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A Scalable LoRaWAN-Based Environmental Sensing System for Cultural Heritage Sites

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***Abstract*—Preserving cultural heritage requires reliable and non-invasive monitoring in different environments, including open-air archaeological sites, museums, and exhibition areas. This study presents a scalable environmental sensing system based on a LoRaWAN architecture and ExoSense sensor nodes. The system is capable of measuring temperature, humidity, pressure, light, and air quality. It is modular and can be easily expanded with additional sensors. In-field tests were conducted in San Marco d'Alunzio, a small Italian village with a rich history dating back to ancient Roman times. The site offers both indoor and outdoor cultural heritage scenarios, such as the Temple of Hercules and the Byzantine and Norman Figurative Arts Museum. Experimental results confirmed stable network coverage and low packet loss rate when adaptive data rate was enabled, even in the presence of complex topographies and architectural obstacles.**

***Index Terms*—Cultural Heritage, Environment, IoT, LoRa, Network, PLR, Sensors**

I. INTRODUCTION

Cultural heritage sites, including museums, archives, monuments, and archaeological areas, are highly sensitive to environmental conditions [1], [2]. Uncontrolled fluctuations in temperature, humidity, light, and air quality can accelerate deterioration processes, causing potentially irreversible damage to artworks and historical structures [3]. For this reason, preventive conservation focuses on carefully monitoring the environment to keep stable conditions around valuable artifacts. Traditionally, such monitoring has been conducted through periodic manual readings or standalone data loggers, but this approach is complex and often fails to capture rapid or small fluctuations in real time [3], [4]. Furthermore, many heritage buildings and sites pose challenges for conventional wired or Wi-Fi sensor systems: upgrading old structures with network cables can be invasive, and Wi-Fi coverage may be unreliable in buildings with thick walls or in underground storage areas. Additionally, the high power consumption requires frequent battery changes [5], [6].

In recent years, the concept of the Internet of Things (IoT) has opened up new opportunities to safeguard cultural heritage through real-time wireless sensing [7]. Among IoT wireless technologies, LoRaWAN (Long Range Wide Area Network) has gained attention for monitoring museums and heritage sites due to its long transmission range, strong signal penetration, and energy efficiency [8]. LoRaWAN operates in unlicensed sub-GHz bands and supports battery-powered sensors with multi-year lifespans. This makes it ideal for installations in historic buildings, where access to power and network infrastructure is limited. For example, in [8] the authors demonstrated that LoRaWAN could reliably cover aproximately 5,600 m^2 of a museum storage facility. It outperformed seven other wireless protocols, including Wi-Fi and Zigbee, in terms of communication performance. Their testbed showed that LoRaWAN maintained a high packet delivery ratio when scaled up to a 500-node network, indicating its excellent scalability for large-scale sensor deployments.

Several recent studies have reported effective uses of LoRaWAN WSNs in this field. In [3] the authors proposed a LoRaWAN-based sensor system to monitor temperature, humidity, and structural parameters in a historical masonry building. After collecting data for over six months, they discovered strong correlations between environmental fluctuations and structural responses, and demonstrated how real-time remote monitoring can inform the preventive maintenance of heritage structures. In [9] the authors developed a LoRaWAN-based solution for monitoring wood moisture in heritage buildings as an early warning against deterioration. Their system combined custom moisture sensors with LoRa modules and a cloud backend, and proved capable of penetrating the thick walls of antique wooden buildings while operating on low power. Other studies from the literature have proposed LoRaWAN to track environmental factors such as light exposure, air pollutants, and vibrations in museums and archives, with the goal of safeguarding artworks through environmental measurements [3], [10].

Although several measurement systems have been proposed in the literature for the monitoring of cultural heritage sites, most of them are tailored to specific environments, such as indoor spaces like museums or archival storage. They often do not address scenarios that involve multiple types of environments simultaneously, particularly those that combine both outdoor and indoor heritage sites.

