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LoRa-based Wireless Sensor Networks for Urban Scenarios Using an Open-source Approach

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Abstract: This work brings together two wireless sensor networks achieved within two European projects aimed at accomplishing novel approaches to urban monitoring. The networks share the same end nodes but differ in the architecture and the communication protocol, namely raw-LoRa and LoRaWAN (868 MHz). By the one hand, the raw-LoRa option allows for the full control on exchanged data, as the network management is implemented at hardware level. By the other hand, the LoRaWAN option provides a standard way to data gathering and comes with enhanced features for devices/applications management. The architectures rely on open-source compliant components both in terms of software (i.e. network management and data storage) and hardware (sensor-nodes and gateways). All these aspects have made it possible to achieve two flexible and low-cost platforms for environmental monitoring applications, among others. Data collected both outdoor and indoor enable us to assess the reliability and the drawbacks of the wireless sensor networks reported.

Keywords: LoRa, LoRaWAN, Low-power wide-area network, Sensor node, Gateway, Timeseries, Environmental monitoring.

1. Introduction

The use of low-power wide-area network (LPWAN) for environmental monitoring is taking hold because of their high energy efficiency and the long coverage range achievable [1]. Despite the limited data throughput, what makes this technology particularly attractive is the low implementation cost. However, communication robustness is still critical. Although gap filling methods and data transmission reduction schemes are becoming more and more satisfactory to cope with data lacks within timeseries [2-3], communication interference for wireless sensor networks (WSNs) remains a critical point to be addressed, especially in urban areas. In this work, we go through this aspect by considering two purpose-built WSNs, where the first one implements only the physical layer raw-LoRa as a communication protocol, while the second one encompasses the LoRaWAN application layer, as well [4]. These communication protocols lay into the Industrial Scientific Medical (ISM) frequency band (Europe 868 MHz)

Experimental data have been collected within the frame of two research projects, which are described in the following section.

2. Urban Monitoring Scenarios

2.1. SINFONIA Project

The European project SINFONIA [5], "Smart Initiative of cities Fully cOmmitted to iNvest In Advanced large-scaled energy solutions", is a five-year initiative to deploy large-scale, integrated and scalable energy solutions in mid-sized European cities. Technically and technologically innovative actions have been implemented in two pilot cities, Bolzano (Italy) and Innsbruck (Austria), with the aim to transform them into smart cities and to propose solutions easily replicable and adoptable by other European cities. Within the framework of SINFONIA, building refurbishment interventions to achieve high-energy performance and to improve interior comfort have been undertaken for six residential complexes in the south district of Bolzano. Among those, the apartment complex located in Via Brescia-Cagliari. Refurbishment interventions on the building included, among others: external insulation with white plaster, substitution of the balconies' parapets, renovation of the roof by converting the space into new apartments and by adding an additional floor, and installation of a new solar thermal plant on the roof and on the south multifunctional façade.

After the completion of the construction works, the area is subject to an in-situ monitoring campaign, which will last for one year and collect data relatively to all the main meteorological parameters. The objective is double; first, to verify the impact of the renovation interventions – as, for example, the modification of the façade color from brown to white - on the microclimatic conditions in the district. The second aim is to collect data useful to calibrate the environmental used to simulate the current conditions (i.e. solar irradiation, microclimate, and airflow) in the area and the potential impacts of future modifications of its surfaces (e.g. installation of a green façade, creation of water urban features, etc.) [6-7].

2.2. BEACON Südtirol - Alto Adige Project

The BEACON Südtirol - Alto Adige project [8] is an ERDF (European Regional Development Fund) funded initiative that aims to create a favorable environment for the development of new ideas, applications and products through the installation of a Beacon Network and the setting up of an IoT Pilot Area at the Technology park of Bolzano (NOI Techpark). Moreover, the project wants to foster the creation of a local community of IoT experts, companies and research institutions that cooperates toward digital innovation in many different sectors.

