An energy-efficient internet of things (IoT) architecture for preventive conservation of cultural heritage

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HIGHLIGHTS

- IoT architecture proposal specific for Heritage Preservation need.
- Sensor node life-span of 20 years without battery replacement.
- Wireless technology based on subGHz bands capable of passing through tick walls.
- Stand-alone sensor based on Sigfox for direct connection to the cloud.
- Evaluation done for typical RH and temperature monitoring needs and based on Italian, European and American standards.
- All kind of artwork containers covered: single isolated artwork, typical artwork containers (museums, churches, etc.), power supply constrained sites (open-air archaeological sites, etc.).

ARTICLE INFO

ABSTRACT

Internet of Things (IoT) technologies can facilitate the preventive conservation of cultural heritage (CH) by enabling the management of data collected from electronic sensors. This work presents an IoT architecture for this purpose. Firstly, we discuss the requirements from the artwork standpoint, data acquisition, cloud processing and data visualization to the end user. The results presented in this work focuses on the most critical aspect of the architecture, which are the sensor nodes. We designed a solution based on LoRa and Sigfox technologies to produce the minimum impact in the artwork, achieving a lifespan of more than 10 years. The solution will be capable of scaling the processing and storage resources, deployed either in a public or on-premise cloud, embedding complex predictive models. This combination of technologies can cope with different types of cultural heritage environments.

1. Introduction

Modern societies tend towards a globalized world with many challenges. One priority is to defend and promote the particular aspects of native cultures in each region and country. Culture is expressed in multiple ways such as art, linguistic aspects or architecture. Cultural Heritage (CH) has an important value that must be promoted and safeguarded for future generations, because the deterioration or destruction of artworks is a serious loss that cannot be recovered in many cases. Also, CH is a source of wealth as it promotes tourism, creative art and native culture. Millions of tourists choose their destination every year based on the artistic and cultural interest of the places visited, such as monuments, museums, exhibitions, historical villages, ruins, etc.

The protection and conservation of CH is an issue of particular interest because every artwork undergoes certain deterioration with time. Such degradation depends on the type of material, the action of external weather conditions and human factors. The ideal is to keep artworks under stable and controlled climatic scenarios, which should be properly monitored and registered, but such conditions are often achieved only in museums.

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The use of controlled atmospheres can be necessary in some cases in order to avoid oxidation (e.g., the Turin Shroud or the US Declaration of Independence). Light-sensitive artworks also require special environments. Nevertheless, in most cases, reasonable conditions are achieved with an appropriate control of temperature and relative humidity (RH) [1]. As a previous step for deciding the best alternative for a microclimate control system, it is necessary to record and monitor the ambient conditions around artworks, particularly in the case of historical buildings. This approach is useful to assess deterioration risks and evaluate the susceptibility of any artworks kept in these places.

As the effects of ambient conditions on a given artwork are cumulative, it is necessary to record real-time measurements in order to detect as soon as possible unexpected harmful events or dangerous conditions, particularly in those places with risk of vandalism, robberies or accidents (e.g. water leaks), the on-line control of artworks would improve it safety and preventive conservation.

Remote monitoring of factors affecting the conservation state of artworks may improve their long-term preservation and promote the value and enjoyment of CH for future generations. According to the current technology, remote monitoring is mainly based on the Internet of Things (IoT) paradigm, where a "thing" could be any type of artwork. An IoT approach for art conservation would involve the installation of small sensor nodes and gateways for data transfer to the cloud. The application of this IoT approach would allow on-line monitoring and continuous supervision of individual pieces, given the easy access from the cloud to data recorded from electronic sensors, improving its safety and preventive conservation.

Such systems would optimize resources and avoid expensive in-situ installations, allowing massive supervision of artefacts contained in museums, historical buildings, open-air archaeological sites, etc. Monitoring these conditions would allow a precise diagnosis of the key factors affecting art displays. This information is useful for restorers and curators in order to identify the zones or items with the highest deterioration risk, as well as to decide any actions to be implemented.

A team formed by experts in art restoration, climate monitoring, statistics, wireless technology, and cloud data processing from the UPV (Universitat Politècnica de València) has launched a project aimed at developing an IoT for CH. The multidisciplinary research team involved in the present research work has experience in microclimate monitoring of open-air sites like the ruins of Pompeii [2,3].

In most cases, given the particular requirements for the preventive conservation of pieces, it is necessary to design specific nodes for data transmission that should be able to efficiently monitor climatic conditions without for short-term maintenance. Therefore, the most critical issue for an IoT approach in CH is the appropriate design of nodes regarding power consumption and communication distances.

The typical IoT systems based on the ISM (Industrial, Scientific and Medical) band at 2.4 GHz are usually developed using available technology, but it cannot be applied to this context given the peculiarity of the sites to be monitored (i.e., thick walls, considerable distances, etc.). It is therefore necessary to apply particular technologies to be able to cope with these problems. The ITACA Institute has experience in the design of ultra-low power consumption miniaturized wireless sensors which have been successfully applied to recording conditions in buildings and wooden materials by means of hidden nodes; overcoming the above-mentioned adverse situations.

As the ideal technical solution does not yet exist, one of the targets of the present work was to develop and compare the our custom previous design and two leading options: LoRa [4] and

Sigfox [5]. Both LoRa and Sigfox are LPWAN (Low-power Wide-area networks) commercial designs for wireless sensorization which are being extensively used for the paradigm of smart cities. These proposals use the European ISM bands of 433 MHz and 868 MHz, and they have provided the best results in previous projects of our research group, hence, they were considered to develop our solution.

The different types of nodes evaluated in the present work span different environments for art conservation. The problems arising from an art display (or archaeological excavation, church, museum, etc.) with an electric power supply and Internet connection are different compared with isolated pieces, for example a statue in the middle of a city; and different to sites without power supply (archaeological excavation, isolated church, etc.). Such different scenarios are represented in Fig. 1, including our proposals discussed later.

In order to assess the performance of our proposal, the scenario elected was the Church of Santo Tomàs y San Felipe Neri in Valencia (Spain). Preliminary tests on the nodes' wireless operations were carried out at this Church and proved to be satisfactory. Then we evaluated the power requirements of the nodes for a standard monitoring problem of air temperature and humidity. As discussed below, the results suggest that it is possible to create a node with a life-span of more than 10 years using standard batteries.

Also, we designed a appropriate cloud infrastructure to deal with CH monitoring requirements. The proposal is based on criteria such as scalability, ease of deployment, openness and flexibility.

The article is structured as follows; the second section presents the related work of previous studies, detailing several examples. In the third section, we summarize the ideal requirements for an IoT for CH implementation. The fourth section describes in detail the proposed IoT solution for CH implementation. The fifth section is focused on assessing the performance of the proposed node from the point of view of radio communications and energy requirements. Finally, the main conclusions and future work are presented in Section 6.

2. Related work

Microclimatic control of museums is quite simple and effective; for example, in a room with paintings on canvas, the requirement is to ensure constant air temperature and humidity throughout the year, with the minimum daily and seasonal oscillations. But if pieces exhibited inside the room are made of different materials, microclimatic control is more complex, given the requirement to achieve specific conditions for certain art displays. In many cases, artworks are protected by hermetic display cases with a confined mass of air that may undergo dramatic RH changes in case of sudden temperature variations. Such oscillations could be extremely harmful for certain art series (e.g., paper is sensitive to relative humidity (RH) changes, though they can be attenuated by using inert buffering agents like silica gel).

