\mathrm{CR} = 4/5$ and a spreading factor of $\mathrm{SF} = 7$.

B. Urban Experiment

In this test, the aim is to evaluate the performance of the network in urban conditions. Located at the Alameda campus of Instituto Superior Técnico (IST), this test was carried out in the center of the Lisbon city. This location was chosen given the accessibility but it is also representative of an urban area. For this test, the gateway was located in the 8th floor of the IST north tower close to the south-oriented window and the test node was positioned in 5 different locations, some of which do not have line of sight to the gateway according to Table II.

It should be noted that the location point **E** is on the 5th floor of the north tower while the remaining locations are at ground level. The location point **A** has direct line of sight to the gateway while the location points **B** and **C** have a slightly obstructed view of the gateway. The location points **D** and **E** are inside a different building and have no line of sight to the gateway. In this way, more information can be gathered regarding the behaviour of the network in different urban scenarios.

The tests run in this experiment differ from the rural experiment in one key point: for each location two different antennas were tested. In order to keep the same 50 message per test in each configuration and location, we only sent 25 messages to each node.

Regarding RTD, the results are as expected. For each physical layer configuration the delay stays approximately

constant. When comparing the RTD values for both antennas, it can be concluded that the delay times are independent as the RTD is the same.

In Fig. 3 the behaviour of the RSSI is shown against multiple communication distances. Furthermore, to widen the scope of this analysis, two scenarios were considered: an indoors scenario (where both the gateway and the node are inside a building) and an outdoors scenario (where only the gateway is inside a building). The RSSI values for the node with the small antenna are consistently lower than the ones for the node with the big antenna. Since the two nodes stay at the exact same place, the medium is the same for both of them and the difference in the RSSI values is most likely caused by different output powers. Given that the same LoRa modem transmission power is selected for both nodes, it means that the larger antenna has a higher gain. When it comes to node location, it is also clear that the indoor test runs yielded worse results in comparison with the outdoor setting. This is also expected as there is no line of sight to the gateway and there are several walls and other obstacles in the signal path. Finally, the same conclusions taken from the previous experiment also apply here: RSSI has a small dependence on the physical layer configuration and overall it is inversely proportional to the distance to the gateway.

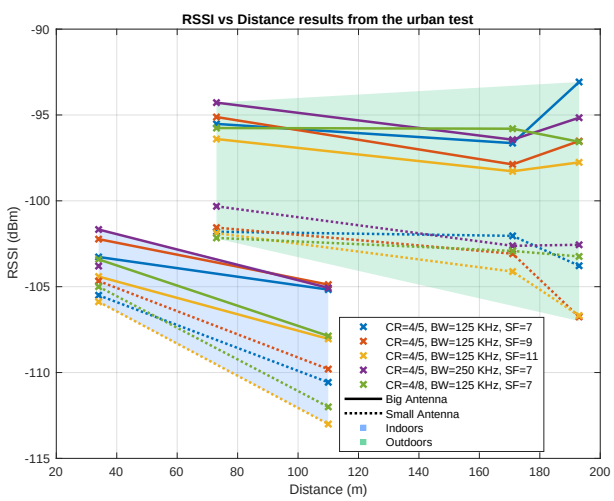

Fig. 3. Results obtained from the urban test. RSSI over distance and across multiple physical layer configurations.

As for the SNR, Fig. 4 shows its behaviour for different communication distances. Similarly to the RSSI, the SNR tends to be lower for the small antenna. This should be explained by the fact that with the small antenna there is a lower signal output power resulting in a higher noise level by comparison. Again, in the indoor test runs, the results are worse. This happens due to the additional noise and interference caused by all the obstacles to the signal propagation. One interesting observation is that on the test run in location **D**, the SNR values obtained were generally better in comparison to using location **E** (even though location **E** was closer to the gateway). This could be explained by the difference in the medium through which the signal must pass. In location **E**, the node was three floors below the gateway, resulting in concrete obstacles while **D** is inside a different building (the buildings had line of sight to each other), leading to less signal interference.