Within the BEACON project, a technology and market analysis regarding the IoT state of art has been carried out, which has led to the release of a whitepaper in 2019 [9]. This first result, together with the feedback collected from the IoT community, suggest that LoRaWAN is one of the most interesting emerging technologies for IoT applications. Therefore, an experimental open-access LoRaWAN network has been made available within IoT pilot area of the NOI Techpark, with a view to:

- Create a free and easy-access infrastructure for developers and companies, where they can develop and test new applications, sensors, etc.:
- Foster the cooperation between research and industry at the level of co-creation approach;
- Facilitate the startup of innovation projects and the setup of new IoT-based services and products.

Next step of the project is to empower the coverage at the NOI Techpark with other promising IoT communication protocols, namely Sigfox, Symphony Link, 5G, among others. By doing that, it will be possible to compare the performances of the different technologies on a specific application and then choose the most suitable one for the final implementation.

3. Network Architectures

3.1. raw-LoRa

Within the SINFONIA project a 20 sensor nodes WSN has been set up and deployed at different height on the external surfaces of an apartment building. The positioning of the sensors has been accurately chosen to characterize the gradients of microclimatic parameters in the building area due to the different materials used, façade orientation, and the presence of natural features such as grass and trees. A crucial aspect in this pilot is that the data acquisition must occur at the same time for all nodes. For this reason, we decided to exploit the raw-LoRa protocol, which makes it easier to set a router as master and the end nodes as slaves, so that the master spreads its own time to the slaves making them synchronized before each measurement. The topology of the WSN is shown in Fig. 1, where a gateway (LoRa/wifi) serves as access point to the Web.

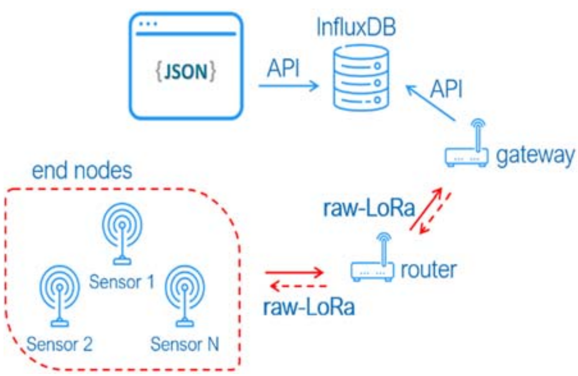

Fig. 1. raw-LoRa wireless sensor network set up for the SINFONIA project. The architecture encompasses 20 end nodes, a router, a gateway, and an InfluxDB database, whose API can be exploited to store and retrieve the data acquired by the sensors.

The LoRa packet management performed in the SINFONIA WSN is sketched in Fig. 2. The functioning has been obtained by programming each component of the network, namely the sensor nodes, the router and the gateway, in a stand-alone way. The operating routine starts with the router spreading its own real time clock (RTC) signal for 40 seconds. In the meantime, all the other system components, set to receiving mode, wait for a LoRa packet containing the router's RTC. Once the sensor nodes and the gateway are synced, the whole system goes into wait mode (machine idle) till a preset time. Then all the nodes acquire contemporary a measurement. That done, the nodes forward the data (temperature, relative humidity, battery level) to the router in a staggered way, i.e. one by one every 2 seconds, and then go into deep sleep mode.

