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Realistic Deployment of Hybrid Wireless Sensor Networks Based on ZigBee and LoRa for Search and Rescue Applications

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ABSTRACT Search and Rescue operations in emergency response to natural or human catastrophes have the main objective of locating and rescuing potential victims as fast as possible, thus quick response and accurate actions are mandatory. While standard communications may be affected, a Wireless Sensor Network can be deployed to support the rescue team. This kind of network allows data acquisition close to events and enables persistence over time, among other advantages. However, enhancements must be made to improve the adaptation to this kind of scenario. This work presents two Hybrid Wireless Sensor Networks, based on ZigBee and LoRa, developed to address some of the challenges that Search and Rescue operations pose to the use of Wireless Sensor Networks, and tested in realistic scenarios in cooperation with first responders. Likewise, several software developments that increase the performance of the networks are described. Finally, the conclusions presented, and the lessons learnt are supported by a high amount of data, gathered in realistic exercises in cooperation with civilian and military first responders.

INDEX TERMS Graphical user interfaces, mobile robots, search and rescue, emergency services, ZigBee, LoRa, Internet of Things.

I. INTRODUCTION

Currently, Wireless Sensor Networks (WSNs) are applied in a wide range of areas such as logistics [1], hazardous environments monitoring [2], emergency and rescue operations [3], [4], catastrophe monitoring [5] and management of urban traffic [6]–[9]. In the case of emergency response scenarios, WSNs enable data acquisition close to events and allow for persistence over time, which are strong needs in this kind of applications [10]. In addition, WSNs feature flexibility and scalability, while providing monitoring capabilities with a low deployment cost [11]. It is a well-known fact that, in these emergency response scenarios, regardless of the cause, quick response and accurate actions are mandatory [12]. However, the standard communications infrastructure may be affected too as the catastrophe occurs [13], thus making the task harder and putting the rescue team at a disadvantage unless it uses an emergency communication technology like a WSN [14]. Nevertheless, the effectiveness of a WSN is closely related to how the node deployment has been planned, i.e., the coverage and connectivity achieved when the sensory network is established [15], its reliability [16] and security [17]. Although nodes are usually easy to deploy, once the sensor network has been set up there is no alternative to adding new nodes or re-deploying the WSN if information needs to be gathered in different areas [18]. An option to deal with this shortcoming is the concept of mobile node. More specifically, combining static WSNs with mobile nodes has improved the performance of Search And Rescue (SAR) teams [19]–[22], due to their ability to expand the area where real-time data can be retrieved. Therefore, more data about the emergency zone and the state of the operation can be shared among the heterogeneous agents in SAR teams. Particularly, WSNs bring the interesting possibility of adding robots, team members or even carrying nodes dogs to the sensor network, allowing capabilities of the SAR team to be further extended [23]

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and turning a WSN into a Hybrid Wireless Sensor Network (H-WSN) where both static and mobile nodes are deployed.

On the one hand, dogs provide an essential assistance to find victims in zones where human rescue teams or robots are not able to explore easily [24], [25]. Moreover, canine units may also be useful to perform the task of obtaining maps of the area of interest [26], though harness-mounted cameras present some drawbacks, because of rapid movements of the dog [27]. In addition, canine units have already been proposed for the deployment of robots in emergency scenarios [28] and rescue dogs are often considered to be part of a biological SAR robot system [29], but integration of canine agents has attracted less research resources than robots, as they add constraints to the deployment [30]. As a matter of fact, the high mobility of rescue dogs usually makes it difficult to ensure coverage. Hence, despite the utility that dogs bring to SAR operations, a WSN including canine agents must take into account these problems and must consider the lessons acquired by the research community to deal with them. However, these drawbacks are outweighed by the benefits of having dogs in SAR operations [31].

On the other hand, robots are long recognized as helpful agents in SAR operations [32]–[35], even if their robustness and resilience need more focus from the research community [36], and several authors have studied robot integration in WSNs within this context [37]. Particularly, [38] makes a detailed review of the use of sensor and tracking methods, stating that an important challenge is to integrate dynamically networked sensors with multilevel information fusion to aid decision making. Finally, [39] discusses the integration of mobile robots, as well as the challenges in providing coordination and communications among the members of the rescue team. In contrast to dogs, mobile robots can cope with problems related to energy consumption by providing additional energy sources for the devices [40], and their movement can be accurately predicted and planned to keep coverage within the sensor network, in relation with the problems known as Coverage Path Planning [41] and Heuristic Path Planning [42], by introducing the WSN nodes as Points of Interest (PoIs). In this sense, coverage is a major concern in H-WSNs. To sum up, the different pros and cons of dogs and mobile robots make them complimentary assets, as there are strong synergies between them. The major drawback of both agents is coverage problems [43].

Therefore, one alternative to address the coverage issues of H-WSNs is to consider a hierarchical topology for networks using mobile wireless nodes. This allows the achievement of enhancements on the overall performance, reductions in energy consumption and in delays, and improvements in the reliability and coverage of the sensor network [44]. More specifically, the integration of a Mobile Sink (MS) element in the sensor network achieves longer lifetimes of the nodes, as multi-hop data collection is avoided [45], [46]. Another effective proposal is to deploy an Air-Ground Collaborative Wireless Network to support SAR teams, with an example operating in hostile alpine environments [47]. In this sense, Unmanned Aerial Vehicles for SAR missions are attracting a high amount of effort from the research community [48], [49], with new algorithms being developed frequently to improve the efficiency of this kind of robots, as e.g. the work described in [50]. Similarly, [51] describes the use of swarm robotics distributed techniques in a search task, presenting challenges related to communication failures. Some other approaches have proven to be interesting too, yet with open challenges. For example, the method presented by [52] uses a Multi Agent System based WSN that improves the performance, with the downside of establishing a communication that may not be secure, a feature that is critical in events such as terrorist attacks. As another example, [53] introduces the concept of a human centric WSN, as an infrastructure that supports the capture and delivery of shared information in the field, although the sensory network throughput may need mules to be increased in certain cases. [54] shows a work on mobile nodes acting as delay- and disruption-tolerant routers, enhancing the sensor network coverage. All in all, while WSNs have been suggested as solutions for natural disasters needs, their application in real scenarios poses many challenges such as data communication reliability, managements of different data types and lack of energy supply. In fact, the experimentation needed to learn lessons and to make the technology able to overcome these challenges is expensive, difficult, heterogeneous, and scarce. Although these challenges can be solved by adding a mobile node to the sensor network, new and different challenges arise and more field tests are required. Some of them have already been addressed by the researchers, but many remain unsolved. To this end, the research community should maintain its focus on the topic and keep carrying out experimental tests, sharing the valuable lessons acquired during them.

This article presents two H-WSN developed to address some of the challenges that SAR operations pose to the use of WSNs, like the integration of several types of agents (such as dogs or robots), the need for dynamic coverage of large and changing areas, the acquisition of data using different types of sensors and the integration and presentation of the information to the first responders. The performance of these H-WSN has been tested in realistic SAR scenarios. These scenarios are part of a series of yearly activities organized by the Chair of Safety, Emergencies and Disasters [55], known as the Conference on Safety, Emergencies and Disasters (CSED). Within this scope, in the first place, a H-WSN based on ZigBee technology has been designed and validated to assist a SAR team in the 12th CSED [56]. Then, a second H-WSN based on LoRa has been conceived and tested to play the same role in the same event one year later, i.e., the 13th CSED [57]. These two H-WSNs have been conceived to make the most of having both static and mobile nodes, which enabled to significantly expand the operational area of the sensor network, and to adapt to the dynamic evolution of SAR operations. The performance of both H-WSNs has been evaluated again after the experiments, i.e., offline, and also in real-time, while the data are synchronized with an external database (DB), which has been made available to the rest of the rescuers in the SAR operation. For this purpose, several developments have also been made, and are described in this work: two data acquisition methodologies and two GUIs (Graphical User Interface). A set of experiments has been carried out to test and compare both H-WSNs in realistic conditions in cooperation with first responders.

II. SENSOR NETWORK ARCHITECTURES FOR SEARCH AND RESCUE OPERATIONS

While each emergency scenario is unique [58]–[60], there are some general requirements that are to be met by a H-WSN designed for disaster response assistance [61]. With that in mind, the authors have conceived original H-WSNs designed to meet the said requirements

- Resilience and flexibility, encouraging modular design.
- Ability to carry out a wide range of measurements.
- Low energy consumption.
- Compliance with the standards to which the technologies employed are subject.
- Easy deployment within a short-time window.

In the first place, to comply with these SAR requirements, the authors developed a novel ZigBee-based H-WSN, since static ZigBee sensor-nodes (S-N) do not support long range due to range limitations and multi-hoping issues. There is little experimental research focused on field tests on SAR scenarios, even with similar emergent technologies [62]. Among them, LoRa [63] was then chosen to develop a new H-WSN to contribute to the community literature with experimental results for complex and realistic SAR scenarios. This way, two novel H-WSN based on ZigBee and LoRa have been compared to find synergies in a combined deployment. Finally, it must be noticed that the proposed H-WSNs are the result of an iterative process of tests and improvements, taking into account the outcomes of a real use-case where the possibility of failure is high, given that the data capture and processing is unique and must respond to SAR operations.

The details of the hardware employed, and the final features of the networks are detailed in this section.

A. ZIGBEE H-WSN DESIGN AND IMPLEMENTATION

The first H-WSN idea is based on ZigBee (2.4 GHz) [64], a short-range, low-power, wireless Personal Area Network (PAN) standard that supports mesh networking and offers high security and robustness [65]–[68]. Each S-N can transmit and receive data [69]–[71], specifically small information packets with a data rate of up to 250 Kbits/sec, within a range of over 700 meters depending on visibility conditions [72], [73]. These capabilities make ZigBee a promising candidate to implement a H-WSN that fulfills the requirements of a SAR application. In addition, it allows for a simple and fast sensor network setup for first response information [74], [75].