In complex cases, pieces are kept under conditions between the most unfavourable case (i.e., open-air archaeological sites) and the optimum situation of a controlled environment in a museum [6]. Such intermediate situations corresponds for example to religious buildings, where the direct action of wind, rain or solar radiation is prevented, but generally it is not possible to control the hydro-climatic conditions [7–10]. Sometimes, it is even possible to deal with problems of rain leaks or condensation. In such cases, the monitoring of microclimatic conditions is important to assess the deterioration risks and to decide corrective actions.

In this context, it is important to monitor air temperature and RH in the long term to evaluate the state of conservation and assess the artwork vulnerability. In the short term, on-line monitoring can detect sudden unexpected situations that should be corrected
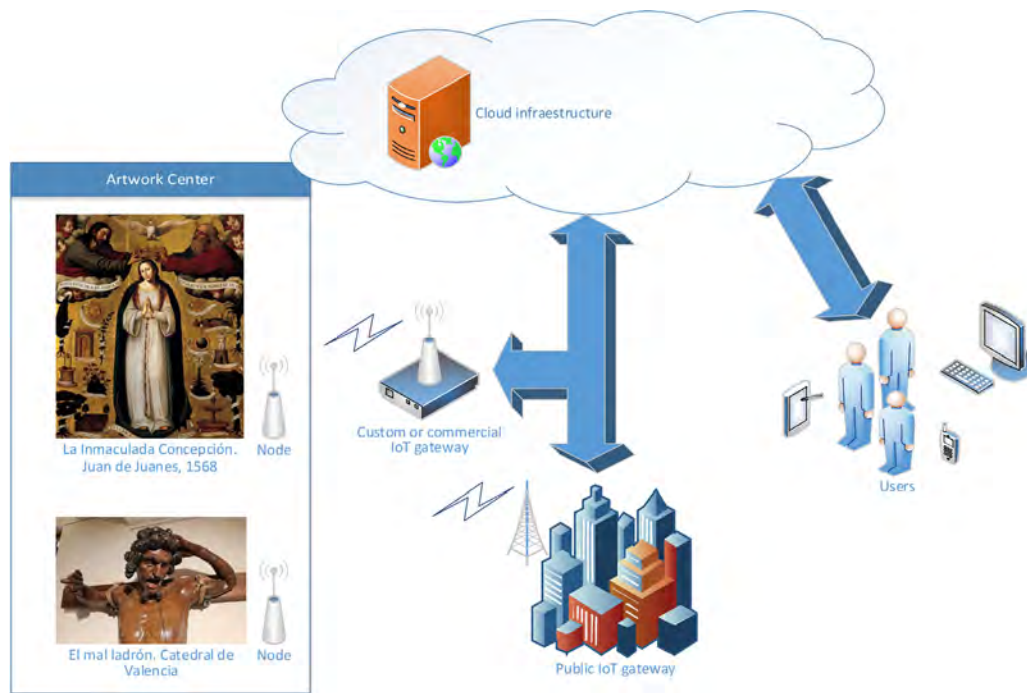
Fig. 1. IoT for CH diagram with different types of scenarios and gateways.

immediately to avoid damage. Hence, microclimate monitoring systems are necessary to develop preventive conservation plans in museums and cultural sites, together with other routine practises like visual inspection, maintenance, control of visitors, etc. [11]. Long-term monitoring is a key issue according to the new requirements for preventive conservation [6].

2.1. Electronic sensing techniques

There are different types of installation systems for microclimatic monitoring. One approach is based on the use of wired sensors, which are typical in industry and domotic, but not in CH monitoring. Such systems are relatively simple, robust, and exhibit minimum maintenance, as no battery replacement is required. Sensors can be complex because power supply can be provided through the wires and data can be transmitted back. It is possible to monitor an array of sensors by means of a centralized computer that records all the data, the sampling rate can be modified easily without serious limitations (e.g., one measurement per hour or per second), etc. The main disadvantage is the wiring installation, which can be a serious problem in large spaces or open-air sites where the wiring can be affected by the action of climatic agents, or when the wires cause aesthetic problems.

Wired systems are ideal in museums or temporary exhibitions when it is required to record ambient conditions inside display cases, or in different rooms. Such systems provide alarms in case of unexpected conditions, i.e., when the parameters are out of a pre-established range.

Another advantage of wired solutions is the off-line control for preventive conservation, which means that the recorded data are downloaded to a computer and analysed from time to time (e.g. every few months or at the end of the temporary exhibition) to assess conservation conditions.

The present research group developed in 2007 [12,13] a wired installation for the microclimate monitoring of the valuable fresco paintings discovered on the ceiling over the main chapel at the Cathedral of Valencia. Fig. 2 shows part of these paintings. Restorers placed wires carefully following the outlines of the figures, so

that they remain practically invisible. The total wire length was more than one kilometre. During the restoration process of these frescoes, certain humidity problems were detected at particular points caused by infiltration of rainwater from the upper roof. In order to monitor this problem after the restoration work, thermohygrometric probes were inserted inside the layer of plaster supporting the frescoes and at several points of the cornice (29 probes in total). Each probe comprised a temperature sensor and RH sensor. Data from all the wired probes were recorded in a computer with a sampling frequency of one datum per hour. Three periods were monitored: February–November 2007, January–December 2008, and February–December 2010.

This system would also have allowed on-line microclimatic monitoring. Nevertheless, the study was focused on off-line data analysis, given the pioneering aspect of the research and because it was not possible to establish beforehand the criteria for alarm signals. A multivariate statistical analysis of the recorded data [12,13] allowed the characterization of differences among sensors, and it turned out that higher RH values were recorded in those zones with deterioration due to rain leaks.

Another approach for artwork monitoring is the use of commercial dataloggers [14,15], which are autonomous devices powered by batteries with the advantages of being easy to install, wire-free, and small. The main disadvantage is their limited data storage, the use of batteries with a certain lifespan, and the recorded data need to be manually downloaded from each datalogger. With a sampling rate of one datum per hour, which is adequate in many cases [6], dataloggers can work autonomously between 6 and 12 months [2,3].

In a previous work performed in 2010, 10 autonomous hygrometric probes with temperature and humidity sensors were installed at the Roman ruins in Plaza de L'Almoina (Valencia, Spain) [16]. Two monitoring campaigns were carried out with a frequency of one datum every thirty minutes in 2010 [16] and 2013 [17]. The statistical data analysis characterized the differences between both campaigns and identified harmful environmental variations. In this context it would be of interest to have real-time wireless sensors able to give warning signals in case of abnormal conditions and switch on the air-conditioning system.

Fig. 2. Renaissance frescoes decorating the vault of the main chapel of the Cathedral of Valencia (Spain).

Fig. 3. Dataloggers (small black pieces) mounted at Ariadnas house at Pompeii (Italy).

In 2008, a similar type of system was installed at Ariadna's house in Pompeii (Italy) (see Fig. 3), which is characterized by a semi-confined environment since two rooms are covered by a roof which protects against the rain. A total of 26 probes were installed in four rooms for 372 days with a sampling rate of one measurement every thirty minutes. The main problem was in travelling from Valencia to Pompeii a total of 12 times to download the data. This system detected high temperature peaks in summer when the sun shone directly onto the transparent roof [2], which urged the authorities to implement corrective actions in 2009, placing an opaque roof in one of the rooms. Between June and September 2010, further data were obtained to check the efficiency of this new roof [3].