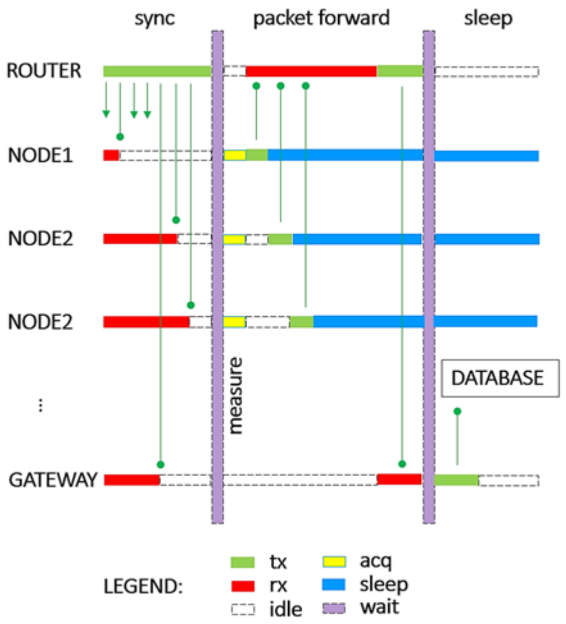

Fig. 2. Sketch of the working plan for the SINFONIA WSN, which repeats itself from left to right in an infinite loop every 10 minutes. The layers represent the main hardware components of the WSN, which are the router, the sensor nodes (only two are reported in the figure), and the gateway. The color code used aims at showing the different modes in which the components operate: green for transmitting mode, red for receiving mode, yellow for measuring, white for idle, cyan for sleeping.

After 60 seconds from the measurement time (violet vertical bar in the figure), the router wraps all the data received from the sensor nodes in a single LoRa packet and send it toward the gateway, which is still set to receiving mode. The gateway, in turn, posts the sensor data into the InfluxDB database [10] through a Wi-Fi connection via an HTTP POST request and goes into deep sleep, as well. The only component still on now is the router, which spreads the RTC signal every 1 minute in case of some nodes went out of synchronization during operation. After 9 minutes from the measurement time, the nodes and the gateway wake up, ready for a new synchronization, and the routine starts again.

3.2. LoRaWAN

In the context of the BEACON Südtirol - Alto Adige project another architecture has been put in place to grant LoRaWAN connectivity inside the technology park of Bolzano. The aim of the pilot was to prove whether an IoT testing network can be set up by using only open source components. LoRaWAN is particularly suited for this, as it can manage many different end nodes at once. Therefore, we exploited a plain LoRaServer installation for the network management, integrated with an InfluxDB instance (see Fig. 3).

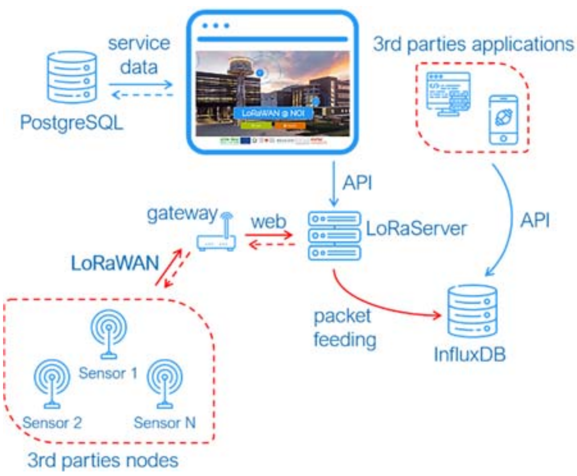

Fig. 3. Schematics of LoRaWAN network deployed at the NOI Techpark for BEACON project. The topology consists of several gateways that ensure indoor and outdoor connectivity in the Technology Park area. The network management is achieved through LoRaServer and a dedicated Web portal allows for the registration of new end nodes. Data transmitted over the network are stored into an InfluxDB.

The information gathered in the sensor-nodes is sent to the gateway over the LoRaWAN protocol. The gateway, in turn, is responsible for data forwarding via a User Datagram Protocol (UDP) link to the back-end, which is made of the LoRaServer and the InfluxDB components. As we wanted to keep the solution as much open as possible, we adopted a Raspberry Pi 3b+ as main board for the gateway and we achieved the LoRaWAN compliance through a RHF0M301 LoRa shield [11].

Several gateways have been deployed within the NOI Techpark area, which serve as access points to the LoRaWAN network. They are set up to have direct access to the network of the NOI Techpark (ScientificNetworkSouthTyrol [12]) through a secured virtual private network (VPN) connection at boot. This way, the gateways, which are assigned to a stack of static internet protocol (IP) addresses, can reach the

LoRaServer from any wireless local area network (WLAN). This strategy allows for a flexible deployment of the LoRaWAN access points, which can also be extended outside the NOI Techpark areal, at will.