Regarding its implementation, the proposed ZigBee H-WSN is made of Libelium [76] hardware components. The coordinator node is based on a multi-protocol router called Meshlium 3.5 (see Figure 1), which can work with ZigBee, WiFi, Bluetooth and 3G/GPRS protocols. This device has the capability to store the information in its internal memory, but it can also send it to an external DB. In addition, all the nodes, including the router, have a GPS module (Jupiter N3 module from Telit) that reports their position. All S-Ns are built upon the same basic hardware module, the Waspmote v1.2, with the addition of a communications module, the XBee Pro S2 from Digi. All S-Ns are encapsulated in IP 67 boxes, allowing for outdoors deployment under any weather conditions, and they have an internal memory of 2 GB. If any S-N falls out of range to transmit via ZigBee, it can save the data in its internal memory and wait to be inside an effective range of communications. The S-Ns used belong to one of the following three types, each one having different sensors

- Gas S-N: MICS-2610 O3 from E2V, SK-25 O2, TGS4161 CO2, TGS2442 CO, TGS2444 NH3, and TGS2600 VOC from Figaro. Additionally, it features a J808H5V5 humidity sensor from Jin Zon Enterprise Co. Ltd., an MPX4115A atmospheric pressure sensor from Motorola and a MCP9700/9701 temperature sensor from Microchip.
- Bluetooth S-N: BLUEGIGA WT12 module integrated with the Waspmote v1.2. It detects and identifies Bluetooth devices within one hundred meters.
- Ultrasound S-N: XL-MaxSonar-WR1 from Maxbotix integrated with the basic hardware of the S-Ns. It detects the number of objects or people that trespass its detection radius.

The proposed ZigBee H-WSN consists of a static coordinator node, a mobile coordinator node, a mobile S-N (carried by a SAR dog) and eight static S-Ns. Figures 1 and 2 show the modularity and connectivity of this H-WSN, where each coordinator node creates its own PAN within the whole H-WSN, conceived as a star topology, being each coordinator node the center of its own star or PAN. The S-Ns capture information from the environment around them and transmit these data to the coordinator nodes via ZigBee in case there is a good Line of Sight (LoS), with the traffic being two-way. This topology can be reconfigured, as the coordinator node enables the addition or removal of nodes, thus providing modularity. Particularly, the PAN created by the static coordinator node has been named PAN-A, and it covers an S-N onboard a mobile agent (SAR dog) as well as eight static S-Ns.

In contrast, the PAN created by the mobile coordinator node has been labelled as PAN-B and is composed of a single Bluetooth S-N and a coordinator node onboard a mobile agent, working in a similar manner as the PAN-A. The complete ZigBee H-WSN architecture, made of PAN-A and PAN-B (shown in Figure 2) is connected to the cloud via 3G/GPRS where the data can be made available remotely in a private external DB. The gathered information is fed into a LabVIEW-based information system.

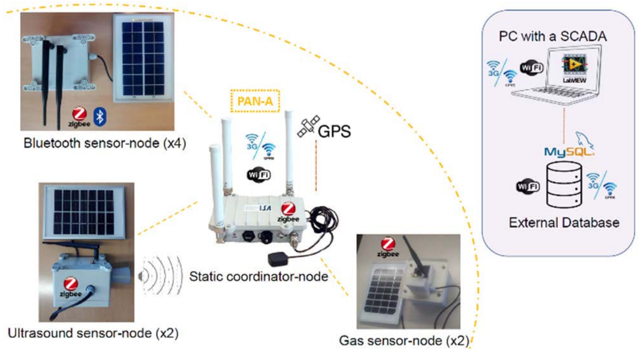

FIGURE 1. System architecture of a ZigBee pan.

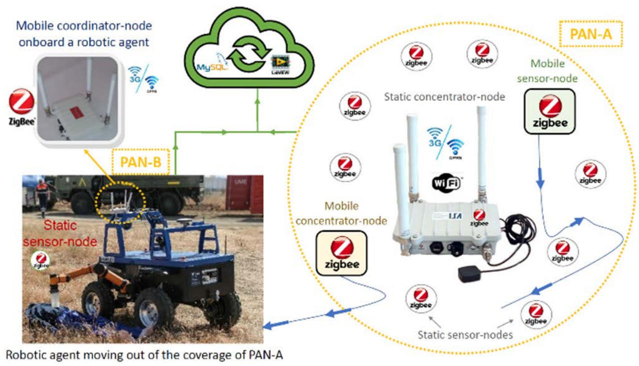

FIGURE 2. System architecture of the zigbee H-WSN with one static coordinator node and a mobile one. Ideal LoS is assumed regarding each PAN coverage area.

The drawback of a static PAN can be compensated by a mobile PAN once the static S-Ns are deployed, detecting a new PoI from where a hybrid PAN (as a whole) could gather more information. Thus, without the mobile coordinator node, the static S-N of PAN-B could not monitor a new PoI. Then, since the range is a handicap, redeployment would be required.

Although S-Ns can be relatively easy to add or reconfigure, their physical relocation after the initial deployment may be unfeasible. Moreover, some use cases of emergency response also require information on a wide area in tasks like exploration or victim search [23], requiring a large number of static nodes. Therefore, the area of operation may change dynamically, and a static sensor network may not adapt to these changes or may not have enough nodes to cover a large area. On the contrary, a sensor network that consists only of mobile nodes may need too many mobile agents, i.e., robots, vehicles, etc., to carry onboard the ZigBee nodes. Those needs and synergies have driven the development of the ZigBee H-WSN, with both static and mobile nodes, meeting the requirements specified for a sensor network to operate within a SAR context.

On top of the ZigBee H-WSN design, a series of software developments were needed to deploy it. All the S-Ns have been programmed on C language using their open-source code framework, and the coordinator nodes have been programmed using their internal web-server services, running under Linux operating system. The use of both open-source platforms allows the expansion and scale of the proposed H-WSN. As a result of these developments, the S-Ns gather data from their environment and send them via ZigBee to the coordinator node of the PAN to which they are linked. Then the coordinator node stores the received data into its internal memory as tables (local DB). After that, the data travel from the coordinator nodes to an external DB through WiFi or 3G, hence they act as intermediaries between the field and the technical users. A Supervisory Control and Data Acquisition (SCADA) system has been developed to present the information received by the ZigBee H-WSN, which must be available to the SAR team in real time. This data is managed using a MySQL DB, which is continually communicating with a LabVIEW Virtual Instrument to run the SCADA, making queries to the DB in the background, so the end-user does not have to do them directly by typing SQL commands. Thus, the SCADA displays real-time information of a given area of interest to the SAR team: graphics, overlayed layers on the map of the area of operations, or the status of the different deployed S-Ns.

B. LORA H-WSN DESIGN AND IMPLEMENTATION

Another technology used to implement a H-WSN that meets the SAR requirements is LoRa [77], a Low Power Wide Area Network technology with the capability needed to transmit data packets of small size on a regular basis [78] in two-way, half-duplex manner. More specifically, LoRa corresponds to the physical layer while LoRaWAN refers to the link layer of the Open System Interconnection model. LoRa technology has been chosen as it has features that were tailored specifically to suit Internet of Things applications [79]–[81]. In that line, the range of effectiveness and the energy managements has the potential to overperform the other technology used (ZigBee). However, as LoRa is a newer technology, there are not the the same amount of field experiments as with ZigBee, especially in the area of robotics and SAR tasks. Finally, as it happens with the ZigBee H-WSN, the H-WSN designed based on LoRa is easily deployed.

The main element of a LoRa H-WSN is the S-N (shown in the left side of Figure 3), composed of two elements: a microprocessor that receives and processes the data captured by the sensor, and a transmission antenna (868 MHz, 4.5 dBi) located on a radiofrequency module (Semtech SX1272). S-Ns are implemented by the Waspmote Plug and Sense! from Libelium. The electronic devices are encapsulated into an IP65 box, which ensures protection from dust and, to some extent, water. Four types of S-Ns are included in our H-WSN

- Ambient Control: measures the most relevant environmental magnitudes, such as temperature, pressure, and humidity.
- Smart Environment PRO: capable of measuring gases present in the air, such as CO. It can also measure temperature, pressure, humidity, and luminance.

- Smart Agriculture PRO: it adds capability to measure solar radiation, rain and wind speed and direction.
- Radiation Control: it features a Geiger sensor, capable of measuring radiation, but also works as a GPS node.

All these S-Ns can serve as GPS modules if they are configured to fit a GPS antenna. Therefore, some S-Ns can be configured to transmit LoRa packets with their GPS position, either together with other data or not, which is especially useful for tracking. Furthermore, the S-Ns have several factors that define the H-WSN behavior, such as

- The class (A, B or C) defines how frequently an S-N can receive data from a server through the concentrator-node (C-N). Regardless of the class, communication is always two-way half-duplex, and devices with different energy class can coexist.
- The S-Ns must be adjusted to the legal requirements of the communication band (868 MHz in Europe).
- The Spread Factor (SF) gives flexibility to the user, who can sacrifice raw communication potential and battery life to gain robustness in the data traffic.
- There are two activation modes of the S-Ns: Over The Air Activation (OTAA) and Activation By Personalization (ABP). For the experiments developed with the proposed H-WSN, ABP has been selected, as it enables multicasting, i.e., a specific data packet may be received by multiple C-Ns, regardless of whether they operate a cloud server or not [9].
- The LoS to the C-Ns. The waves propagate with the information acquired by the S-Ns through the free space (air as a means of transport), and therefore the presence of obstacles or moving bodies may lead to loss of information, which has been assessed with real experiments.

All these S-Ns have been grouped into clusters, called sensory groups (SG), in order to transmit different measurements and packet lengths from the same location, thus being able to evaluate the behaviors of the signals, depending on the configured SF for each S-N.

The C-N is the other important element of the LoRa H-WSN. For experimentation, the model MTCDTIP-H5-220L from MultiTech (shown in Figure 3) has been selected. It consists of a data hub node (a LoRa radio transceiver), and a Linux-based host that has internal memory and allows connection to the Internet via SIM card or Ethernet but does not support WiFi.

These hardware components are encapsulated into an IP67 box, able to withstand outdoor conditions. This C-N receives the data captured by S-Ns and saves them in real-time in its internal memory, what enables saving data even if an Internet connection is not available, thus allowing for offline operation. It also hosts its own MQTT (Message Queuing Telemetry Transport) broker, from which topics of interest are published.