Moreover, in [3], [9] the authors provided no information about the power consumption of the peripheral nodes and the estimated lifetime. Conversely, the paper [11] proposed an architecture devised for monitoring cultural heritage, reporting

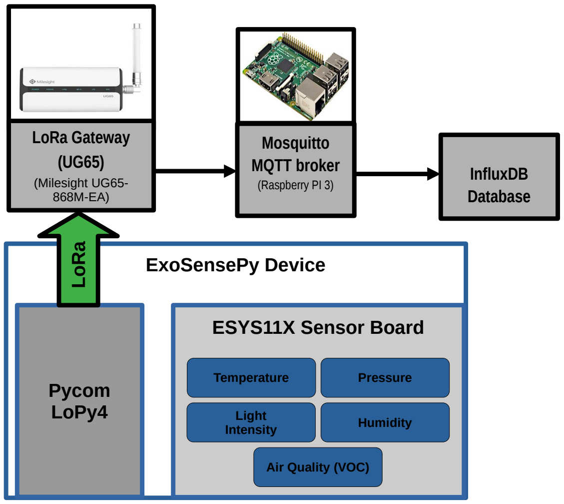

Fig. 1. WSN architecture based on SferaLabs ExoSensePy nodes.

the power consumption values. However, these data were related to a LoRa microcontroller not integrated to a separated sensor board and, thus, able to measure only temperature and humidity.

In this paper, we propose a scalable LoRaWAN-based environmental monitoring system for both indoor and outdoor heritage scenarios. The system relies on modular ExoSensePy sensor nodes, compact IoT devices equipped with a set of environmental sensors and integrated LoRaWAN connectivity. The network architecture is meant to be scalable and can be easily adapted to monitor various environmental parameters as needed for different cultural heritage contexts. The system was validated through real-world field trials conducted in both indoor museum settings and outdoor heritage environments. The experimental results demonstrate reliable communication indoors, with packet loss rates below 3 % even through thick museum walls, and also the outdoor deployment achieved acceptable performance. The paper provides an estimation of the node lifetime.

The paper is organized as follows. Section II presents the LoRaWAN network architecture, including a detailed description of the hardware components. Section III outlines the methodology adopted for the onsite testing of the network in both indoor and outdoor scenarios and reports the main results obtained. Finally, Section IV provides concluding remarks.

II. SYSTEM ARCHITECTURE AND COMPONENTS

The proposed LoRaWAN-based Environmental Sensing System is based on the SferaLabs ExoSensePy multi-sensor node, a flexible platform developed by SferaLabs [12]. The wireless sensor network (WSN) architecture is illustrated in Fig. 1.

The ExoSensePy device combines two primary components: the ESYS11X sensor board [13] and the LoPy4 communication board [14].

TABLE I
RESOLUTION AND MEASUREMENT UNCERTAINTY OF THE SENSORS MOUNTED ON ESYS11X BOARD

	Sensor	Resolution	Uncertainty
Brightness	OPT3001	0.01 lx	0.2 %
Temperature	BME680	0.01 °C	± 1.0 °C
Humidity	BME680	0.008 %rh	± 3 %rh
Pressure	BME680	0.18 Pa	± 0.6 hPa
IAQ	BME680	1	3

The ESYS11X board incorporates multiple environmental sensors, including a Bosch BME680 [15] capable of measuring temperature, relative humidity (%rh), pressure and indoor air quality (IAQ), and a Texas Instruments OPT3001 [16] capable of measuring ambient brightness.

According to [15], BME680 estimates air quality by means of a sensitive layer that reacts by adsorption to most volatile organic compounds (VOCs) as well as to other air contaminants. Typically, an increase of VOC concentration lowers a physical quantity known as gas resistance. A software determines IAQ in function of the raw value of gas resistance measured by BME680, taking into account also other parameters (e.g., the humidity level). AIQ ranges between 0 (clean air) to 500 (heavily polluted air). The sensors specifications in terms of resolution and measurement uncertainty are reported in Table I.

The ESYS11X board also supports digital I/O, I2C and Wiegand protocols, RS-485 serial communication, environmental noise sensors, a buzzer for acoustic feedback, optional modules for real-time clock and earthquake detection and a PIR sensor.

The LoPy4 module, produced by PyCom, is based on the Espressif ESP32 chipset, a dual-core microcontroller operating up to 240 MHz with hardware floating-point acceleration. It supports multiple wireless protocols including Wi-Fi, Bluetooth, SigFox, and LoRa [17], [18], and provides serial communication interfaces (UART, SPI, I2C), 12-bit ADCs, analog inputs, GPIO pins, microSD card access, and DMA for all peripherals.

The LoPy4 has been programmed to read data produced by the 6 different sensors available on ESYS11X board. Data values were encapsulated into a message using the following syntax:

```
ID[seqid]C1[d1]C2[d2]...Cn[dn]
```

where `seqid` is a sequence number that uniquely identifies the message, `C` represents the character identifier for each sensor, and `d` corresponds to the data value obtained from the respective sensor.