In order to ensure the stability of the connection between the sensor-nodes and the backend, we took measures to make the gateways resilient and fault tolerant. To accomplish this goal, all the gateways have been provided with periodic checks to the status of the Wi-Fi and VPN connection and a fully automated routine makes them connect to the Wi-Fi network and to the VPN right after boot, in case of power outage. This design was created with the intention of keeping the downtime of the whole network low, which implies a low percentage of lost information. In such way, we achieve a network that, in case of faults, doesn't require any human intervention to get restored.

We also set up a Web portal through which both custom and commercial sensor nodes can be added to the network without taking any subscription out. It acts as a unique access point to the LoRaServer and the InfluxDB application programming interface (API). By the one side, the LoRaServer API allows to register and manage the devices on network server. On the other side, the InfluxDB API can be used to retrieve the stored timeseries in a JSON format.

The portal (https://lorawan.beacon.bz.it/) is a Java Web Application running on Apache Tomcat [13], which implements registration, deletion, device status check, application and user management by means of servlets. These are defined as services inside the Web application to allow the Webpage to be a dynamic one.

Fig. 4 shows the administration page of the LoRaWAN Web portal. It has been developed in such a way to make network's users autonomous in managing their own end nodes. After registration, the user is immediately redirected to the administration dashboard that encompasses five tabs: *Your devices*, *Add new application*, *Add new device*, *Get data*, *Settings*. At the first log-in, the devices list (first tab) is empty and the user needs to go through the creation of a new application (second tab) and the registration of new device (third tab).

Fig. 4. Admin Webpage of the LoRaWAN portal. The Web portal consists of a Java Web Application running on Apache Tomcat.

After doing so, a new line will appear in the devices list, which will carry the LoRaWAN device parameters in the format: *Device address*, *Application session key*, *Network session key*. If these three values match the ones of a working sensor node, the user will be able to retrieve the transmitted data through the InfluxDB API (fourth tab). Such an API can be consumed by Structured Query Language (SQL) through HTTP GET request. The result is a JSON carrying the requested timeseries. In the end, the settings page (fifth tab) allows to update/delete the user profile.

4. Sensor-nodes

To assess the performances of the two architectures, similar sensor-nodes have been added to both the raw-LoRa and the LoRaWAN networks (Fig. 5 - left).

The sensor node schematics is detailed in Fig. 5 - right. It encompasses a Pycom LoPy4 with expansion board version 3.0 as core unit. A DFrobot solar LiPo Charger, coupled with a 3.7 V – 5200 mAh battery and a 0.5W monocrystalline Seeed solar panel, manages the power supply. The sensing element is a Honeywell Humidicon HIH6121 enclosed into a plastic radiation shield and connected to the microcontroller via the I2C bus. The sensor node carries a microSD flash memory for local storage of acquired data. The system is completed by a Laird 868MHz 2 dBi antenna and a Bopla IP68 case.

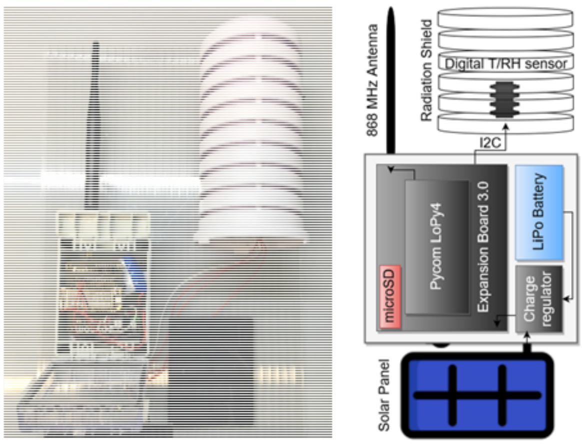

Fig. 5. Picture and schematics of one the sensor-node.