In this reported study carried out in Pompeii, sensors were installed at different heights on the same wall in order to assess differences in the measurements. In such cases, when the aim is to detect small variations between individual sensors, it is necessary to calibrate correctly the nodes and to apply multivariate statistical techniques for data analysis, which are powerful to characterize the differences among sensors [2,3,16–19].

In this particular case, the use of wireless sensors for on-line monitoring would have allowed a direct access to the information from anywhere in the world, which would be of special interest in world-famous sites. However, as the environment is semi-confined, it is difficult to adopt corrective actions when the monitored parameters are not in the appropriate range.

Some authors [6] have proposed both wired and wireless systems given their advantages and disadvantages. In any case, the complexity of the installation and the inconvenience of data downloading makes it difficult to achieve the real objective, which is to preserve the cultural heritage by appropriately splitting the work between restorers and those responsible for the installation.

Given the technological evolution undergone in recent years in the field of IoT and cloud computing, new perspectives appear with respect to wireless microclimate monitoring of artefacts. The approach proposed in this work is based on microelectronic wireless systems of great autonomy able to record sensor data and to transfer them wirelessly, so that measurements can be processed or downloaded on-line by means of a computer connected to Internet or a mobile telephone. Apart from avoiding wiring, the main advantage is the possibility to access the data in real time, which allows the detection of abnormal situations that require urgent action.

2.2. IoT and heritage

Given the current enormous competition in the market that supplies products for the so-called IoT [20,21] and the development of cloud computing, their application for preventive conservation of artworks is justified. Our research team has participated in several scientific projects related with cloud computing [22] that could be translated to this context.

Our group has experience in the development of wireless sensor networks which have been applied satisfactorily for the monitoring of air conditions [23] and the wireless monitoring of wooden structures [24]. Such systems have turned out to be efficient for assessing the conservation conditions of wooden pieces such as altarpieces or carvings. Thanks to the autonomy achieved, the devices can work continuously for more than a decade without battery replacement, which notably reduces maintenance and the impact on artworks.

The IoT paradigm applied to different CH needs is complementary to other information technologies (IT). In this context, the "smart city" concept becomes straightforward in a wide approach, from art monitoring and management to embedded experiences in Smart Tourism Destinations [25–27].

An IoT architecture has been proposed [28] able to support the development of a smart museum. This reported work transforms a static cultural space into an intelligent one by setting up a model of services and sensors which enhances the user experience. Nodes based on technologies such as RFID (Radio Frequency Identification) and Bluetooth Smart were embedded in the artworks in order to allow interaction with visitors through their smartphones, providing an enhanced experience. Additionally, humidity and temperature sensors were also included in the nodes for microclimate monitoring. From preservation stand point, one drawback of this proposal is the use of energy-demanding nodes and inefficient RF technologies (WiFi) which are not appropriate for long-term maintenance-free monitoring.

The deployment of efficient sensor nodes in archaeological sites, cathedrals or open areas is not straightforward. Sensor nodes use RF to transmit information that has to travel relatively long distances and/or pass through thick walls, moreover, the energy requirements must be kept low to give the nodes a long life-span.

Most typical standards for the development of wireless sensor networks (Bluetooth, WiFi, Zigbee, 6LowPan, etc.) use the RF band of 2.4 GHz or 5 GHz. Both bands exhibits troubles in case of long distances, thick walls and low power requirements. For example, [29] proposes an interesting monitoring system for the Mosque–Cathedral of Cordoba (Spain) based on open-source hardware sensor nodes. In this experience, the application of wireless communication technologies was unpractical due to the thick walls, forcing the use of local data storage in each node and the subsequent manually download of data. Most similar approaches [30,31] use this RF band for heritage monitoring.

Our practical experience in developing ultra-low power embedded systems for wireless sensor networks showed us that subGHz bands are the best for these scenarios. In a previous research [24] we designed an ultra-low power sensor node appropriate for heritage building monitoring. This node was initially designed for monitoring the equilibrium moisture content in wood and the detection of termites [32]. The node uses the 868 MHz band in order to deal with thick solid materials, and the communication range turned out to be adequate. From our point of view, the main drawback of our implementation is the lack of standard communication protocols, which restricts interoperability with other available products on the market, reducing its applicability.

CH monitoring can greatly benefit from the advances in technologies for smart city implementation. In this scenario, there is a need for low power wireless nodes for monitoring/controlling infrastructures, and these nodes tend to use subGHz bands, either licensed or unlicensed. Currently, there is strong competition to standardize protocols for the ISM band, which could benefit derived developments for CH applications.

3. Requirements analysis

Regarding the design of an IoT approach for CH microclimate monitoring, this section discusses the requirements of each aspect of the solution, starting with the measurement requirements, technical aspects of the node design, gateway design, cloud infrastructure and, finally, user interface.

3.1. Measurement requirements

It was decided to record temperature and RH parameters for our proposal of artworks monitoring. Taking into account the sensor accuracy, standard guidelines and other requirements, we decided the data acquisition interval (sampling rate).

Most widely used standards in CH are the Italian UNI10829:1999 [33], the European EN 15757:2010 [34] and the guidelines of ASHRAE (American Society of Heating, Air-Conditioning and Refrigerating Engineers) [35] guidelines. The Italian regulation UNI 10829:1999 specifies the hygrothermal ranges recommended for different types of materials. European standard EN 15757:2010 defines the concept of historical climate, i.e., climatic conditions to which an object has been subjected for a long period under acceptable conditions and to which it has acclimatized. This standard recommends to maintain the historical climate, especially as far as RH is concerned, if object remains in good condition. The ASHRAE guidelines establish five classes of quality control according to seasonal and daily temperature and RH fluctuations.

Based on these standards and a previous study [6], we decided to record one measure every hour in accordance with instrumental metrological characteristics recommended in EN 15758:2010. The accuracy of sensors used to measure air temperature was ± 0.5 °C in the range of measurement from -10 °C to $+85$ °C. Regarding relative humidity the accuracy was of $\pm 3\%$ in the range of measure from 10% to 95% in accordance with EN 16242:2012.

With respect to the need of sensor calibration, in certain cases the manufacturers calibration may be sufficient. If the manufacturers precision is inadequate which sometimes occurs, a calibration procedure must be performed before any experimental tests [12,13]. Regarding the RH sensors used in the present work, with aqueous solutions of two salts (lithium chloride and sodium chloride) may be performed according to the ASTME 104-02.

For the microclimate monitoring of large rooms, it may also be necessary to obtain vertical gradients that give rise to micro-flows of air that affect the state of conservation, e.g. on high church walls. In these cases the correct calibration of sensors is a key issue to detect small differences between individual sensors [2].

3.2. Node requirements

The most critical issue in a viable deployment for CH microclimate monitoring is the availability of electronic nodes able to record the physical parameters and to transmit information wirelessly.

These nodes should embedded in the artefact ensuring the lowest possible visual impact and without requiring the intervention of a technical specialist. The responsibility for the installation and, therefore, the intervention in the artwork should be the task of a preservation expert in order to ensure the best fit for the piece. Restorers and curators are experts in art conservation, but not in the area of electronics or computers, which means that the nodes should be simple to handle from the point of view of electronic technology and handling risks.

As working on a piece always involves a deterioration risk, it is necessary to use nodes with an extremely long life (tens of years) without any requirement for either maintenance or further handling of the piece.