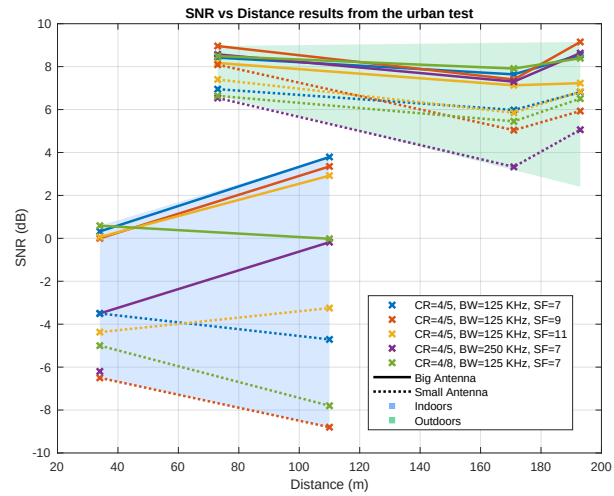

Fig. 4. Results obtained from the urban test. SNR over distance and across multiple physical layer configurations.

Regarding packet loss, a trend of higher values for the indoor nodes as well as for the small antenna was registered.

In summary, the urban experiment explored the capabilities of the developed LoRa based WSN in an urban environment, which can be quite challenging for a network using LoRa as its high efficiency feature requires using a very low signal transmission power. In addition, two different antennas were also tested. The results in this experiment showed how communication is possible from devices in different buildings and how well the network performs in better conditions, such as when the node is outside and with line of sight to the gateway. Similarly to the rural experiment, the default physical layer configuration appeared to show the best overall results. With this configuration a maximum packet loss of 40% for the big antenna and 81.25% for the small antenna was obtained for communication between devices in two different buildings with a communication distance of up to 110 m. For communication where only the gateway is inside a building and with a communication distance of up to 193 m, a maximum packet loss of 0% and 8% was obtained for the big and small antennas, respectively.

IV. WIRELESS SENSOR NETWORK INTEGRATION WITH AUTONOMOUS VEHICLES

A. *Surveillance System and Mission Flow*

To detect events requiring surveillance using the UAV, each node is equipped with a *HC-SR501* Passive Infrared (PIR) motion sensor, given its adequacy for battery operated devices and included automatic control module. Moreover, this sensor main applications include security products, which makes it suitable for this project. The *HC-SR501* [16] module consists of the *BISS0001* Micro Power PIR

Motion Detector Integrated Circuit (IC) (specifically developed to process the signal from PIR motion sensors) and the *LHI778* pyroelectric sensing element. This type of sensor works based on the principle that every body with temperature will emit infrared radiation in the form of heat. PIRs use two sensing elements to read the infrared levels in the environment. When a body enters the sensor's field of view, it first causes a positive differential between the two sensing elements due to the difference in temperature. Analogously, when the body leaves the sensing area, the reverse happens leading to a negative differential. In this way, motion is detected through these differentials in the pyroelectric sensing elements readings.

The sole task of each node is to generate an UL message whenever motion is detected and send it through the LoRa network to the base station. In a future development, the nodes can implement tracking algorithms using reachability analysis [17] to better determine the position of the intruders.

The final surveillance system is composed of the integration between the WSN and the UAV which is used as a means of autonomous inspection of the mission plane. Moreover, the UAV is equipped with the *PX4* autopilot, capable of autonomously flying to the areas where sensor nodes have been triggered as well as across the mission plane in a more passive surveillance task. Specifically, the system contains the WSN nodes equipped with motion sensors and the ROS package stack that reads the data and creates a mission as a sequence of waypoints to be inspected by the UAV. The architecture of this system is described in Fig. 5.