The architecture of the proposed LoRa H-WSN consists of several SGs (both static and mobile ones), made of different elements (S-Ns), and C-Ns that allow multicasting.

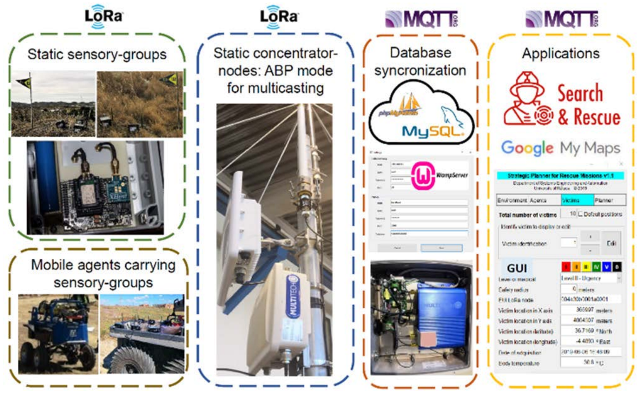

FIGURE 3. Elements of the LoRa H-WSN: S-Ns grouped in static and mobile SGs, C-Ns and end-users' applications.

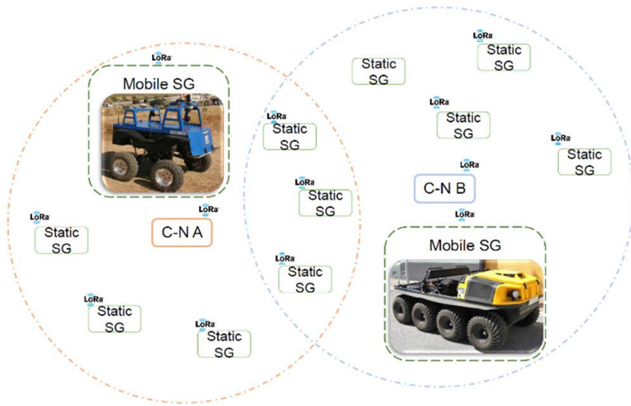

FIGURE 4. Scheme of the proposed LoRa H-WSN.

Figure 4 depicts a generic deployment in which ideal LoS has been assumed.

It is important to remark that thanks to the integration of mobile SGs, different LoS occurs in each data transmission from each SG to the C-Ns, enabling to gather extensive data about the performance of the LoRa technology in a wide range of locations, without having to re-deploy. As the S-Ns have been arranged in SGs, it is enough for one member of the group to send the GPS position to know the location of the rest, as all S-Ns are unequivocally identified by tags. Thus, in case of interference problems or an unexpected displacement of the SG traceability is possible. A basic and short explanation of the process is that S-Ns send data packets via LoRa to the C-Ns, with multicasting allowed. These data packets are received by the C-Ns that are sensitive to get a particular transmission within their respective coverage areas. Finally, the information is stored in the internal memory of the C-Ns in real-time and accessible through the Internet.

For that, a specifically developed software application called LorApp, presented in [9], serves as a link between MQTT brokers running inside each C-N and an external MySQL DB hosted on a web server, as it can be seen in Figure 3. This way, the LoRa packets coming from each S-N of the same SG can be joined and dumped in real-time to the

MySQL DB. Therefore, both C-Ns must have access to the intranet, either by Ethernet or a mobile network (4G, LTE, etc.). For the experiments, both C-Ns have been connected to a switch via Ethernet cable, which gives them access to the same Local Area Network (LAN). One of the C-Ns is located on a turret in the experimentation field, while the other one is located on the roof of a building close to the catastrophe area. Thus, both C-Ns can be accessed through SSH protocol, port 22, by a PC located in a control center within the LAN. This way, thanks to LorApp, end-users can see the data gathered by each SG, available in the control center, as a whole (instead of viewing each S-N data). This information is ordered in tables of a MySQL DB to easily dump the data to external applications (see Figure 3). For instance, by means of a GUI developed by our research lab or via Google MyApps, where each SG could be overlayed on top of the area of operations. To this end, the MySQL DB may be exported to CSV format.

III. SEARCH AND RESCUE EXERCISES

Every year, the Chair of Safety, Emergencies and Disasters from the University of Malaga organizes the Conference on Safety, Emergencies and Disasters (CSED). This event includes a series of activities that gathers experts from different fields to discuss and test new emergency response techniques and technologies, such as triage protocols, communication equipment, or rescue procedures in emergency and disaster scenarios. While the main hazard usually changes each year (earthquake, terrorist attack, wildfire, etc.), the purpose of these activities remains the same. To this end, the University of Malaga has arranged an experimentation area of 90,000 square meters that consider outdoor scenarios in natural and urban environments [82]. It consists of a testing ground in unstructured environments, presenting terrain with different access difficulties. It presents a very heterogeneous orography, including a stream bed, debris, and a cut-and-cover tunnel of about 100 meters long, to create GPS-denied conditions. Within this experimental zone (see Figure 5), an area near the SAR intervention is reserved to install the Command, Communication and Control Area (CCCA). There, the high-level decisions are taken by the SAR team leaders and some services may be provided to the SAR team and the rescued victims.

FIGURE 5. Area of experimentation. The groups of tents compose the CCCA. Specifically, the red tent serves as the FCC.

In the case of the experiments presented in this work, the CCCA has consisted of a fenced area with some tents. One of these tents has served as the Forward Control Center (FCC) where our research group has deployed the required material to support the H-WSNs, i.e., computers, power supply equipment, chairs, desks, etc.

On top of that, the Robotics and Mechatronics Lab from the Department of Systems Engineering and Automation (ISA, for its Spanish acronym) of the University of Malaga participates every year in these dynamic SAR exercises, together with other civil and military entities, such as the Military Emergency Unit of the Spanish Army or the Red Cross.

These exercises provide an opportunity to experiment with new technologies for emergency intervention, such as SAR robots. Thus, they seek to deliver an adequate response to the different types of emergencies and disasters, whether they are caused by natural elements or derive from human action, either accidental or intentional. In that context, the goal of our Lab is to assist the SAR teams, particularly in the planning and execution of exploration and rescue. Among the robots, the most relevant to the experiments carried out in this work is Rambler [83], as it participates both in the ZigBee (see Figure 8) and the LoRa H-WSNs (see Figure 16). Rambler is a 4-wheeled brushless-motors skid-steering mobile robot with active suspension, designed by the Robotics and Mechatronics Lab. Each of the motors is controlled by an embedded board which integrates a microcontroller and an independent H-bridge power stage (see Table 1). Rambler follows a path planned and shown in a GUI developed by our research group [84], [85], which has been integrated with original software developments made for the H-WSNs experiments.

TABLE 1. Mobile ground robot rambler key characteristics.

Feature	Unit
Dimensions	1.6x1.2x0.66 m
Vehicle weight	370 kg
Payload	>320 kg
Wheel radius	0.5 m, pneumatic
Suspension	Active / Semiactive pneumatic.
Distance between left and right axis	1.05 m
Distance between front and rear	0.95 to 1 m
Maximum linear speed	80 km/h
Battery (LiFePO4)	44.8 to 59.2 V, 4x40 Ah 16S4P

The second most relevant vehicle is an 8×8 extreme terrain manned vehicle (see Figure 5) manufactured by Argo, the Argo XTI [86], with custom modifications, such as a thermal imaging camera and a LiDAR, to meet the needs of our research group. This platform has been used in the implementation of the LoRa H-WSN, carrying S-Ns and therefore acting as a mobile SG.

IV. EXPERIMENTS

A. ZIGBEE H-WSN IMPLEMENTED IN THE 12th CSED

At the 12th CSED, held in 2018, a series of exercises were carried out to test different SAR technologies and strategies, with the participation of multiple entities including civilian and military assets. A realistic SAR experiment was set up, and the performance of the deployed ZigBee H-WSN by the rescue staff was evaluated. A dummy, acting as a victim, was hidden out-of-sight on the floor under debris in a vegetation area, recreating the event of an earthquake and its consequences. The summarized elements that compose this ZigBee H-WSN are:

- 1 static coordinator node, creator of the PAN-A.
- 1 mobile robotic agent (Rambler) that carries a second coordinator node, creating the PAN-B. This way, this ground robot acts as an MS, capable of storing information in its local DB from S-Ns isolated or far from PAN-A.
- 1 dog, trained to aid in victim localization in SAR scenarios, also acting as a mobile agent that carries an S-N, capable of measuring gases and environmental values, as well as transmitting the dog's geolocation.
- 8 static S-Ns in the PAN-A and another one in the PAN-B, these being the end devices of their respective networks.

1) DEPLOYMENT AND METHODOLOGY

The creator of the PAN-A, located at the FCC, at a height of two meters above the ground, has a good LoS of the area of experimentation, but the ZigBee radio link has a limited range. To address this limitation, the Rambler robot carries the coordinator node of the PAN-B (see Figure 6), which has been configured to detect S-Ns lost or without LoS from the FCC. Therefore, PAN-B is a mobile sensor network, since the mobile coordinator node, which acts as the creator of its coverage area, moves along with the robot. The initial position of Rambler is away from a PoI (indicated with a purple marker in Figure 7 and 8), so the planned trajectory starts from a point where the robot is unable to receive packets from any S-N registered in PAN-B. A Bluetooth S-N was set up for PAN-B in that PoI (far away from the PAN-A coverage area), acting as a potential victim detector by discovering wearable Bluetooth devices.

Since the terrain is rough and uneven (with several hillocks) the LoS between the robot and the lost Bluetooth S-N is often obscured, causing various communication outages. That is the reason why in Figure 7 the coverage from the mobile coordinator node (Rambler) has been depicted with a smaller radius than the one from the static coordinator node (FCC). This combines with a hostile telecommunications environment, due to the presence of a multitude of overlapping signals in the frequency spectrum, especially in the ZigBee band (2.4 GHz), including Bluetooth and WiFi signals, apart from the military radios.

Consequently, regarding the possible communication outages, a methodology based on the software developments made for the ZigBee H-WSN was put in place to avoid loss of information. Specifically, when data from a lost end-device are ready but Rambler does not provide coverage to it, these data are stored in the end-device own SD card. As the robot approaches this out-of-coverage node, it starts to gather all the information saved into the SD card, as well as the new data collected from that moment. Some preliminary tests that had been performed with ZigBee S-Ns configured with the same PAN ID as the mobile PAN (PAN-B ID), led the authors to choose a location to deploy S-Ns out of coverage far away from the PAN-A coverage (see Figure 7).