Taking into account that our proposal is to monitor/act on individual artworks, it is desirable to develop low-cost nodes to facilitate their massive deployment. This means spending money on the rest of the IoT architecture (gateways, cloud, etc.).

From our experience in developing embedded systems, a critical requirement of the project is a node with a flexible and open design to keep up with the fast-changing scenario in the area of electronic sensors, radio modules, etc. An open design would simplify the addition of new sensors (for example, using I2C communications bus) or changing the radio subsystem using standard commercial modules.

In 2008 we developed an ultra-low power sensor node that complied with some of the requirements but lacked openness and flexibility in the radio part, so in cannot be offered as an interoperable design. One of the objectives of this work is to solve these issues by means of a new node design.

The CH environment restricts the use of widely accepted consumer-grade technologies for wireless transmission, such as Zigbee 3.0, Thread, WiFi or the recently approved Bluetooth 5, but they can be a plus for enhancing these deployments. The main problem is that transferring wireless data is expected to pose problems due to the thick walls and long distances. Typical inter-node communication protocols such as star, clustering and multi-hop would not perform correctly, given the particular characteristics of the environment. We evaluated such protocols in a previous work [24] and concluded that the use of intermediate nodes using clustering techniques can be effective, but such intermediate nodes should be developed using an infrastructure of gateways.

CH monitoring can greatly benefit from the advances in technologies for smart city implementation. In this scenario, there is a need for low-power wireless nodes for monitoring/controlling infrastructures, and these nodes tend to use subGHz bands, either licensed or unlicensed. Currently, there is strong competition to standardize protocols for the ISM band, which could benefit in the future derived developments for CH applications.

Short distance communication technologies such as RFID and NFC can be added for simplifying artwork identification and enhance user experience.

Summarizing, the requirements for the node design are:

- It should follow a modular design.

- The cost of individual nodes should be low.
- The node lifespan (including batteries) should be of tens of years without maintenance.
- No technical skills should be required for node installation.
- The RF band should be based on subGHz in order to cope with the environment requirements (thick walls, long distances, etc.).
- The data exchange should be encrypted to warrant privacy.
- It should ensure the minimal visual impact on the artwork.

3.3. Gateway requirements

Our previous experience in the development of monitoring systems showed us that the best option for node simplicity and power saving is the use of specially designed gateways able to collect data and redirect them directly to Internet; avoiding, if possible, the application of clustering or multi-hop techniques. The keep-it-simple principle provides the best experience in these cases.

Aimed at simplifying deployment and promoting its adoption, it is desirable to elect standard-based commercial gateways/routers, although there is a limited range of options in the IoT market nowadays.

It is also possible to use public gateways specially targeted for IoT designs. The most successful option in this area is probably the SigFox network [5], but fast changes are expected in this field in the near future due to the interest of mobile operators in IoT.

Finally, it is common in CH that the artwork container has a constrained power supply, which is often absent in open-air sites or isolated churches. Taking into account this limitation, the design of a specific gateway with very limited energy requirements is essential. As there are no options on the market for this case, a solution must be found that should be open enough to deal with both the fast-changing scenario of wireless communications and cloud computing platforms. Summarizing, requirements for the gateway design are:

- It should be based on IoT standards for promoting competitive prices.
- Public operators can be used for the IoT infrastructure.
- It should be able to deal with highly energy-constrained artwork environments (i.e. in case of lacking power supply).
- It should support fast-changing scenarios.

3.4. Cloud requirements

On-line monitoring the conditions of valuable pieces of art requires continuous data gathering and processing. As energy consumption of sensors must be low, intensive processing must take place elsewhere. Moreover, by gathering the proper information from multiple sensors, data analyses may be able to provide more accurate predictions. Cloud resources can achieve this computing capacity and cloud elasticity can provide the required energy content, even on the service-side.

The analysis and processing of data recorded from nodes and gateways as well as their visualization involves the following requirements for the cloud infrastructure.

The non-functional requirements are the following:

- It must enable the processing of both streamed and batch data gathered by the nodes and gateways.
- It should provide an efficient execution context for frameworks based on BigData such as MapReduce, Spark, STORM or DataTorrent RTS.

- It should provide data stores based on HDFS and NoSQL databases such as MongoDB. It should provide elasticity at the storage level, at least enabling new resources to be added on-demand. The resources deployed will be dynamically adjusted according the tasks in execution.

The functional requirements are the following:

- The architecture should be cloud agnostic, that is, compatible with different IaaS providers, both on-premise systems (e.g. openNebula, OpenStack) or public cloud providers (e.g. Azure, AWS).
- It must provide access to the information distributed over the archaeological site or artwork under monitoring, including an optimal way to query and fetch the relevant data from the data stores (e.g. MongoDB).
- It should facilitate the access to data visualization from client applications, providing standard Internet protocols.
- It must provide an open source solution and a property-based configuration mechanism to enable additional processes of components, and to specify the network port where the services provided by the framework listens for incoming requests.
- It must support secure access to the data stores.
- It must support secure access to database stores.
- It must support a simplified deployment mechanism consisting only of three steps: (i) adjust the configuration; (ii) deploy the infrastructure and configure the services; and (iii) run the services of the framework.

3.5. User-side requirements

Finally, a design premise for our CH IoT infrastructure was to enhance the clear separation of three end-user roles involved in this project, which are restorers, artwork administrators and scientists, by assigning different rights and functionalities to each category.

For all type of users, the requirements are the following:

- Users must be provided with web-based interfaces supported by as many browsers as possible.
- The design must provide a clear separation of the three end-user roles involved in this project, which are restorers, artwork administrators and scientists.
- It must deny access to a non-authenticated user, including data visualization.
- It must provide means to query metrics according to their dimensions (artwork piece, measurement, time...).
- It must provide the definition of customized alarms to trigger the execution of different kinds of actions (e.g. notifications, web hooks, processes...).
- It must support the exporting of data in different formats.
- It must be able to execute processes embedded on containers in the database.
- It should support both interactive (i.e. triggered by the user from the web interface) and batch periodic jobs (jobs that are executed on schedule such as model predictions or data aggregations).

The global requirements should be enhanced with user-specific requirements.

We are currently working an early web prototype definition (see Fig. 4) which only supports real-time representation of collected data, and download sensor data information and RF communications behaviour using a comma-separated values (CSV) format. This is sufficient for off-line analysis of data.
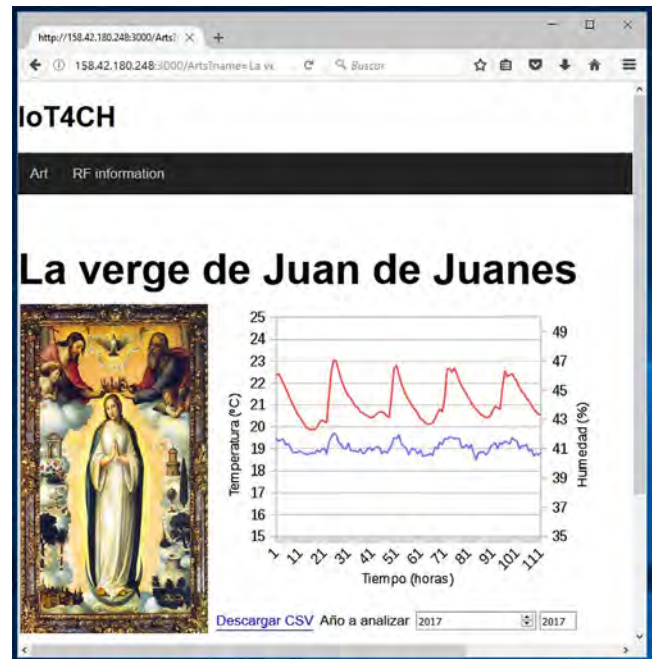

Fig. 4. Aspect of the current website prototype.