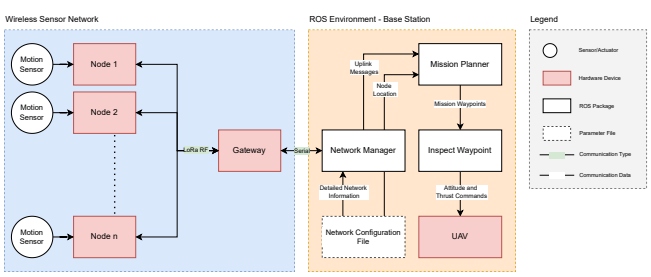

Fig. 5. Final system architecture diagram showcasing its different components and how they interact with each other.

V. EXPERIMENTAL VALIDATION AND RESULTS REGARDING THE WIRELESS SURVEILLANCE SYSTEM

In order to experimentally validate the proposed surveillance system, we conducted a real trial in the Institute for Systems and Robotics (ISR) flight arena at the IST *TagusPark* facilities using the *Intel Aero Ready to Fly* quadrotor [18]. The flight arena has an area of approximately 7 m by 4 m, which poses some difficulties to test a larger WSN. In this experiment, node n_1 was placed in the location $p_{n_1} = [-2, 0]$, node n_2 was placed in the location $p_{n_2} = [2, 0]$ and the UAV was placed at the origin (located at the center of the arena) as shown in Fig. 6.

The test procedure consisted in having a person passing as an intruder to follow a path that intersected the detecting

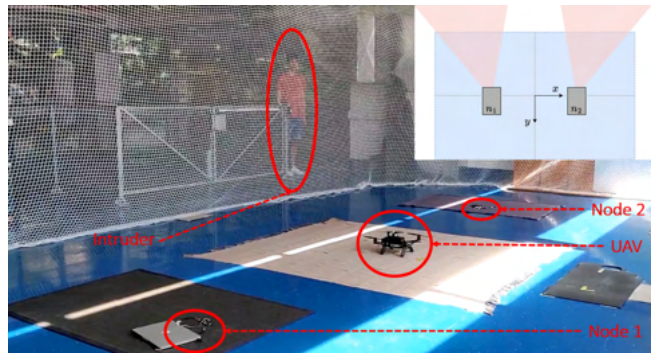

Fig. 6. Experimental setup at the ISR flying arena. The diagram on the top right shows the used coordinate frame as well as the sensors position and approximate sensing area.

zones of both motion sensors (footage from the trials can be seen here `youtu.be/q-0wVMqG7CQ` [19]). Additionally the network was initialized with a bandwidth of BW $= 125$ KHz, a coding rate of CR $= 4/5$ and a spreading factor of SF $= 7$.

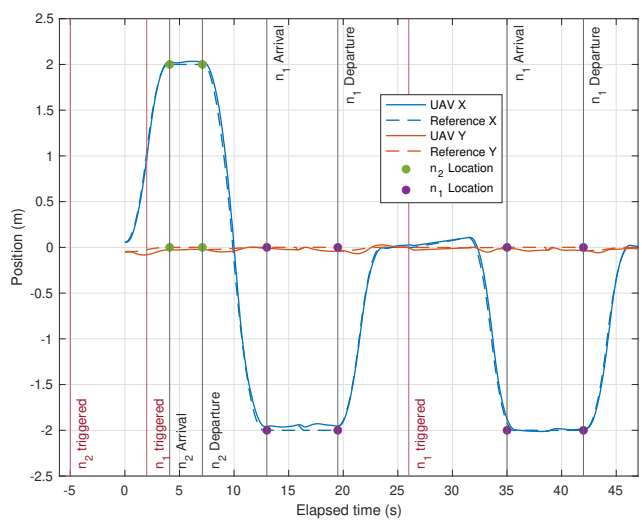

Fig. 7. Results obtained from the real trial with the motion sensors. Plot of the UAV position and reference over time with timestamps over the major events.