The sensor-nodes added to the WSNs share the same hardware, but they slightly differ in the programming script and data acquisition. In fact, for the raw-LoRa it is only needed to open a socket to start transmitting packets toward the gateway, while for the LoRaWAN a network session and an application session authentication must be performed to allow the data flow to the LoRaServer. Moreover, the sensor-nodes acquire different parameters. In the first case (raw-LoRa), the sensing element is inside a radiation shield so as to acquire outdoor temperature and relative humidity. In the second (LoRaWAN) the sensor is enclosed into the electronics box to investigate the hygro-thermal stress the micro-controller unit undergoes during operation.

However, these differences do not impact on the performance comparison we want to carry out, which will focus only on the communication reliability of the two WSNs being examined.

5. Experimental Results

5.1. Outdoor

Fig. 6 brings together some early timeseries from the SINFONIA's study-case. The charts have been obtained by means of Grafana [14]. The use of this analysis/visualization Web-tool is particularly suited to this purpose, as it comes with a native data source plugin for InfluxDB database and allow for automatic updates when new data are uploaded.

In the first three charts from top, temperature (red curves) and relative humidity (blue curves) from three sensor-nodes of the raw-LoRa WSN are reported. The data are acquired every 10 minutes and acquisition slot shown is 931 hours long. The daily oscillation of temperature and relative humidity are clearly visible in all plots, as well as the effect of a strong raining event in the middle of the timeseries. The difference between the three curves of temperature and the three curves of humidity is due to two main reasons. The first is sensor accuracy, which is 0.5 °C for temperature and 4 % for relative humidity. The second reason is because the sensor-nodes are located at different positions (mainly different heights) on the façades of district to be monitored.