The gateway used in the architecture is the Milesight UG65-868M-EA [19] (hereinafter UG65), which supports LoRaWAN, IEEE 802.11 (Wi-Fi) and Ethernet connections, enabling integration within a local network. The UG65 gateway was configured to forward incoming LoRaWAN messages to an MQTT broker hosted on a Raspberry Pi 3 [20], [21]. Upon receiving a message from an ExoSensePy node, the broker triggers an event handled by a Python script running on the Raspberry Pi. This script parses the message and publishes the corresponding sensor data as individual MQTT topics. Each topic includes the unique identifier of the originating node.

Sensor data are then stored in an InfluxDB time-series database running on a commercial laptop. Data are written into a dedicated bucket. Every time a topic is published or updated, the MQTT broker (Mosquitto on Raspberry Pi) sends a notification to the Telegraf Input Plugin, which retrieves the payload and stores it in the appropriate InfluxDB bucket.

III. EXPERIMENTAL RESULTS

A. PLR measurements

The firmware running on the ExoSensePy node was configured to acquire five environmental parameters using the onboard sensors of the ESYS11X board, i.e., brightness, pressure, temperature, humidity, and indoor air quality (IAQ). Measurements were performed every $T = 30$ s (hereinafter, we refer to T as the transmission time). Each data sample was serialized into a 74-byte payload and transmitted to the Milesight UG65 gateway using LoRa packets. For each trial, $n_{tx} = 200$ packets were transmitted. The goal of these trials was twofold: to monitor the evolution of the measured environmental parameters over time in different deployment locations, and to evaluate the reliability of the LoRa communication link by computing the Packet Loss Rate (PLR). The PLR related to a sensor node was calculated using the following expression:

$$\text{PLR} = 1 - \frac{n_{rx}}{n_{tx}} = 1 - \frac{\text{\#packets received by UG65}}{\text{\#packets sent by ExoSensePy node}} \tag{1}$$

All trials were conducted with Adaptive Data Rate (ADR) enabled on both the ExoSensePy node and the UG65 gateway. ADR is an optional LoRaWAN feature that dynamically adjusts parameters such as spreading factor and transmission power to optimize energy consumption while maintaining reliable connectivity.

The experimental testbed is illustrated in Fig. 2. The ExoSensePy node was powered by a 10,000 mAh battery pack. Since the ESYS11X board requires a 12 V power supply and the battery outputs only 5 V via USB, a 5 V to 12 V converter was used.

On-field tests were carried out in San Marco d'Alunzio, Italy. This small village has a long history dating back to ancient Roman times. Today, it hosts several culturally significant sites, including the Temple of Hercules, historic churches, and the Byzantine and Norman Figurative Arts Museum. The location is particularly suitable for testing purposes, as it provides both indoor and outdoor cultural heritage scenarios. Five trials were carried out in various spatial configurations:

1) In the first trial (A), the ExoSensePy node was positioned near the Temple of Hercules, at a distance of 236 m from the Byzantine and Norman Figurative Arts Museum, where the UG65 gateway was located. The transmission path was non-line-of-sight (see Fig. 3).