Fig. 7 shows the UAV and reference positions over time during the experiment in order to better convey the position error involved. As expected from the simulations, the UAV was able to fly to the locations of the nodes n_1 and n_2 when these were activated. Furthermore, Fig. 7 shows timestamps for all the major events, including arriving and leaving the location of a node and when a motion sensor trigger message is received. The results obtained showed great reliability as the system commanded the UAV to fly to the sensor location every time it was triggered. Moreover, by commanding the UAV to stop at the inspection point, the surveillance task can be carried out (i.e.: by using a camera pointed at the inspection zone). Finally, the UAV was able to follow its reference trajectory closely, with an overall average position

Root-Mean-Square-Error (RMSE) of 0.0381 m.

VI. CONCLUSIONS AND FUTURE WORK

A. Conclusions

The extensive testing of the proposed WSN is one of the main contributions of this paper, which can increase the interest of other researchers in the topic and provide a sense of how the communication network operates in a real scenario as opposed to the information provided by the manufacturers. In the rural context, communication was possible for distances of over 1 km with a RTD delay of down to around 133 ms., even when the physical layer configuration is not set up for maximum range.

Running a WSN in a rural context has the advantage of having direct line of sight for most of the devices. Whenever such a network is established in an urban environment, the LoRa modulation technology decreases in its performance. However, the data from the tests showcases promising results with successful communications even from inside different buildings at a distance of around 110 m. Moreover, it was shown how the RSSI and SNR decrease with distance and partial or complete obstructions.

Motion sensors were installed in the WSN nodes that connect to the ROS environment running the UAV package. The overall surveillance system was validated in experiments at ISR flying arena with good reference error and visit of all locations generating events in the WSN. Moreover, the proposed modular architecture comprised of sub-systems working over a communication network can be extended to use other ground vehicles, contact authorities, add additional sources of data, etc.

B. Future Work

The research developed in this document points towards interesting points of future work in order to improve the efficiency and reliability even further:

- Implementation of transmission time slots (assigned periods of time where each device can transmit) to avoid multiple nodes trying to transmit at the same time when using a single channel gateway (this is not a problem in the current sparse communication pattern in the network) and minimizing the node up-time thus reducing power consumption. This can resort to an implementation of the optimized algorithms in [20], [21] and its robust version in [22];
- Integrating the developed network with other types of vehicles such as Unmanned Ground Vehicles (UGVs), giving the system additional means of dynamic sensing;
- Adding more UAVs to the mission poses interesting research problems in terms of overall battery management in order to have continuous operation in case automatic charging stations are available;
- Considering potential attackers that can perform replay attacks and implementing reputation-based strategies such as [23], [24] can further increase the robustness of the proposed system.

REFERENCES

[1] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Computer networks*, vol. 52, no. 12, pp. 2292–2330, 2008.

[2] M. Dong, K. Ota, M. Lin, Z. Tang, S. Du, and H. Zhu, "Uav-assisted data gathering in wireless sensor networks," *The Journal of Supercomputing*, vol. 70, no. 3, pp. 1142–1155, 2014.

[3] R. Ribeiro, D. Silvestre, and C. Silvestre, "A rendezvous algorithm for multi-agent systems in disconnected network topologies," in *2020 28th Mediterranean Conference on Control and Automation (MED)*, 2020, pp. 592–597.

[4] R. Ribeiro, D. Silvestre, and C. Silvestre, "Decentralized control for multi-agent missions based on flocking rules," in *CONTROLO 2020*, J. A. Gonçalves, M. Braz-César, and J. P. Coelho, Eds. Cham: Springer International Publishing, 2021, pp. 445–454.

[5] Wildfire statistics. (accessed: 29.12.2021). [Online]. Available: https://crsreports.congress.gov/product/pdf/IF/IF10244

[6] Firepuma project. (accessed: 28.12.2021). [Online]. Available: https://welcome.isr.tecnico.ulisboa.pt/projects/forest-fire-prevention-through-uncertainty-minimization-in-surveillance/

[7] S. Kim, H. Lee, and S. Jeon, "An adaptive spreading factor selection scheme for a single channel lora modem," *Sensors*, vol. 20, no. 4, p. 1008, 2020.