As the exact position of the lost end-device is known beforehand, and it is possible to track the position of Rambler and hence the position of the mobile coordinator node, the distance at which Rambler starts to give coverage to this lost S-N is known (shown in Figure 6). This way, the Bluetooth S-N can send to the mobile coordinator node the acquired information (Received Signal Strength Indicator -RSSI-, type, and MAC of the device) via ZigBee, who then makes this information available at the FCC.

Thus, as a result, the mobile coordinator node makes it possible to extend the ZigBee coverage provided by the static coordinator node located at the FCC, making the system more reliable due to the synergies between static and mobile elements of the proposed H-WSN. Although both coordinator nodes create their own PAN, with their own local DB, these are synchronized thanks to the software developments made, using WiFi/3G connectivity with an external DB, which permits monitoring all the synchronized information at the FCC by means of the developed SCADA. Thereby, the staff at the FCC can monitor, in real time, the state of the deployed S-Ns and manage the rescue of potential victims, providing technical support to the SAR team members at a quick glance.

After the detection of the victim, which was close to this Bluetooth S-N, this element is used to take information of the identity of the rescuers present in the area (as the ones behind Rambler in Figure 6).

Finally, the S-Ns of the PAN-A were distributed around the experimental area, relatively close to FCC to guarantee coverage. Specifically, all the S-Ns were accurately geolocated at the time of deployment (see Figure 7, 8 and 9).

FIGURE 6. Rambler carrying the mobile C-N (PAN-B coordinator) assisting the dummy-victim. At the same time, it is providing coverage to the lost Bluetooth S-N. Behind the robot, human agents attend to buried victims.

In addition to these static S-Ns, the rescue dog mentioned above was carrying an S-N (a gas module plus a GPS module) adhered to PAN-A. Both modules are installed on a harness especially developed for the application and it does not affect the dog's behavior. It includes two compartments, one at each side for each module, whose weight has been balanced to be comfortable for the SAR dog. Then, the dog is sent by its trainer to explore the area, in a series of short routes, defined according to a regular exploration pattern, starting from FCC. This mobile S-N is capable of measuring and transmitting (via ZigBee) the position of the dog and the following measurements: temperature (°C), relative humidity (%), absolute pressure (kPa), and the concentration (p.p.m.) of some gases (oxygen, carbon monoxide, nitrates, etc.).

2) RESULTS

6862 ZigBee packets have been registered into the local DB of the static ZigBee coordinator node located in the turret next to the FCC (see Figure 7 and Figure 8). Packets have been captured over a period of 4 hours, 39 minutes and 5 seconds, with the distribution showed in Table 2.

FIGURE 7. PANs of the zigbee H-WSN. The mobile coordinator node embarked on Rambler generates a dynamic coverage radious.

In addition, 113 ZigBee packets have been captured by Rambler over a period of 25 minutes, and always from the same static position (that of a lost Bluetooth S-N detector), receiving the MAC of the lost end-device.

However, during the Rambler's path towards the lost S-N, 41 of the 113 data frames were not received at the time of transmission but were recovered when the robot regained coverage of the lost S-N and was able to transmit the data stored in its internal memory (SD card). Thus, it was possible

TABLE 2. ZigBee packets received by the static coordinator node (PAN-A).

Mobile S-N (carried by the SAR dog)	Static S-Ns of PAN-A			
GPS and other high rate data	Gases		Ultrasound	Bluetooth
86 (the SAR dog exercise lasted 4 minutes and 34 seconds)	S-N1: 149	S-N2: 89	S-N1: 200	S-N1: 851
			S-N2: 1153	S-N2: 1422
				S-N3: 877
				S-N4: 2035

to recover the ZigBee packets lost because of the unevenness of the terrain between the robot and its destination varied as it moved, with the LoS varying as well. Moreover, Rambler has operated with differential corrections for its GPS position, thanks to the installation of a Real Time Kinetic antenna placed high up in the experimental area. This allows to measure the distances at which the robot is in relation to all the static S-Ns, and to estimate the distances at which each of the packets are captured. Thus, it is possible to establish dynamic coverage zones within the unknown scenario as the robot detects ZigBee packets.

To outline the main points, the next figures show the results obtained with the deployed ZigBee H-WSN at the realistic exercises. In addition to the static S-Ns, Figure 9 shows the movement of the SAR dog as it is tracked by GPS, carrying an S-N. As the search for the victims begins from the FCC, the mobile S-N transmits the information that it gathers. However, as the SAR dog moves deeper into the tunnel zone, the difference in level becomes greater, and the loss of communication with the S-N it is carrying occurs.

To evaluate more clearly the importance of the LoS between the transmitting and receiving antennas, a 3D map of the experimental area has been obtained, and thus being able to know the unevenness of the terrain (see Figure 10). For this purpose, an orthophoto taken from a drone was used, achieving a resolution of 0.5 cm. In this way, it is feasible to obtain the terrain profiles between the nodes.

Figure 11 demonstrates that not only the range but also the LoS is important. According to the Fresnel zone (ellipsoid-shaped volume of revolution covering the distance between the antennas) theory and formulation [87], [88], we can affirm that radiocommunication is affected not only by obstacles, but especially by greater unevenness in the terrain. For the representation of the direct LoS, it has been considered that the receiving antenna at the FCC is 2 meters above the ground on which it is located. Green LoS indicates good connectivity while red LoS means no coverage for the S-N.

As soon as the SAR dog moves away from the coverage area of PAN-A, ZigBee packets from its S-N are no longer received. It is observed that the last ZigBee packet detected for the SAR dog from the FCC was transmitted from

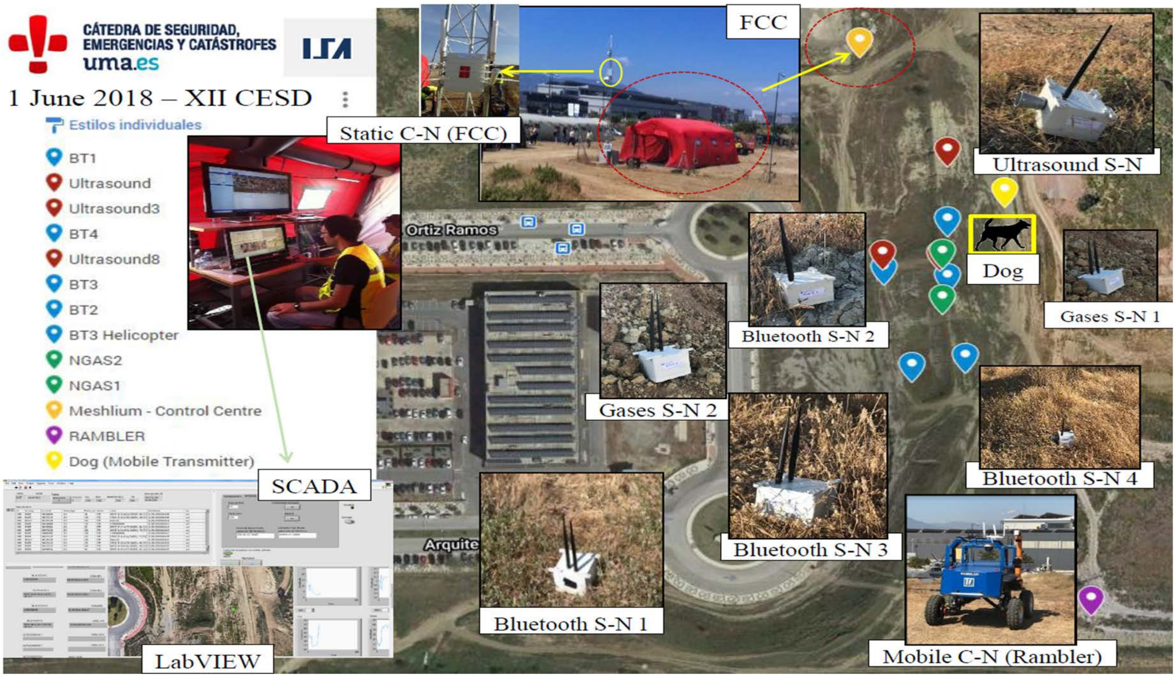

FIGURE 8. Mosaic that summarizes the experiments carried out at the XII CSED (2018).

114.8 meters (see Figure 12). It was impossible to establish connectivity from positions that were closer but more hidden in the terrain (see Figure 11). For this reason, when the SAR dog entered the area of the stream, looking for victims in front of the tunnel entrance, it was not possible to obtain information from the canine agent.

Furthermore, Figure 13 shows the environmental information transmitted from the static gases S-Ns around the experimental area. Each point in the graphs represents a ZigBee packet. Figure 14 shows the ground profiles and LoS between antennas, signifying the green LoS that the connection and transmission were successful. In addition, LoS from FCC to the lost S-N is bad, thus the use of Rambler as the coordinator of a mobile PAN is justified.

B. LORA H-WSN IMPLEMENTED AT THE 13th CSED

At the 13$^{\text{th}}$ CSED, held in 2019, the context changed slightly with respect to the previous year. The exercise of this edition was a terrorist attack on a non-governmental organization facility. A medical unit of the Spanish Army had to rescue various civilians while the rest of the emergency teams provided medical assistance to the victims, supported by the different robotic and manned vehicle agents. Thus, the proposed LoRa H-WSN has been deployed in a realistic SAR scenario, providing real-time information to the SAR members to assess the current situation of the operation. The deployed LoRa H-WSN consists of

- 2 C-Ns.
- 14 static S-Ns, grouped into 7 SGs.
- 2 SGs onboard two mobile agents (Rambler and Argo XTI).

1) DEPLOYMENT AND METHODOLOGY

The first stage has been the deployment of two static C-Ns with the objective of contrasting the behavior of the RSSI values of the packets depending on the distance between the SGs and them. These C-Ns have been set up with ABP mode to enable multicasting operation without the need of Internet, as in [9]. One of them has been placed next to the FCC, mounted on a 14-metre-high turret (see the upper part of Figure 16) that also provides WiFi coverage to human and robotic agents. The second C-N has been installed on the roof of one of the buildings of the School of Engineering, located about 200 meters from the area of interest, having a good LoS to the terrain. The positions of both static C-Ns as well as the SG embarked on the robot Rambler are marked in Figure 15.