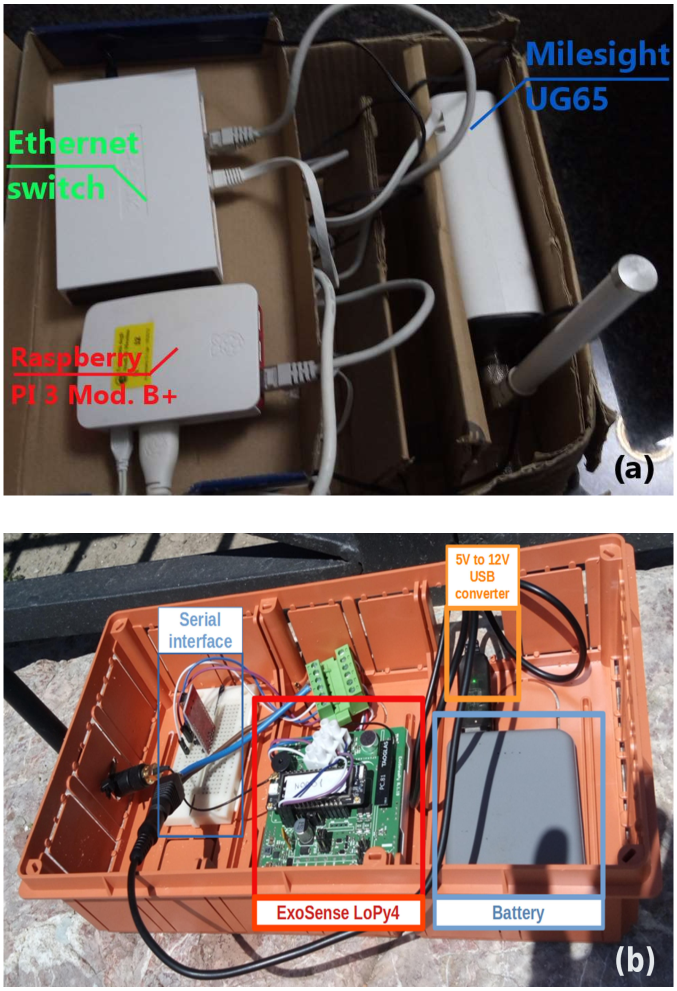

Fig. 2. Hardware used during the test campaign: (a) UG65 gateway, ethernet switch, and the Raspberry PI; (b) SferaLabs sensor node powered by a battery pack using a 5 V to 12 V USB converter.

2) The second trial (B) placed the node on the ground floor of the museum, almost vertically aligned with the UG65 gateway installed on the first floor.
3) In the third trial (C), the node was deployed in the first floor, in a different room from the gateway. The distance from the gateway was approximately 9.2 m.
4) The fourth trial (D) involved placing the node in another exhibition room, also on the first floor, at a distance of about 6 m from the UG65 gateway.
5) In the fifth and final trial (E), the ExoSensePy node was located in the museum archive in the second floor.

Table II summarizes the results of the five field trials conducted in San Marco d'Alunzio. Each row reports the node-gateway distance, the PLR, two indicators of signal quality (RSSI and SNR), and the physical quantities measured by each ExoSensePy node: brightness, temperature, humidity, pressure, and the IAQ. All these measures were calculated averaging the n_{rx} values which were successfully received by UG65 from each node.

Trial A, conducted near the Temple of Hercules (236 m

Fig. 3. Map of San Marco d'Alunzio with the Temple of Hercules and the Byzantine and Norman Figurative Arts Museum.

TABLE II
PLR AND ENVIRONMENTAL PARAMETERS MEASURED DURING THE FIVE TRIALS

Trial	Location	Distance (m)	PLR (%)	Average RSSI (dBm)	Average SNR (dB)	Brightness (lx)	Temperature (°C)	Humidity (%rh)	Pressure (hPa)	IAQ
A	Temple of Hercules	236	27.0	-109.80	3.36	2923.7	25.4	49.2	977.9	317.9
B	Museum (ground floor)	n.a.	3.0	-103.39	9.14	134.0	20.3	84.5	972.9	394.8
C1	Museum (1st floor)	9.2	0.0	-79.30	12.55	393.3	22.9	82.3	972.0	403.7
C2	Museum (1st floor)	6.0	0.0	-83.04	12.38	37.9	24.6	75.9	971.8	371.3
D	Museum (2nd floor)	n.a.	0.0	-56.69	12.83	257.3	27.0	71.8	971.1	385.5

TABLE III
POWER MEASUREMENTS

Transmission time T (s)	Energy consumption E (mWh)	Average power consumption P_{avg} (mW)	Expected lifetime $t_{lifetime}$ (h)	#Packets transmitted	PLR (%)
20	124.5	249	237.75	90	0.00
45	116.5	233	254.08	40	0.00

from the museum), showed the highest PLR at 27 %, likely due to the non-line-of-sight configuration and obstacles such as buildings between the node and the gateway. Despite Adaptive Data Rate (ADR) being enabled, signal degradation led to a significant number of lost packets. This trial also recorded the highest average brightness value (2923.7 lx), consistent with it being the only trial performed outdoors.

Trial B took place indoors, on the ground floor of the museum. It showed a PLR of just 3 %, and much lower brightness and temperature values, while the humidity value increased significantly compared to the outdoor test. These results reflect the expected environmental differences between indoor and outdoor settings.

Trials C1 and C2 were both conducted on the first floor of the museum, with the ExoSensePy node placed within a few meters of the UG65 gateway. In both cases, the PLR was 0 %, demonstrating robust communication when the node is in close proximity to the gateway and within the same floor. The marked difference in brightness between the two trials (393.3 lx vs. 37.9 lx) is explained by the presence of artificial lighting during Trial C1.