[8] U. Raza, P. Kulkarni, and M. Sooriyabandara, "Low power wide area networks: An overview," *ieee communications surveys & tutorials*, vol. 19, no. 2, pp. 855–873, 2017.

[9] R. Ratasuk, N. Mangalvedhe, and A. Ghosh, "Overview of lte enhancements for cellular iot," in *2015 IEEE 26th annual international symposium on personal, indoor, and mobile radio communications (PIMRC)*. IEEE, 2015, pp. 2293–2297.

[10] S. Shin, A. G. Forte, A. S. Rawat, and H. Schulzrinne, "Reducing mac layer handoff latency in ieee 802.11 wireless lans," in *Proceedings of the second international workshop on Mobility management & wireless access protocols*, 2004, pp. 19–26.

[11] Benchmarking bluetooth mesh, thread, and zigbee network performance. (accessed: 09.11.2021). [Online]. Available: https://www.silabs.com/wireless/multiprotocol/mesh-performance

[12] M. Siekkinen, M. Hiienkari, J. K. Nurminen, and J. Nieminen, "How low energy is bluetooth low energy? comparative measurements with zigbee/802.15. 4," in *2012 IEEE wireless communications and networking conference workshops (WCNCW)*. IEEE, 2012, pp. 232–237.

[13] H. V. Sampaio, A. L. C. de Jesus, R. do Nascimento Boing, and C. B. Westphall, "Autonomic iot battery management with fog computing," in *International Conference on Green, Pervasive, and Cloud Computing*. Springer, 2019, pp. 89–103.

[14] R. S. Sinha, Y. Wei, and S.-H. Hwang, "A survey on lpwa technology: Lora and nb-iot," *Ict Express*, vol. 3, no. 1, pp. 14–21, 2017.

[15] Semtech sx1276 datasheet. (accessed: 30.12.2021). [Online]. Available: https://semtech.my.salesforce.com/sfc/p/\#E0000000JelG/a/\\2R0000001Rbr/6EfVZUorrpoKFfvaF_Fkpgp5kzjiNyiAbqcpqh9qSjE

[16] Hc-sr501 pir motion detector. (accessed: 25.07.2022). [Online]. Available: https://www.mpja.com/download/31227sc.pdf

[17] D. Silvestre, "Constrained convex generators: A tool suitable for set-based estimation with range and bearing measurements," *IEEE Control Systems Letters*, vol. 6, pp. 1610–1615, 2022.

[18] Intel aero ready to fly drone. (accessed: 23.11.2022). [Online]. Available: https://docs.px4.io/v1.9.0/en/complete_vehicles/intel_aero.html

[19] Collection of digital files concerning this project. (accessed: 23.11.2022). [Online]. Available: https://github.com/hardtekpt/Thesis

[20] D. Silvestre, J. Hespanha, and C. Silvestre, "Desynchronization for decentralized medium access control based on gauss-seidel iterations," in *2019 American Control Conference (ACC)*, 2019, pp. 4049–4054.

[21] D. Silvestre, J. Hespanha, and C. Silvestre, "Fast desynchronization algorithms for decentralized medium access control based on iterative linear equation solvers," *IEEE Transactions on Automatic Control*, vol. 67, no. 11, pp. 6219–6226, 2022.

[22] D. Silvestre, J. P. Hespanha, and C. Silvestre, "Resilient desynchronization for decentralized medium access control," *IEEE Control Systems Letters*, vol. 5, no. 3, pp. 803–808, 2021.

[23] D. Silvestre, "Reputation-based method to deal with bad sensor data," *IEEE Control Systems Letters*, vol. 6, pp. 43–48, 2022.

[24] G. Ramos, D. Silvestre, and C. Silvestre, "General resilient consensus algorithms," *International Journal of Control*, vol. 95, no. 6, pp. 1482–1496, 2022.