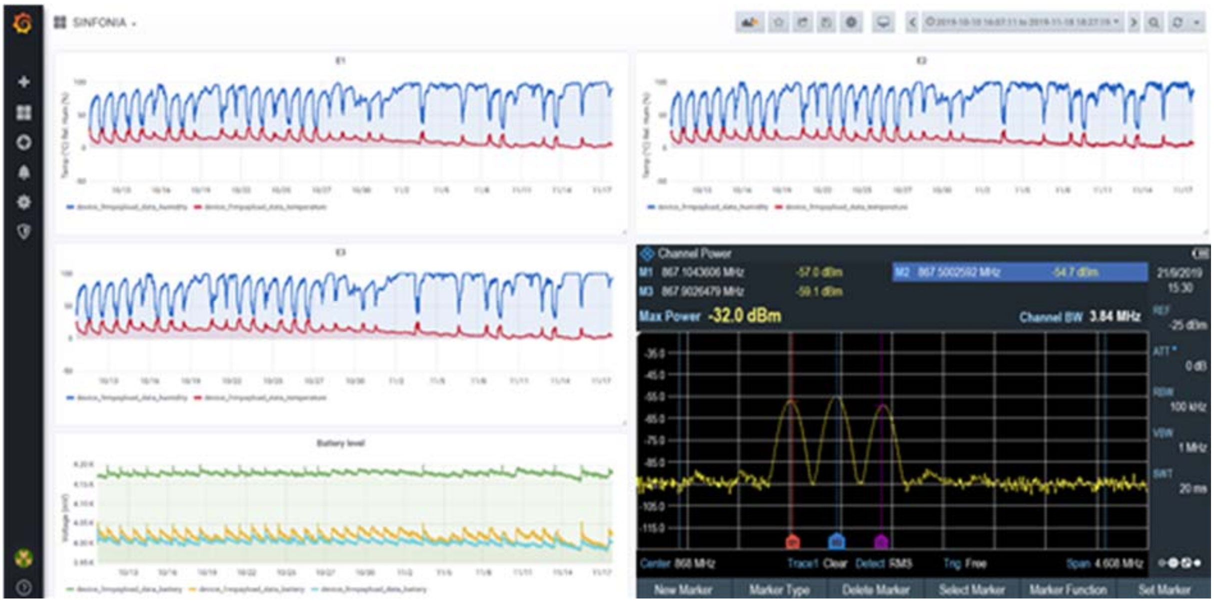

Fig. 6. Grafana dashboard created to monitor SINFONIA's campaign in real-time. The upper charts represent the temperature (red curve) and relative humidity (blue curve) acquired by four sensor-nodes placed on the façade of the building under analysis. The bottom-left chart shows the battery level of all sensor above, measured in residual voltage amplitude. In bottom-right, the screenshot of the frequency splitting on the LoRa channels is demonstrated when the three sensor-nodes transmit at the same time.

The bottom-left chart carries the battery level of all the sensor-nodes. The difference in the average level of the green curve in respect to the other ones is due to a better health status of that precise battery. The sawtooth behavior can be ascribed to the fact that the curves show the voltage amplitude of the batteries, which decreases steeply immediately after recharging phase has ended. Then the voltage undergoes a shallower decrease till the next charging peak, occurring during daytime. It would be easy to include some algorithms into the micro-controller script that convert the voltage in the residual capacity [15]. However, this falls out of scope for this work, as it would bring more complexity and more power consumption at node level, possibly lowering the reliability of the solution.

In the bottom-right of Fig. 6, the screenshot of an FPH Rodhe&Schwarz spectrum analyzer is added to show how the transmission of the different sensor-nodes occur over the LoRa channels. This condition where all the nodes transmit information at the same time is not common in the raw-LoRa architecture, as the packet forwarding is scheduled to be split in time among nodes. However, the measure demonstrates that unwanted emissions and leakage power form adjacent channels is negligible in such a system.

Permissible frequency deviation and RF waves emitted by the secondary will be detailed in a future work.

5.2. Indoor

Even if LoRa-based protocols are not particularly suited for indoor connectivity, mainly due to the long-wave nature, we tried to get the best out of this communication protocol within the spaces of the NOI Techpark.

Coverage and performance obtained with a single gateway onto a floor of more 500 m^2, with void space in the middle, are reported in Fig. 7. In order to estimate Received Signal Strength Intensity (RSSI) and Signal to Noise Ratio (SNR) in the different rooms, the figures of merit collected at the gateway have been analyzed. In fact, the LoRaWAN data model carries RSSI and SNR, as well, and the LoRaServer allows for an easy access those values. The maps shown in the figure have been obtained by acquiring multiple measurements per each room, where the gateway is kept steady into the upper-left room, and a 14dBm transmitting end-node is moved from space to space. The averaging over 10 measures per room demonstrate an RSSI ranging from -23 to -95 by passing from the gateway room to the most far apart location of the floor. Same happens for SNR, which varies from 12.8 to 4.2.

We want to remark that during the test, all the packets have been correctly delivered even if the building has steel-reinforced walls surrounding the void space in the middle.