4. IoT for CH architecture proposal

Based on the requirements mentioned above, we designed an IoT architecture that fulfills them. In a typical IoT deployment [21] there are sensing/actuating nodes that communicate with the cloud infrastructure through gateways. These gateways are responsible to collect the data provided by nodes in custom format or using typical IoT formats such as MQTT [36], to adapt these data formats and transport them to the cloud infrastructure using an Internet connection which may be wired-based or GSM-based.

Collected data can be used for developing and executing predictive models which can anticipate the advent of a risky episode. For example, we could analyse the correlation of humidity and temperature variation with artwork degradation for all the pieces, and then build predictive models on the cloud that could forecast future damages, provide recommendations and the active specific protocols. In technical terms, the architecture will enable the execution of processes embedded in containers on the cloud consuming the data stored in the database (MongoDB), as defined in the requirements.

IoT deployments for CH has different needs compared with common applications as shown in Fig. 1, which tries to summarize the different scenarios. The key difference between common IoT deployment and one focused on CH preventive conservation is the node design (not unique) and the requirement for different types of gateways.

In an art display (or archaeological excavation, church, museum, etc.) provided with an electric power supply and Internet connection, the best solution is to use an IoT commercial gateway. This gateway can be maintained active to collect data from the local nodes installed in the artworks. If connection-less protocols are utilized, the nodes do not require to spend too much energy for their communication, thanks to the relative proximity of the gateway and given the simplicity of the communication algorithm. Redundant gateways can be utilized to better cover the area of interest, the cloud infrastructure being responsible for eliminating data duplicates. In the case of large artworks (e.g. an altarpiece)
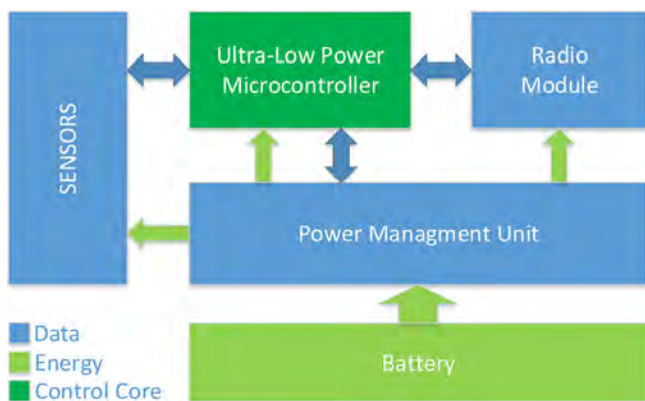
Fig. 5. Sensor node architecture.

or specific needs (e.g. a gas sensor), more than one sensor can be attached to the artwork.

For isolated pieces, for example a statue in the middle of a city, the best solution is to try to use a public IoT operator, provided that this service is available in the target country and area. For example, in Valencia (Spain), the Sigfox IoT provider has good coverage. Using Sigfox, it is feasible to develop an ultra-low power sensing node that transfers information directly to the cloud.

These two gateway types cannot cover open archaeological sites, or isolated churches, etc. In these cases, the main limiting factor is, often, the unavailability of power supply. To overdue this problem, we developed a prototype of open gateway architecture focused on dealing with energy-constrained environments and/or complex Internet connectivity.

The following subsections describe in detail each aspect about the proposed architecture.

4.1. Wireless node

For the node design, we fell back on our previous experience of building ultra-low power wireless nodes, updating the requirements and the lessons learned. The initial node design was based on a previous wireless node designed for Equilibrium Moisture Content (EMC) measurement and termite detection [24,32] shown in Fig. 6 left, which can be inserted into wood on artworks. This node has a lifespan of more than 10 years using an 1 Ah battery.

The same design principles were applied to the CH node. Fig. 5 shows a block diagram in which the main principle is the use of

loosely coupled blocks to facilitate node upgrading or adaptation (sensor types, battery technology and radio protocols). This is not an ideal design for massive market deployment, but it fits perfectly into the specification/evaluation phase.

Due to the highly constrained energy requirements it was not advisable to use general-purpose microprocessors for the node design. Thus, we opted to use an available ultra-low power microcontroller capable enough to support a wide variety of interfaces. Actually, the most microcontroller architecture for this purpose is the ARM Cortex-M due to its wide adoption.

From the point of view of energy consumption, a good starting point is to take a look at the ULPBench (ultra-low power benchmark) [37] ranking and to be wary of the manufacturers claims. In our case, we selected the STMicroelectronics STM32L4x, which has a good score, but we also relied on our wide experience with STM32 family given their good tools and support. This microcontroller has plenty of interfaces for sensor connection (I2C, SPI, AD, DA, etc.) and provides a set of programming libraries that simplify code development.

To decide the mos suitable RH and temperature sensors, we reviewed the market offer and selected the Sensirion SHT3x, which is a low-power sensor with an accuracy of $\pm 2\%$ for RH and $\pm 0.5 \,^{\circ}\mathrm{K}$ for temperature.

The radio-frequency (RF) part is the most complex and critical element of this type of node design, which should be kept separate from the main microcontroller to favour wireless part replacement/upgrading. Thus microcontrollers with embedded wireless or wireless modules with processing capabilities should be avoided.

As mentioned in Section 3.2, the RF band should be chosen in the subGHz frequencies in order to facilitate the signal propagation through thick obstacles. Typical 2.4 and 5 GHz ISM unlicensed bands do not perform well in these scenarios but are a perfect fit for consumer-level IoT products.

As we were using unlicensed bands, the available choice in Spain includes the ISM bands of 868 and 433 MHz for the European area which are subjected to local regulations. The communications scheme and power in the European area should also follow the ETSII regulations.

There is nowadays a flourishing market of devices for these bands due to the demand of low-power wide-area network (LP-WAN) solutions (e.g. smartcity, smart-farming, etc.). Most of proposals are not available as commercial products or are in the research phase, although there are plenty of acronyms, such as WAVIoT, NB IoT, LTE-M, Greenwaves, Weightless, UNB (Sigfox, Telensa, NWave), LoRa, etc.

Fig. 6. Left: ITACA's custom node for 868 MHz ISM band. Central: LoRa compatible Multitech's .mDot evaluation kit. Right: Sigfox compatible Arrow's Smarteverything evaluation kit. Top: 4.5 dBi gain antenna.

Currently, according to the market trend, there are two clear leaders in this market: Sigfox and LoRa. Sigfox is an IoT operator with a good worldwide coverage network, but due to local regulations, laws or other operating constraints, the network configuration can differ from one country to the other. LoRa is an alliance organization devoted to standardizing LPWANs which has a good range of products ready for the market.

Both LoRa and Sigfox can be scaled up relatively well for this application. LoRa scalability is an actual research area not well studied. It is suggested [38], that using typical LoRaWAN settings, 20 bytes per packet and 16.7 min between packets, around 120 nodes can be supported. This number can be greatly enhanced by increasing the time between transmissions and/or using dynamic LoRa settings. In our proposal, the application of Sigfox becomes a good option for disseminated arts, so the scalability is not an issue given the ultra-narrow band approach utilized by this LP-WAN.