Trial D was conducted on the second floor into the museum archive, with the gateway located one floor below. Despite the vertical separation, the PLR remained 0 %, indicating strong signal propagation through the building structure. The environmental conditions in this location led to the highest recorded average temperature (27.0 °C) among the five trials.

B. Power consumption

A second experiment was performed, aimed to measure the average power consumption and the expected lifetime of a ExoSensePy node when it is powered by a power source whose capacity C is known a-priori.

Two trials were carried out, aimed to reproduce conditions similar to those described in Sec. III-A.

The ExoSensePy peripheral node was placed at a distance of 5 m from the UG65 gateway. The duration of each trial (i.e., the testing time $T_{testing}$) was 30 minutes (1800 s).

During both the trials, the ExoSensePy node was powered by a Varta 57978 USB powerbank. According to the specifications reported in [22], the nominal capacity of this device with a voltage of 5 V is 11840 mAh (thus, the energy provided by the device is no less than $E_{batt} = 59200$ mWh). A 5 V to 12 V converter was used to power the ESYS11X board.

The node acquired from the ESYS11X board the environmental measures related to brightness, pressure, temperature, humidity, and IAQ. The measures were encapsulated into a payload of 74 bytes and transmitted to UG65 using LoRa packets every T seconds. The transmission time T during the first and second trial was set to 20 s and 45 s, respectively. ADR was enabled during both the trials.

At the end of the testing time, the overall energy consumption E of the peripheral node was measured using a KEWEISI KWS-1902C USB Tester [23].

The average power consumption during the testing time (measured in mW) was calculated using the formula:

$$P_{avg} = \frac{E}{T_{testing}} \tag{2}$$

The expected lifetime of a ExoSensePy node (in hours) was calculated using the formula:

$$t_{lifetime} = \frac{E_{batt}}{P_{avg}} \tag{3}$$

where, E_{batt} is the minimum energy provided by the powerbank, measured in mWh, calculated by multiplying the battery voltage (V) by the nominal capacity (mAh).

The power measures acquired during the trials are shown in Tab. III. The experimental results demonstrated that the Varta 57978 USB battery pack guarantees about 10 days of lifetime. Moreover, in both the trials the measured PLR was 0% (no packet loss), as the distance between UG65 and the ExoSensePy node was very short (5 m).

In both the cases, the power consumption of the ExoSensePy node was lower than 250 mW, thus leading to the conclusion that integrating the battery pack with a small 500 mW solar panel (e.g., the panel in [24] whose size is only 55 mm × 70 mm) would guarantee an endless lifetime. More details about power consumption will be provided in an extended paper.

It is worth noting that increasing the transmission time T determines only a slight increase of the expected lifetime. This indicates that the contribute of the LoRa transmitter to the testbed energy consumption is marginal. The energy is mainly consumed by the LoPy4 node and by the ESYS11X sensor board.

IV. CONCLUSIONS

This study evaluated the performance and radio coverage of a LoRaWAN-based wireless sensor network architecture developed for cultural heritage sites monitoring. The system is based on ExoSensePy sensor nodes and was tested in real deployment conditions at the Temple of Hercules and the Byzantine and Norman Figurative Arts Museum in San Marco d'Alunzio. Experimental trials demonstrated that indoor communication performance was consistently reliable. PLR of 3 % or lower were observed even when the UG65 gateway and ExoSensePy nodes were located in different rooms and on different floors. These results confirm the effectiveness of LoRaWAN in complex indoor environments with architectural barriers. In contrast, the outdoor scenario showed a higher PLR of 27 %, despite the use of ADR. This was attributed to non-line-of-sight conditions and the presence of obstacles, such as buildings, between the transmitter and receiver. The outdoor trial involved a node positioned near the Temple of Hercules and the UG65 gateway placed indoors on the first floor of the museum. To address the limitations observed in outdoor conditions, several improvement strategies are currently under investigation. These include the use of antennas with higher gain and the adjustment of LoRa parameters, such as the Code Rate (CR), to increase redundancy and enhance communication robustness. A potential direction for future work is the adoption of more efficient Medium Access Control (MAC) protocols, which can optimize channel utilization and reduce collisions, thereby improving overall network performance [25].

ACKNOWLEDGMENT

This work has been partially funded by European Union (NextGeneration EU), through the MUR-PNRR project SAMOTHRACE (ECS00000022).

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