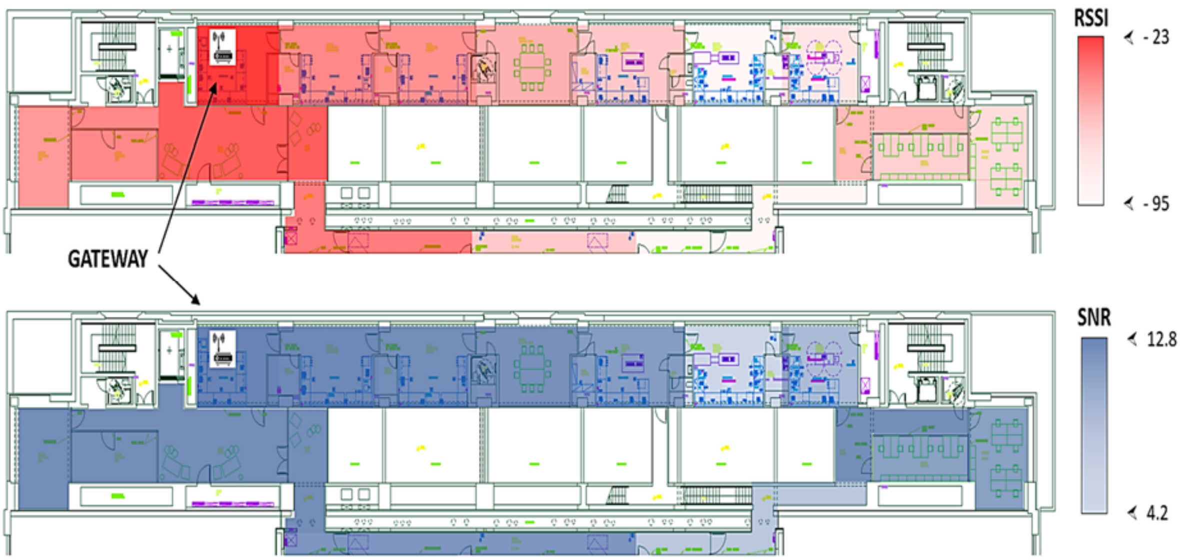

Fig. 7. Maps of Received Signal Strength Intensity (top) and Signal to Noise Ratio (bottom) superimposed to the layout of one of the NOI Techpark floors. The contour plots have been obtained by placing a 14dBm transmitting end-node in each room of the floor and averaging the stats data measured at the gateway.

5.3. Comparison of raw-LoRa and LoRaWAN

In Fig. 8, the two WSN architectures is compared in terms of reliability performances. The 160 hours long timeseries shown in the plots show the temperature in red solid line, the relative humidity in blue solid line (for a longer timeseries comparison see [16]). Despite the overall behavior is quite similar, the data from the two sensor nodes differ in range due to the different placement of the sensing element, which in the raw-LoRa node is within a radiation shield (outdoor sensor), while in the LoRaWAN node is inside the IP68 case (enclosed sensor). This aspect brings also to smoother trends of the temperature and the relative humidity in the second chart, because the sensor suffers from an enhanced sensing inertia [17] within the sealing case.

The figure insets aim to focus on some specific moments when lack of communication/connectivity has occurred during the acquisition. From the scatter plot we can see that network-failures happen to be randomly distributed. Moreover, a deeper data analysis allows us to claim that no communication lacks longer than 30 minutes (3 consecutive measurements) have occurred since the acquisition has started.

It is worth to note that this issue happens for both the WSNs in like manner, meaning that this is mainly related to interference/collisions at the LoRa frequencies [18-19]. Packet loss ratio figures for both the WSNs have been calculated over two 10000-sample timeseries. The obtained results are reported in Table 1.

The value reported in Table 1 for LoRaWAN is in agreement with previously reported analysis [20-21], as the node is less than 100 m far from the gateway.

Table 1. Packet loss ratios calculated on 10000 packets transmitted over the two WSN in comparison.