From the security standpoint, both LoRa and Sigfox offer some basic mechanisms but these should be enhanced using the appropriate firmware.

Finally, the Power Management Unit of the node is responsible for providing electric power to those components of the node that require energy at any given instant of time. This unit is more a concept than an independent block; for example, our custom node uses a simple output pin for providing energy to the RH and temperature sensor when a measure is requested. The idea is to completely eliminate the "stand-by" energy of all subsystems when not in use.

To evaluate our node design elections, we decided to compare the performance of the three nodes shown in Fig. 6. The leftmost node is our node design customized for this project. The central node is an evaluation kit for the LoRA network using a Multitech .mDot module. The rightmost node is an Arrow's Smarteverything evaluation kit that includes a Telit LE51-868S module for Sigfox. It should be noted that these are not definitive nodes, as the idea was to use them to evaluate the RF performance of LoRa and Sigfox.

4.2. Gateway

Three different types of gateway were considered for the CH IoT platform: the Sigfox IoT operator gateway, a LoRa commercial gateway and a custom gateway for energy-constrained scenarios.

The Sigfox gateway is relatively straightforward to use because we only need to deploy the nodes and follow a pay-per-use basis for using the service. Sigfox provides coverage through country-specific operators that deploy antennas to cover urban areas, which is an ideal solution for isolated artworks. From the point of view of the cloud, it is simple to recover data from the Sigfox gateway using REST methods. In Europe, the Sigfox IoT solution has a restriction of 140 messages per day with a maximum pay-load per message of 12 bytes, mainly due to ETSII.

When power is available, the best option to monitor many artworks is to use a LoRa commercial gateway. For our evaluation, we chose a Multitechs MultiConnect Conduit MTCDT-210A gateway shown in Fig. 7 and used the IBMs Bluemix PaaS Cloud already configured in the gateway to collect data from the nodes.

To deal with energy-constrained environments and/or complex Internet connectivity (satellite-based or private point-to-point antennas) we decided to design a low power gateway architecture which is rich from the point of view of openness, programming options and flexibility. In a typical gateway, there is a general-purpose microprocessor (an ARM Cortex-A microprocessor in most cases) which runs a general purpose OS, such as Linux, which allows a rich set of functionalities to be performed. Replacing this general purpose microprocessor by an ultra-low power microcontroller is not a good approach because it enormously complicates the development effort of the software and reduces flexibility.
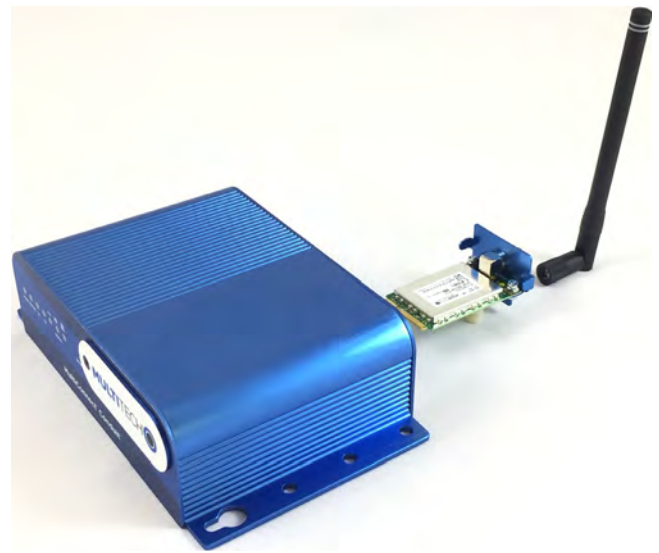

Fig. 7. Multitech's MultiConnect Conduit MTCDT-210A router/gateway and accessory card for LoRa in Europe.

Our gateway proposal is to mix the benefits of general purpose microprocessors and ultra-low power microcontroller to keep energy requirements to a minimum. The only element that requires to be kept switched on is the radio module. The microcontroller is awakened every time a new packet arrives to the radio module. The general-purpose microprocessor is kept off until it is decided to recollect data, analyse them and, if desired, transfer them to the cloud. Fig. 8 shows a block diagram of this proposal.

A drawback of this design is the lack of full-time availability of the gateway for reconfiguration from the Internet side, which is only feasible on gateway wake-ups.

To prove this concept we decided to build a demonstration prototype using widely available and well documented components. Fig. 9 shows a Raspberry Pi 2 with a ARM Cortex-A based general-purpose processor with Linux OS. To control the on/off cycle of the main processor, a Spell Foundry's Sleepy Pi board was selected; for the ultra-low power microcontroller we chose the same model as for the nodes in the form of an StMicroelectronics STM32L476-Nucleo board, and for the radio we used a Texas Instrument's CC1101EMK868-915 evaluation module, that pairs with our custom wireless node.

Upgrading the gateway prototype to other radio modules involves the connection of the extra module to the microcontroller and the implementation of the corresponding piece of software.

The use of Linux and well-documented hardware provides an enormous set of possibilities, including the ability to control environmental systems such as air conditioning, lights, alarms, etc. From the software point of view, we were able to move Docker-based containers from the cloud to the custom gateway so that some cloud processing could be transferred to the gateway if necessary.

4.3. Cloud

The IoT for CH framework deployment proposed in this work uses a cloud infrastructure for hosting the server-part of the architecture. It hosts the databases (we choose Mongo DB for its performance with unstructured data), processing services (a SPARK cluster) and a web application to provide end users with a user interface including the real-time visualization of the data stored in the database. A reactive programming framework such as Meteor is used to implement the application.
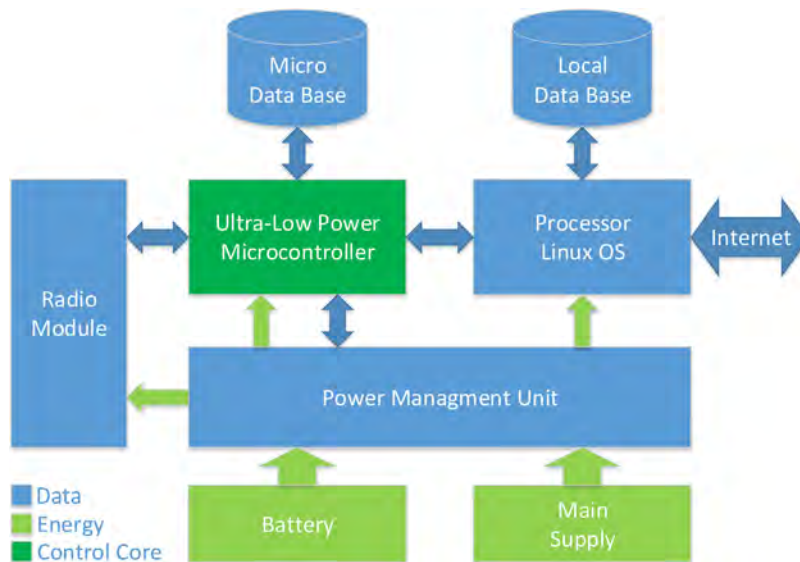
Fig. 8. Block diagram of the low-power CH gateway.

Fig. 9. Low-power gateway prototype.