Furthermore, each C-N has its own internal memory where the packets are stored during the experiments, and they are linked to an external DB by means of an application developed for this purpose (LorApp). The software developments allow end-users of the FCC to see the information gathered in a visual way in the GUI developed by our Lab, shown in Figure 16, accessible through the LAN or the Internet.

Additionally, several static S-Ns have been deployed, consisting of seven SGs (each one marked with a flag and a label, to make their location visible to SAR teams, and capable of providing its GPS position) at a greater distance from the FCC, compared to the static S-Ns of the previous H-WSN based on ZigBee. Also, at this CSED, two mobile S-Ns have been used to test different configurations of the SF, and thus to be able to check the effect of interferences from the other signals (civil and military) present, as well as the unevenness of the terrain (characterized by various embankments

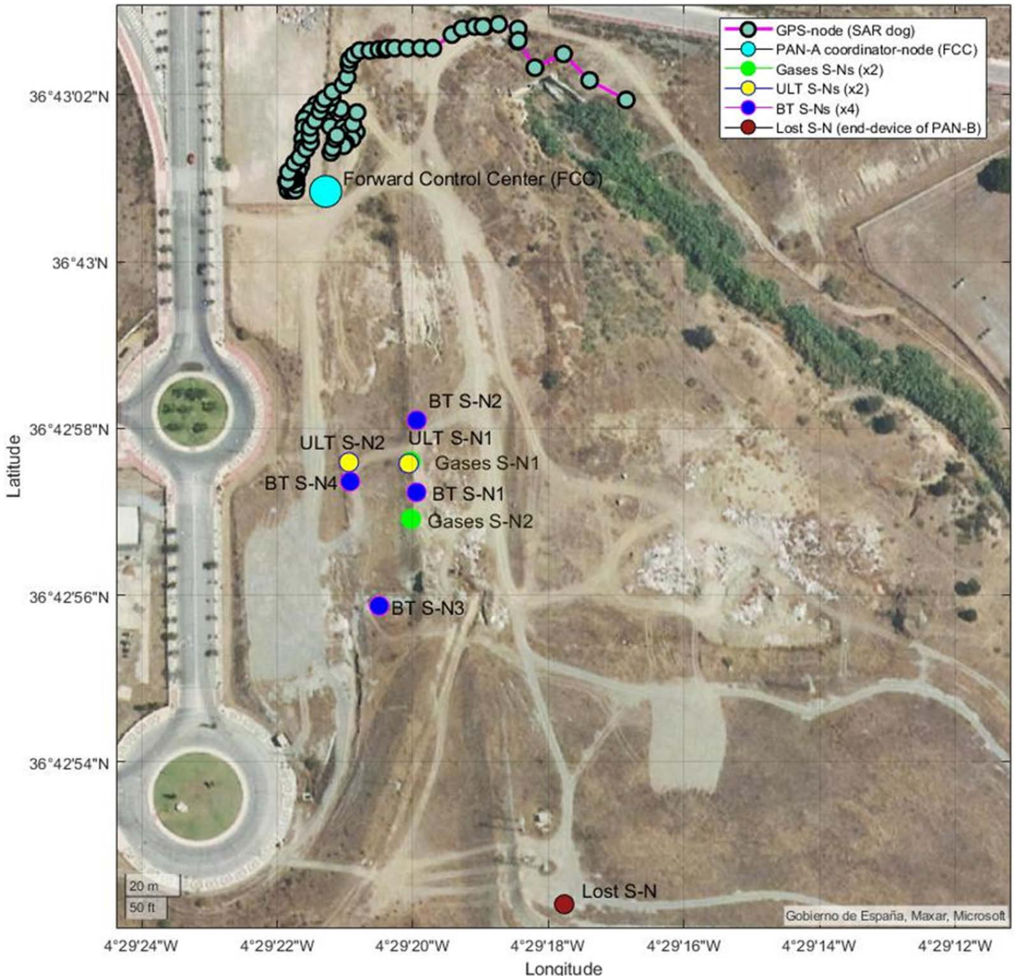

FIGURE 9. Location of the end-devices (S-Ns) during the experiments.

and mounds). One of the mobile S-Ns has been carried by Rambler, the same robot used in ZigBee experiments as an MS. Rambler moved around the field of operations while the mobile S-N was collecting and sending data packets to the static C-Ns. Similarly, with the same strategy, the other mobile S-N was been embarked on Argo XTI (see Figure 16). These mobile S-Ns transmit measurements of temperature, pressure, humidity and GPS. Table 3 lists the S-Ns deployed around the experimental environment. Each SG receives the name of ISA-N, where N denotes the group number and is visible on each flag placed next to the group. The gas S-N (ID=14) of the ISA-7 group has been located far away and with a bad LoS from the C-N, to test the behavior of LoRa technology in harsh conditions. The distance between these S-Ns and the C-N located next to the FCC was 230 m, measured in a straight line. While it may not be a great distance, as LoRa itself allows ranges of several kilometers in rural areas, it is an outstanding improvement over ZigBee S-Ns in the same locations that failed to communicate with the FCC, as it resulted from the ZigBee H-WSN experiments. In addition, the scenario poses significant communication challenges that do not exist in rural areas.

The key parameters of the deployed S-Ns are summarized in Table 4. For instance, the proposed H-WSN has its S-Ns set to the class A [89], the most energy efficient option with the drawback of the lowest communication potential among the three. Specific restrictions on the duty cycle of the S-Ns, transmission power and their antenna' gain have been imposed regarding the legal requirements. In this case, the transmissions are limited by the time of use of the eight channels of the physical layer (duty cycle equal to 0.1% of use time), thus with a relatively slow transmission frequency. Moreover, the S-Ns have been configured to be activated by ABP. To this end, the parameters needed are the DevAdrr, NwkSkey and AppSkey. The first acts in a similar manner to a MAC address, while the other two are parameters that must contain the same value both in the S-N and the C-N to proceed with a successful activation.

For the experiments, the most robust (highest SF value) approach has been taken for three S-Ns -including the farthest

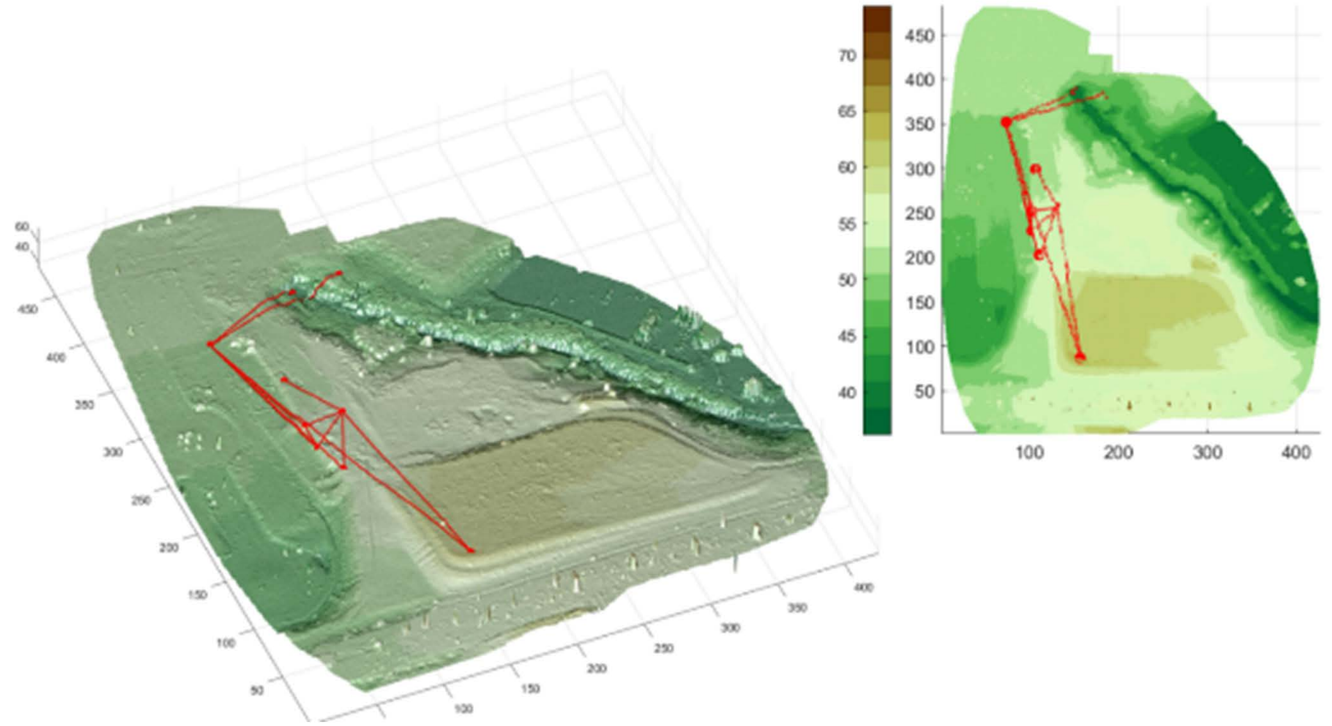

FIGURE 10. **LoS over the 3D map of the terrain obtained from orthophoto processing.**

one, while a balanced configuration has been chosen for the rest of the S-Ns. In this case, it should be noted that the LoRa S-Ns that were out of LoS (ISA-7), successfully transmitted the packets due to a high SF. Data updates of between 6 and 9 seconds have been achieved, depending on the SF applied to the class A S-Ns. The length of the packets is crucial to achieve fast flight times, being smaller for higher SF, at equal packet length. Fast and slow dynamic sensors have been included in the same static SG, to receive different information from the same location, and with different reception rates.

2) RESULTS

As a result of the aforementioned developments and deployment, good-quality data were collected, processed, and plotted, which is a valuable contribution itself. In particular, the following figures show some graphical representations of these data. For example, the RSSI values from both mobile S-Ns (onboard Argo XTI and Rambler), which vary depending on the C-N from which the data was gathered, is presented in Figure 17, as well as the values from the C-N on the turret are shown. As it can be seen, Argo was operating closer to it than Rambler.