	raw-LoRa	LoRaWAN
Packet loss ratio	1.9 %	1.5 %

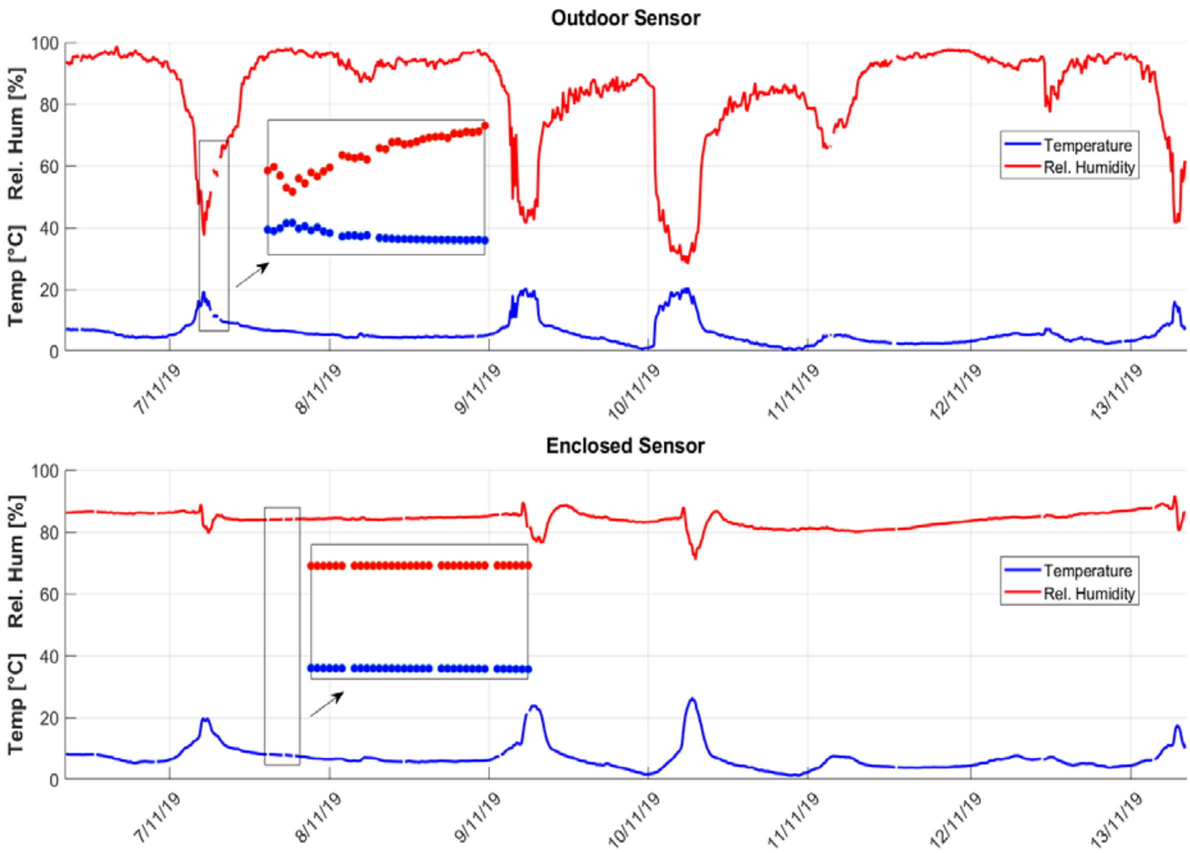

Fig. 8. 160 hours long timeseries acquired by one sensor node of the raw-LoRa network (top) and by one sensor node of the LoRaWAN network (bottom). Both the sensor nodes measure the temperature and relative humidity every 10 minutes. The lack of communication occurred in specific moments are highlighted in inset. The difference between the two charts comes from the fact that, despite the hardware is the same, the raw-LoRa node measures outdoor parameters while the LoRaWAN node is sensing temperature and relative humidity inside the IP68 case.

6. Conclusions

With this comparative analysis, we show that the raw-LoRa and the LoRaWAN protocols share similar reliability. However, the first one happens to be more appropriate for use cases where there is the need of specific requirements, like synchronous acquisitions or direct communication among devices. Instead, the second one is best suited to integrate many different data sources with enhanced information management and sharing capabilities.

A common feature to both the approaches described in this work is that they entirely rely on open-source software. This proves that reliable acquisition systems based on low-cost and vendor un-locked components are now within reach. In fact, the solutions presented in this work are easily replicable and can be modified to the need or upgraded with ease. Data sharing is also eased, as we put special attention to use unified and standard data model. In such way, we gain full control on data work-flow, from the sensor-nodes to the final dashboard for the end-user. Moreover, the proposed architectures are suitable for integration within wider digital platforms [22], and eventually they can be part of future developments toward a hybrid multi-protocol network for open IoT.

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