Cloud Computing enables to dynamically deploy virtual infrastructures consisting on a fleet of Virtual Machines (VMs) running on top of Physical Hardware Resources (PHRs) in an Infrastructure as a Service (IaaS) Cloud service model. Virtualization enables to increase the usage of hardware and thus to reduce the investments on additional hardware. In the case of a public Cloud provider such as Amazon Web Services (AWS), a pay-per-use model is employed so that users are charged for the resources consumed in terms of hours or minutes of computing, network traffic, etc. In the case of private or on-premises cloud resources (OpenStack or OpenNebula), it allows system administrators to deploy Cloud infrastructures on top of the educational institution PHRs.

The cloud architecture must be cloud-agnostic and be supported by a different IaaS provider. Applications and components are defined as a topology of services and dependencies (software and hardware) so that the application can be deployed on different cloud infrastructures. The component called Infrastructure Manager (IM) [22,39] was employed in this work. IM allows the management of infrastructure deployments on a cloud provider. IM is an open-source solution that can deploy customized virtual computational environments on a wide range of Cloud IaaS. IM supports both on-premise (e.g. OpenNebula, OpenStack) and public (e.g. Amazon Web Services, Microsoft Azure). IM uses RADL (Resource and Application Description Language) recipes [40] and the Ansible language to define the virtual hardware and the software to be installed and configured. This provides high-availability, reproducibility and portability, as we separated the logical infrastructure from the physical resources.

The application topology includes all components of the framework, such as web interfaces (i.e Meteor), database back-ends (i.e. MongoDB) and processing components (i.e. SPARK). To facilitate the execution of general-purpose processing tools, we defined a Docker Swarm virtual infrastructure. Docker Swarm manages a set of resources to distribute Docker workloads, managing internal overlay networks within the containers. We chose Virtual Machines for hosting the Docker Swarm, as Docker is not multi-tenant and therefore the resources could not be directly shared among different sites and projects. Docker Swarm is managed by means of EC3 (Elastic Cloud Computing Cluster) [41,42], a cluster management system which can deploy and undeploy nodes on demand.

EC3 fulfils the requirement of the horizontal elasticity of the resources (i.e. adding/removing virtual machines where the Docker engine is installed). EC3 creates elastic virtual clusters on top of cloud providers, is IM based and implements recipes to deploy elastic clusters with different resource management systems (such as TORQUE, SLURM, MESOS and DOCKER SWARM) which can be self-managed with CLUES [43]. It starts with a single-node cluster and working nodes are dynamically deployed and provisioned to fit increasing loads. Working nodes are undeployed when they are idle, which is a cost-efficient approach. It also provides good energy contention, as no resources remain idle (potentially incurring costs) for long periods.

A set of RADL recipes were developed that define the four main blocks of the virtual infrastructure: the web application and their
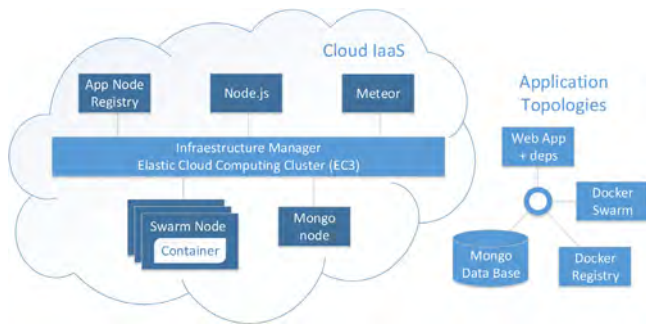
Fig. 10. Architecture of the cloud infrastructure.

dependencies; the Docker Swarm, which consists of one master and multiple agents; the Docker registry, which can be deployed on the same node as the web application or the Docker master; and the Mongo DB database (see Fig. 10).

4.4. Data representation

The information handled by the monitoring system has been split in two categories: heritage specific and communications specific.

In the field of Heritage Conservation, there are standards for the documentation of museum collections, promoted by the International Council of Museums (ICOM), through the International Committee for Documentation (CIDOC). CIDOC provides the museum community with advice on good practises and developments in museum documentation, with the creation of a general data model for museums, with a particular focus on information interchange based on draft ISO 21127:2014 and previous ones.

The CIDOC Conceptual Reference Model (CRM) provides definitions and a formal structure for describing the implicit and explicit concepts and relationships used in cultural heritage documentation.

These standards has been elected as a basis for representing each object in a database. Physical variables collected by the sensors are associated to their corresponding object by saving their value at the instant of acquisition using UTC time units. The specific node identity is not considered here, only the measure.

For the communications infrastructure, we record the status of each node, such as battery energy, signal RSSI and SNR of each received data package, data packet count sequence, etc. That simplifies diagnostics of the performance of each node and to react in case of unexpected issues.

In the current prototype implementation, sensors information arrives to the collecting cloud machine using MQTT representation for LoRA and an https callback for Sigfox (as required for this platform). Node information is separated into the two categories and stored in the corresponding record.

To store all this information, we use a MongoDB database in order to simplify data representation and exploitation. The MongoDB information can be exploited using cloud-based application for reporting alarms, but this has not been implemented yet because we are focused on the correct data acquisition system.

5. Evaluation of the nodes

At this stage of the project, we evaluated the performance of the elected nodes technology from two points of view: RF performance and energy requirements. These evaluations are basic to discuss if the design of the node was appropriate.

5.1. Historical building test site

For the case study we selected the baroque 17th century Church of Santo Tomás y San Felipe Neri in Valencia (Spain) (see Fig. 11), declared as National Monument in 1982. Apart from the inherent value of the building itself, it contains an important collection of diverse artefacts, including works by renowned painters such as Juan de Juanes (1507–1579), Jerónimo Jacinto de Espinosa (1600–1667), José Vergara (1726–1799), and Vicente López (1772–1850), as well as murals, panels and several wooden altarpieces made to replace those destroyed in the Spanish Civil War.

Fig. 11. Panoramic view of Santo Tomas y San Felipe Church at the centre of Valencia (Spain). Long: 39.47, Lat: −0.37.

Fig. 12. RF performance of the Sigfox node inside the church.

The target was to monitor the environment inside the church by considering different zones and a range of objects in order to determine possible risks, including the following:

- Central Nave: monitoring of ceramic plinth affected by sources of damp.
- Major Altarpiece at the apse: since there was access to this altarpiece at different levels, the aim was to study the correlation between readings of environmental conditions with the moisture content in different parts of the wood aimed at detecting possible pests.
- Central Nave: monitoring of mural for possible rainwater leaks, condensation and damp.
- Sacristy: some canvas paintings are exposed here as well as wooden furniture with textiles and religious clothing which can be affected by humidity, light or pests.

5.2. RF performance evaluation

The proposals for Sigfox and LoRa were assessed under the scenario of CH monitoring.

To evaluate Sigfox a node was moved to different parts of the church containing important artworks. Fig. 12 shows a view of the web page with the collected data packets. Packets were sent at intervals of 10 min and none was lost. In general, the SNR and RSSI was excellent, but faded near the limit in some places. The results were better than expected considering that the signal had to pass through thick walls to reach the Sigfox antenna. This result reveals that the Sigfox signal level should be evaluated in advance before installing the nodes and before choosing the antenna gain (i.e. its size). The experiment was developed with the default antenna.

To evaluate LoRa, the Multitech gateway (see Fig. 7) was placed at the centre of the church at a height of 1 m. The node displayed in Fig. 6 equipped with the 4.5 dBi antenna was placed in different parts of the building. For any easily accessible space, the minimum RSSI obtained was −107 dBi, showing excellent coverage of the space.