Furthermore, during the experiments, the channels (LoRa modulation) have been used dynamically, depending on their availability, with the assiduity shown in Table 5, for a total of 675 packets. Note that the experiments have been done in Spain, which uses EU 863-870 frequencies plan. In addition, both for uplinks and downlinks, the same 8 channels are used. However, for downlink slot 2, there is an extra channel (8) on 869.525 MHz frequency. Interestingly, most transmissions have been concentrated in the first three channels, due to the different limitations of each sub-band. In this context, the European Telecommunications Standards Institute divides the 863-870 MHz band into 5 sub-bands: G, G1, G2, G3 and G4 [65]. For example, for the channel 4, the relationship between bandwidth (0.125 MHz) and its carrier frequency (867.3 MHz) is calculated as in (1) and (2). To conclude, 49 uplink packets have been transmitted through this channel, between these two boundaries frequencies (f_{low} *and* f_{high})

$$f_{low} = 867.3 - \frac{0.125}{2} = 867.2375\ MHz \tag{1}$$

$$f_{high} = 867.3 + \frac{0.125}{2} = 867.3625\ MHz \tag{2}$$

Data acquired and sent by different SGs is monitored, in real time, on the Research Grou's GUI (see Figure 16), operational at the FCC. Specifically, Figure 18 presents the data packets sent by ISA-2. This SG has two S-Ns which have taken measures of pressure, temperature, and relative humidity. The number of packets is different for each one, given that they transmit data with different data rate or SF in spite of transmitting from the same location and during the same time.

Figure 19 presents the data packets sent by ISA-3 and it shows that the battery of the S-Ns does not vary too much during the entire time period of the experiment.

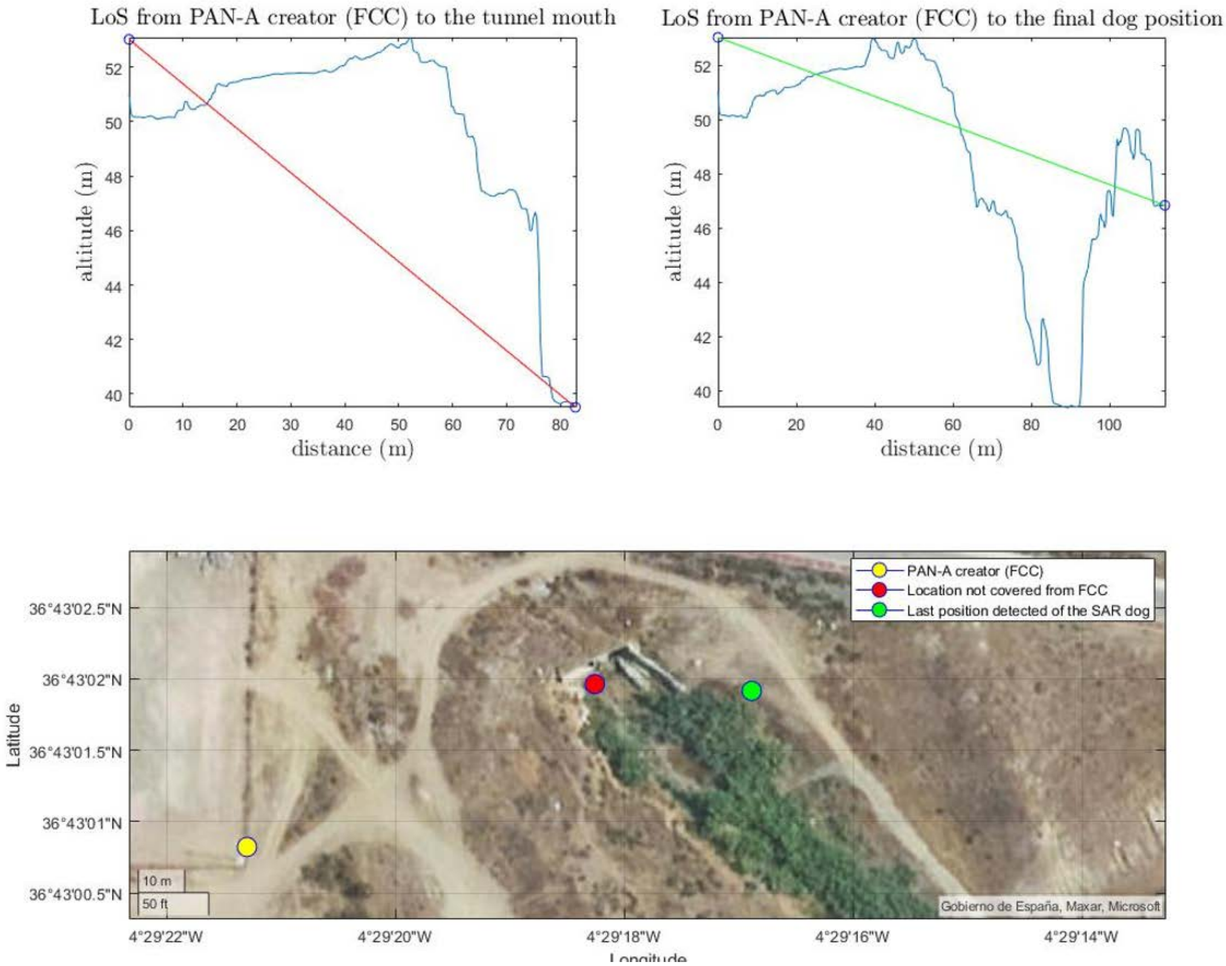

FIGURE 11. **Importance of LoS and range between S-N and PAN creator (red means without coverage; green indicates good connectivity).**

V. DISCUSSION AND LESSONS LEARNT

The first experiment pursued the assessment of ZigBee in a realistic SAR scenario. A ZigBee H-WSN was deployed, including one static coordinator node, a mobile robotic agent (Rambler) acting as an MS, a dog trained to aid in victim localization in SAR scenarios, also carrying a S-N, and eight static S-Ns in the PAN-A and another one in the PAN-B. Data gathering is synchronized with an external database (DB) via 3G or WiFi, and all the information can be monitored from an FCC.

The experiment was performed as part of the sequence of the overall rescue exercise, without the possibility to repeat any part. The system allowed the acquisition of data around the operation area, as well as the extension to a zone out of the original deployment thanks to the MS. The exercise took from 9:00 to 15:30. While the conditions were realistic, the limited duration of the exercise does not provide the ground to draw conclusions on power consumption.

The deployment of the S-Ns was limited by the range of the transmission using ZigBee. Thus, S-Ns in PAN-A were located at a maximum distance of 154.86 m. It is worth to mention the case of the node carried by the rescue dog. In this case, the maximum distance achieved with an effective transmission via ZigBee was 114.8 m, although it must be remarked that the scenario was full of interferences due to the exposition to different radio waves. At that point, while the dog is still seeking for the victim, it remains out of the coverage of PAN-A. The track of the dog also illustrates the relevance of the LoS (see Figures 10 and 11).

Preliminary tests were performed to identify locations where there was not coverage by PAN-A. One of these locations was selected to deploy the lost S-N (which acted as a wearable device Bluetooth detector). Rambler acted as a MS to provide coverage to this isolated end-device within PAN-B. In this configuration, the approach used differs from the one described in [31] and [39]. Here the control station operator (previously managed by a technician) has been replaced by Rambler in the task of providing communication coverage to the dog. Rambler has greater movement capabilities and autonomy for this large and harsh terrain features, and at the same time, contributes to reducing the workload of the human

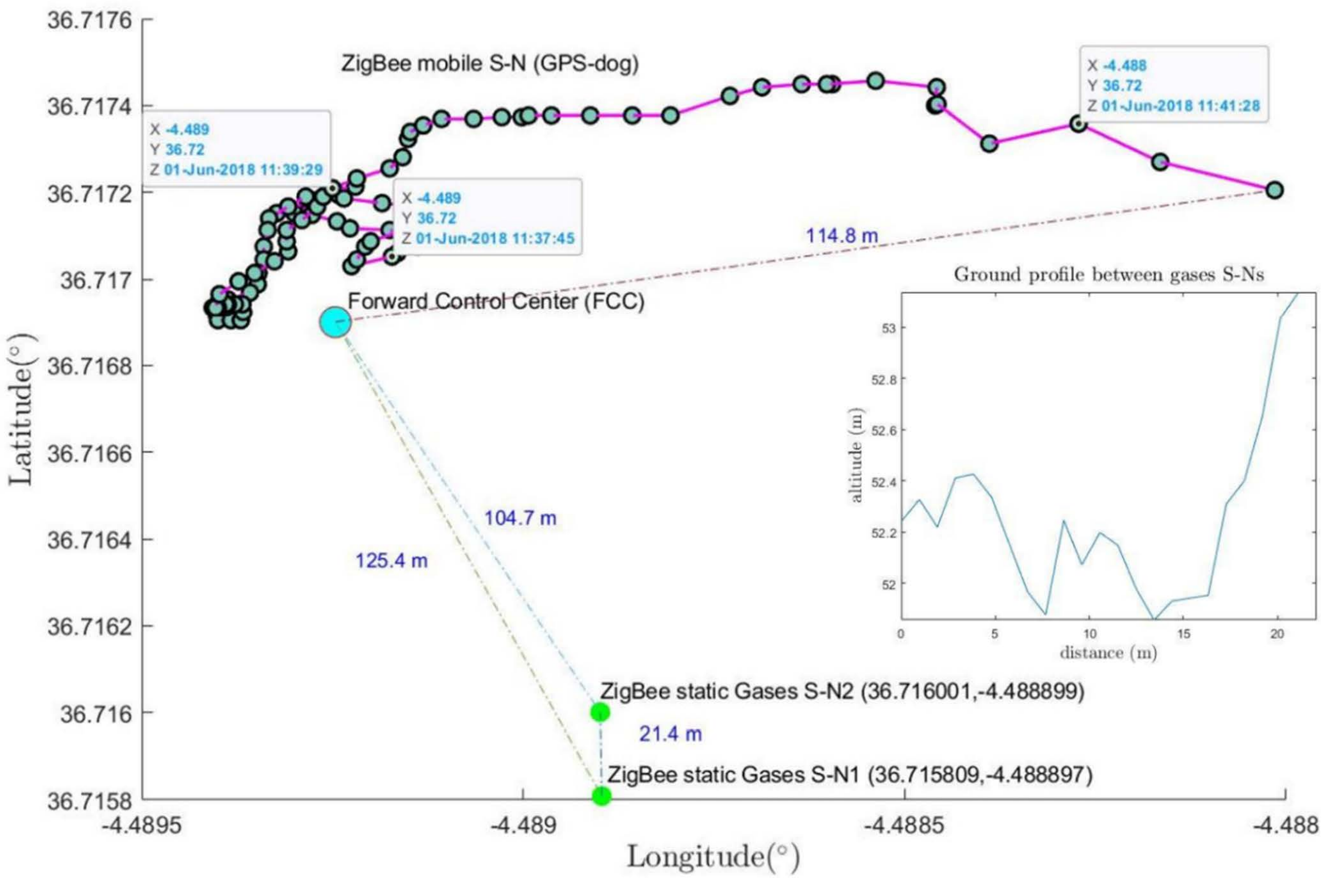

FIGURE 12. Tracking of the SAR Dog and locations of two static S-Ns with respect to their PAN-A creator (FCC).

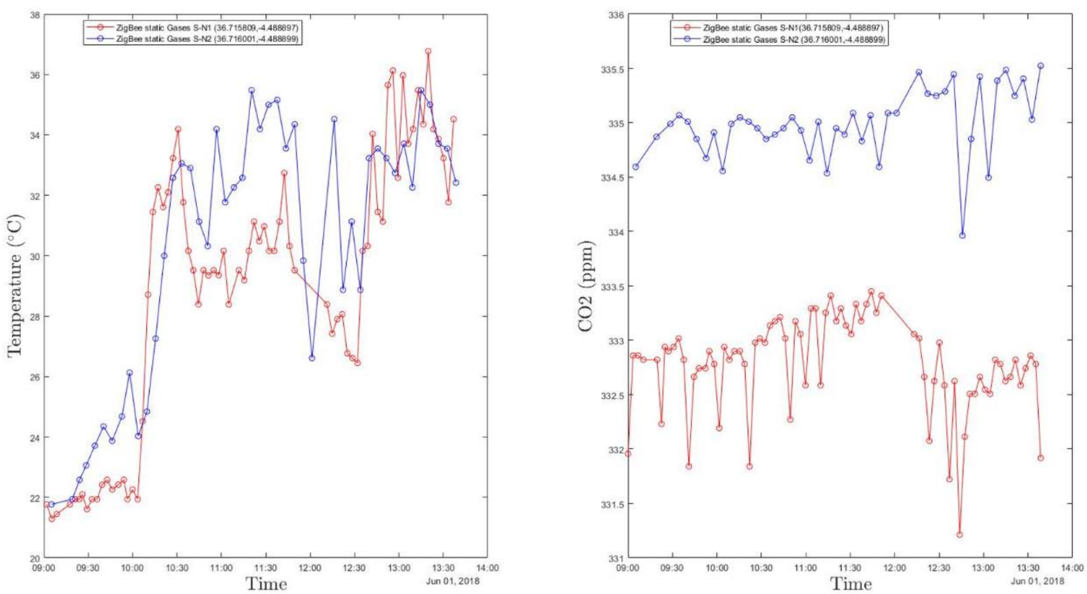

FIGURE 13. Visual comparison of the ZigBee packets received from the two static environmental S-Ns.

agent, who can now focus on victim search details, instead of tracking the dog to provide communication coverage. The operator also carries a control-station backup, but it is used only for searching the potential victims around the zone, with the support of the live video stream captured by a drone flying over the whole exercise area.

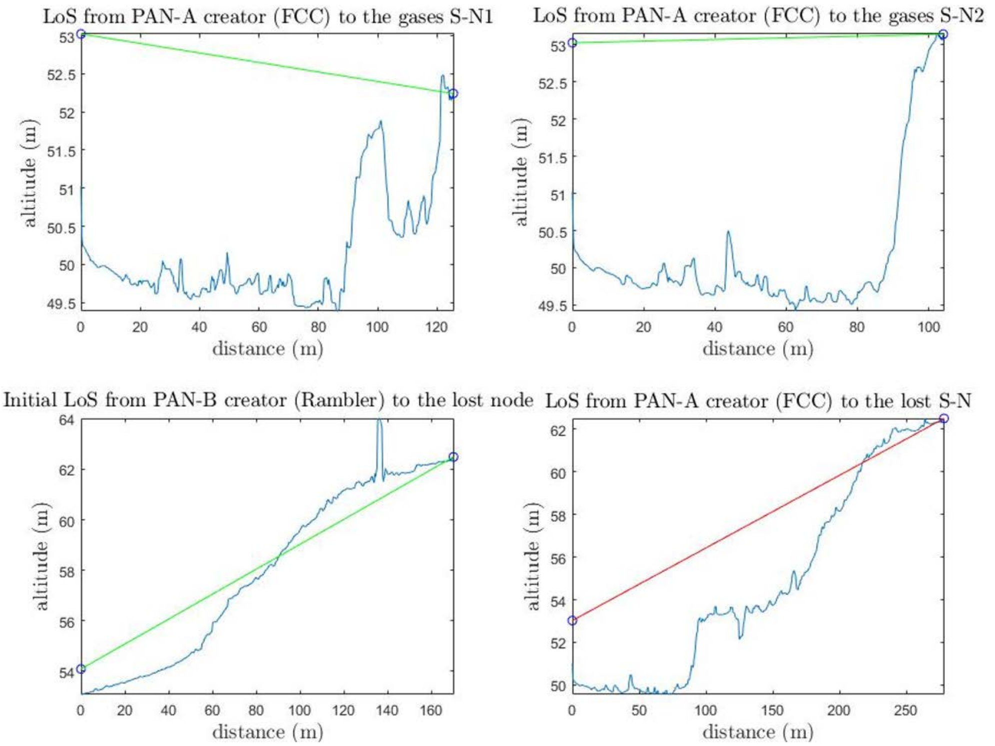

FIGURE 14. Ground profiles and LoS from the creators of both PANs to different S-Ns.

The main drawbacks are penetrability and range. Thereby, based on the results described in this work, it can be deduced that its use is recommended for medium range situations if the LoS is acceptable. In contrast, we can conclude that ZigBee is not recommended for the detection of buried victims, but we do recommend it for the tracking of events of interest in SAR operations. In terms of assessing the viability of ZigBee technology to support this kind of SAR rescue tasks, it is worth noting that the described methodology, the software developments and the results of these experiments have made it possible to contribute to determine the effective range of a ZigBee H-WSN in this kind of scenario, with the aforementioned interferences and features. This result is of great value as it contributes to the process of designing and determining the capabilities of ZigBee H-WSN for SAR operations beforehand.

During the following annual edition of the CSED, LoRaWAN was deployed in a similar SAR scenario. With respect to the ZigBee H-WSN implemented in the previous event, a clear win of this change has been the longer ranges and similar low energy cost obtained with LoRa for exercises of the same duration. Besides, LoRa presents less influence on disturbances due to its chirp spread spectrum modulation, although it is also intended for transmitting small packets (maximum 222 bytes). However, the strategy and architecture has been changed to obtain enhancements. Two mobile agents carrying one SG have been deployed with different roles. Robot Rambler acted as a mobile SG for areas farther away from the main coverage area (served by a static C-N), while the Argo XTI vehicle did the same for distances closer to the checkpoint, located closer to the FCC. Several additional developments have eased the managing and monitoring of the data and have made it possible to extract valuable results from the complex experiments.

FIGURE 15. Location of the C-Ns and intervention of rambler (mobile SG).

On the one hand, LoS and SF play a fundamental role in the application of this technology, especially in the context of catastrophic environments, involving civilian and military communications, as well as a multitude of obstacles, despite being an outdoor application. The length of the packets is crucial to achieve fast flight times, being smaller for higher SF, at equal packet length. Therefore, it is more efficient to

TABLE 3. LoRa S-Ns deployed and their information.

Ending of DevEUI (ID)	SG (packets)	Data (length in bytes)	SF (data rate in bit/sec)	Device Add. (port)
E1F45 (1)	ISA-1 (16)	NO2 (50)	9 (1760)	3011 (93)
E6A93 (2)	ISA-1 (13)	CO2 (50)	10 (980)	3012 (106)
FA4FB (3)	ISA-1 (35)	GPS (50)	12 (250)	3013 (25)
F547B (4)	ISA-2 (44)	T, AP, HUMA, GPS (50)	9 (1760)	3001 (12)
F1782 (5)	ISA-2 (41)	T, AP, HUMA, GPS (50)	9 (1760)	3002 (15)
E1783 (6)	ISA-2 (79)	T, HUMA (50)	12 (250)	3003 (18)
F1784 (7)	ISA-3 (11)	T, AP, HUMA, GPS, BAT (50)	8 (3125)	3004 (21)
E33FF (8)	ISA-3 (79)	CO2, NO2, T, HUMA, p (50)	8 (3125)	3005 (24)
F1787 (9)	ISA-4 (38)	T , AP, HUMA, GPS (50)	9 (1760)	3006 (88)
BECE (10)	ISA-4 (12)	CO, O3 (50)	10 (980)	3008 (101)
F1789 (11)	ISA-5 (112)	T, AP, GPS (124)	9 (1760)	3009 (156)
BAAB (12)	ISA-6 (38)	GPS (50)	11 (440)	3010 (81)
F1794 (13)	ISA-6 (38)	T, AP, H, GPS (50)	9 (1760)	3014 (26)
E5048 (14)	ISA-7 (17)	CO2, NO2 (50)	12 (250)	3016 (100)
F19E1 (15)	Rambler robot (45)	T , AP, HUMA, GPS (50)	9 (1760)	3007 (90)
F1795 (16)	Argo vehicle (48)	T, AP, HUMA, GPS (50)	9 (1760)	3015 (94)

TABLE 4. Key parameters of deployed LoRa S-Ns.

Property	Value	Impact
Class	A	Longest battery life, but lowest raw communication capacity.
Frequency band	868 MHz	Adjusted duty cycle of S-Ns to European regulation.
SF	Medium to high	Remote S-Ns lean towards reliability; rest of the S-Ns deployed at equilibrium point.
S-N activation	ABP	Preconfigured activation that allowed multicasting.

transmit the information in byte format, rather than in ASCII, although the latter is easier to decode and interpret. In the case of S-Ns with slow dynamic probes attached, the LoRa limitation is not a problem given that the data is sent when it is available. This may take two to three minutes, depending on the gas to be measured.

TABLE 5. Transmissions on each LoRa channel during the experiments, for a total of 675 packets.

Channel	0	1	2	3	4	5	6	7
Uplink Frequency (MHz)	868.1	868.3	868.5	867.1	867.3	867.5	867.7	867.9
Sub-Bands	G1 (duty cycle < 1 %)			G (duty cycle < 0.1 %)				
SF (Bandwidth, kHz)	7 to 12 (125)	7 to 12 (125,250)	7 to 12 (125)	7 to 12 (125)	7 to 12 (125)	7 to 12 (125)	7 to 12 (125)	7 to 12 (125)
Number of Tx.	149	133	136	47	49	62	50	49

On the other hand, due to the slow displacement of the robot while it is exploring the zone (looking for a potential victim), the transmission of the faster dynamic sensors allows for an almost immediate update of field data, given the limited use of channels inherent to LoRa technology.

The LoRa H-WSN was configured to use ABP mode. This way, it has been possible to operate with multicasting, even without Internet connectivity. In this test, we have deployed two static C-Ns, which are connected to the FCC, via LorApp, using the Local Area Network of our University. In contrast, in the case of ZigBee H-WSN, it has been necessary for the robot to have WiFi coverage to be able to transmit the information it collected from the environment (when it approached the static ZigBee lost end-devices). Furthermore, not only does LoRa enables to get much more information from the static SGs than ZigBee does, but it can also be done farther away from the C-Ns. This has been proved by testing mobile LoRa S-Ns and a ZigBee mobile S-N, which have transmitted the information captured by the S-Ns they carry on while moving. In the case of LoRa, these transmissions achieved a greater distance. To achieve this distance with ZigBee, several coordinator nodes operating as intermediary routers throughout the experimental area would have had to be set up. Likewise, ZigBee has a limitation in the number of hops, and for a high number of hops, it could produce traffic issues (lots of collisions or retries) on the H-WSN, apart from big latencies and less energy efficiency. However, the strongest limitation is that it is not possible to obtain information from the same S-N from two different coordinator nodes, as multicasting is not allowed. With LoRa, this is possible, and it allows to analyze the duplicated packets stored in the independent DBs (associated to each of the C-Ns), so that the RSSI and SNR values can be studied from the same remote position, up to the two locations. This way, different SF can be set to obtain more noise immunity and range, or higher data rates depending on the needs. This allows areas to be served from different points so, for future editions of the CSED, an

FIGURE 16. Mosaic that summarizes the experiments carried out at the XIII CSED (2019).

interesting future line of work is to create RSSI maps for each static C-N so that they could serve as beacons in this unstructured environment. The behavior of the LoRa signals might enable localization strategies without GPS, using high SF to detect buried victims with LoRa transceivers. However, the variability of the terrain and the reflections of the signals with the own body of the mobile agent affects to the values in a random way. Using RSSI values to estimate distances from S-Ns to concentrators could be very useful for detection purposes (e.g., LoRa S-Ns in hidden areas without GNSS, Global Navigation Satellite System), but a model associating the RSSI values, and the GPS position of the mobile S-Ns is needed. Besides, the slow transference of data inherent to LoRa limits this application due to the need to send the maximum number of packets from the mobile agent during its movement. Another limitation found in these experiments is the accuracy of the GPS used in LoRa S-Ns, which is too low for precise tracking by LoRa.

From an energy standpoint, all S-Ns were deployed at 100battery power. The time established in the events' experiments made that the configuration set up for the S-Ns did not involve such a consumption that they could be rendered inoperative. This is supported by the literature [40], [90], [91], and therefore, the analysis of power consumption it is not the purpose of this article. Nevertheless, it is advisable to turn off LoRa locators that may be carried by the victims at the time of rescue. This will also free up space on the transmission channels and reduce the number of collisions.

As a result of the developments made, the presented data, the used methodology and the two deployments, the authors conclude that the LoRa implementation cannot be carried

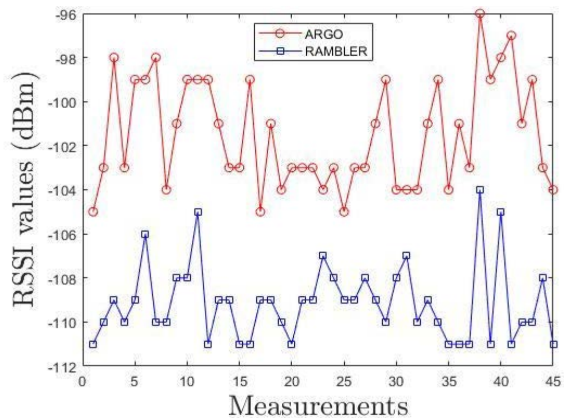

FIGURE 17. RSSI from both mobile S-Ns for every packet received at the static C-N of the FCC.

out using ZigBee, due to the need of routers or intermediary coordinator nodes to extend the coverage generated by a single receiver (the PAN coordinator node). In contrast with the case of the ZigBee H-WSN, an MS (hence a mobile coordinator node) is not needed in the LoRa H-WSN because of the greater LoRa coverage compared. In that sense, to test the LoRa technology two mobile S-Ns have been integrated along with the different SGs composed of static S-Ns, showing that the effective range of LoRa is greater than the one of ZigBee. However, LoRa technology, while proving to meet SAR requirements, has also shown some drawbacks. The most important one is the limit to localization applications resulting from the slow transfer of data inherent to LoRa.

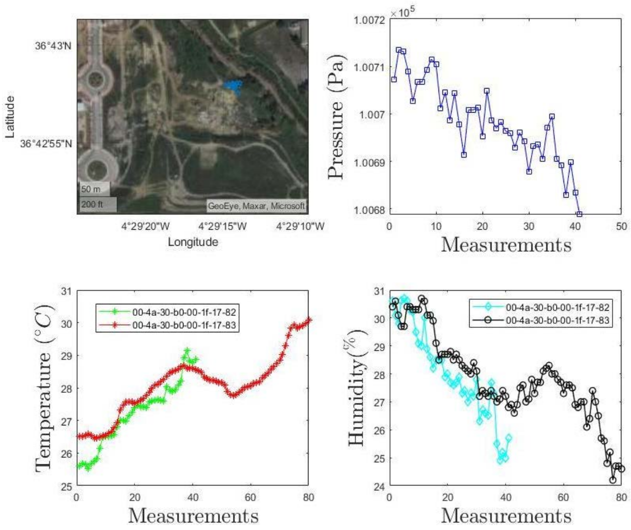

FIGURE 18. **Pressure, temperature, and relative humidity, measured and sent by sensory group ISA-2.**

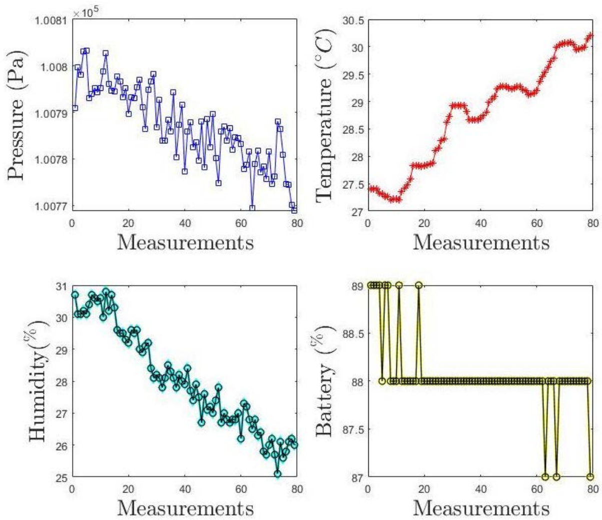

FIGURE 19. **Pressure, temperature, relative humidity, and battery measured and sent by sensory group ISA-3.**

To sum up, LoRa has demonstrated an overall superior performance to that of ZigBee, although the latter is recommended in certain applications. These two technologies are complementary and can cover different ranges in SAR operations.

VI. CONCLUSION AND FUTURE WORK

In the first place, this paper has introduced the work developed during both the 12th and 13th Conference on Safety, Emergencies and Disasters (CSED), organized by the Chair of Safety, Emergencies and Disasters of the University of Malaga in its 2018 and 2019 editions, respectively, by focussing on the use of Hybrid Wireless Sensor Networks (H-WSN) for supporting Search and Rescue (SAR) tasks. Within that scope, the aim of this article is to raise awareness of this annual event and to share the lessons learnt in terms of the use of different technologies for H-WSNs to assist SAR teams. Thus, we present what we regard as an interesting process of development, test and comparison between ZigBee and LoRaWAN, both designed to collect valuable information from a terrain where different agents cooperate alongside humans to find potential victims in harsh conditions.

Finally, it should be noted that the area of experimentation has a direct view of the sky, which means facility to connect with the satellites, but this can only be seen as a positive point to compare it with the development of localization applications (either by trilateration or multilateration) using LoRa, which could be even supplemented by detection techniques using Bluetooth Low Energy. In this sense, it would be possible to place a LoRa C-N on the Rambler robot, in order to act as a mobile beacon. All in all, next goals are currently being pursued in order to provide more precise support to rescue teams, especially in the easternmost area, where even GPS does not have good coverage, due to the large vegetation, as well as in certain underground locations. For that, another line of future work is to use Unmanned Aerial Vehicles with LoRa C-Ns, working as a swarm, which may help to reduce the error of distance calculation using RSSI or Time of Arrivals methods.

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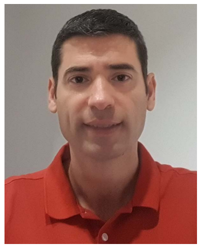

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