To get a rough idea of the maximum reach of the LoRa node, we decided to move the node outside the building. The maximum distance achieved with no package dropping reached the point shown in Fig. 13, i.e. around 750 m in the church's line of sight, but rapidly fading when buildings were interposed.

As for Sigfox, the results with LoRa were excellent, considering the type of environment. Since the type of antenna is a key factor for both Sigfox and LoRa, it is advisable to provide a method for replacing it easily.

The custom node was not tested for distance because it was designed to focus on getting the minimum size at the expense of antenna size. The maximum reachable distance in perfect line of sight was around 70 m.

Table 1
Maximum payload size in bytes for each type of node.

Node type	Payload size (bytes)
Custom (Texas Instruments CC1101)	64
Sigfox	12
LoRa	51

5.3. Energy requirements evaluation

A critical aspect of the proposal is the lifespan of the proposed nodes. In this subsection, we calculate the energy requirements of each type of node, that is: our custom node, the LoRa node and the Sigfox node according the design proposals of Section 4.1.

Total energy requirements are the mathematical integration of the energy required by all components. Assuming the same voltage for any component (3 V), this can be measured in mAh. Note that each communication protocol has different time requirements; for example, Sigfox needs 6 s of transmission per frame, and LoRa requires 60 ms. The CPU requirements were considered to be similar because the CPU can be kept in sleep mode while the RF module is transmitting data. No downlink data (reception) was considered.

To transmit these parameters, they must be encoded on the data payload of the transferred package. In this case, each technology has a maximum payload size in bytes that can be seen in Table 1. These values should be elected carefully because they are limited by local regulations (Sigfox has this limitation prefixed because it follows ETSII regulations). For the three node types, this payload size is sufficient for encoding a timestamp and two parameters using floating point single-precision encoding.

The electric current required for each electronic element depends on its state over the time, it is typical that a modern device support three modes: active, sleep and complete shut-down. Less current is utilized in sleep and shut-down modes. Since some devices only support sleep mode, sometimes a good option is to cut off (shut-down) completely the power to some circuits to save energy. For example, in the custom node, we cut off power to the SHT1x sensor, but not to the RF part, because we added extra circuits to reduce its relatively high consumption. In the new LoRa and Sigfox node, energy to the RF modules was turned off. Table 2 summarizes these energy requirements in different modes, were energy requirements has been obtained from manufacturer's datasheet and laboratory measurements.

In order to evaluate the energy requirements, a reference sampling rate must be established. According Section 3.1, we fixed one sampling per hour of the RH and temperature parameters. Given this sample rate, Table 3 indicates the energy requirements in a per day basis and the annual amount of energy required.

Adding together the energy required for each component at each state for every type of node, we obtained the total amount of energy required during a year of operation. There is no remarkable energy requirement difference between the custom and the LoRa node. Sigfox has higher energy requirements.

Battery lifespan can be estimated from these values; for example, Table 4 summarizes the estimated life of a typical coin-cell battery (CR2032) and two high-density energy batteries assuming 75% of useable energy. We choose lithium technology because they exhibit very low self-discharge figure, so they are for long-life systems, but as it is not negligible. According these results, LoRa technology is clearly ideal for a CH scenario, but Sigfox can be considered if there is a good trade-off between node maintenance and gateway requirements.

For the custom gateway a similar analysis can be applied. In order to evaluate the energy requirements of the gateway, we need to assume a number of working nodes connected to it. We

Fig. 13. LoRa's node maximum reached distance.

Table 2
Current requirements for the different states of the main electronic components @ 3 VDC.

Description	Node type	Current (μA)
Microcontroller St STM32L476 sleep + RTC	Sigfox&LoRa	0.42
Microcontroller St STM32L476 stop + RTC	Sigfox&LoRa	1.40
Microcontroller St STM32L476 active @16MHz	Sigfox&LoRa	$1.60 \cdot 10^3$
Microcontroller Silabs C8051F920 sleep + RTC	Custom	1.00
Microcontroller Silabs C8051F920 active	Custom	$3.00 \cdot 10^3$
Sensor Sensirion SHT1x sleep	Custom	0.30
Sensor Sensirion SHT1x active	Custom	$0.90 \cdot 10^3$
Sensor Sensirion SHT3x sleep	Sigfox&LoRa	0.20
Sensor Sensirion SHT3x active	Sigfox&LoRa	$0.80 \cdot 10^3$
RF Texas Inst. CC1101 sleep	Custom	1.00
RF Texas Inst. CC1101 act. + trans.	Custom	$35.00 \cdot 10^3$
RF Telit LE51-868S (EU) sleep	Sigfox	1.00
RF Telit LE51-868S (EU) receive	Sigfox	$32.00 \cdot 10^3$
RF Telit LE51-868S (EU) transmit	Sigfox	$55.00 \cdot 10^3$
RF Multitech mDot 868 (EU) sleep	LoRa	40.00
RF Multitech mDot 868 (EU) receive	LoRa	$32.00 \cdot 10^3$
RF Multitech mDot 868 (EU) transmit	LoRa	$41.00 \cdot 10^3$

Table 3
Energy required for each component assuming one sampling per hour.

Description	Node type	Daily time (s)	Annual ener.(mAh)
Micro. St STM32L476 sleep + RTC	Sigfox&LoRa	$86.39 \cdot 10^3$	3.68
Micro. St STM32L476 stop + RTC	Sigfox&LoRa	5.00	0.00
Micro. St STM32L476 active @16 MHz	Sigfox&LoRa	1.00	0.16
Micro. Silabs C8051F920 sleep + RTC	Custom	$86.39 \cdot 10^3$	8.76
Micro. Silabs C8051F920 active	Custom	2.00	0.61
Sensor Sensirion SHT1x sleep	Custom	0.00	0.00
Sensor Sensirion SHT1x active	Custom	12.00	1.10
Sensor Sensirion SHT3x sleep	Sigfox&LoRa	0.00	0.00
Sensor Sensirion SHT3x active	Sigfox&LoRa	12.00	0.97
RF Texas Inst. CC1101 sleep	Custom	$86.39 \cdot 10^3$	8.76
RF Texas Inst. CC1101 act. + trans.	Custom	9.00	31.94
RF Telit LE51-868S (EU) sleep	Sigfox	0.00	0.00
RF Telit LE51-868S (EU) receive	Sigfox	0.00	0.00
RF Telit LE51-868S (EU) transmit	Sigfox	144.00	803.00
RF Multitech mDot 868 (EU) sleep	LoRa	0.00	0.00
RF Multitech mDot 868 (EU) receive	LoRa	0.00	0.00
RF Multitech mDot 868 (EU) transmit	LoRa	10.00	41.57

Table 4
Estimated battery life.

Battery model	Capacity (mAh)	Custom (years)	LoRa (years)	Sigfox (years)
Panasonic CR2032	220.00	3.0	3.0	0.2
Maxell Lithium-thionyl 2/3 AA 3.6 V	1700.00	23.2	22.8	1.6
Maxell Lithium-thionyl AA 3.6 V	3100.00	42.3	41.7	2.8

Table 5
Energy requirement for a standard gateway configuration.

Description	Current (μA)	Daily time (s)	Daily energy (mAh)
RF Texas Inst. CC1101 sleep	1.00	0.00	0.00
RF Texas Inst. CC1101 act. + trans.	$32.00 \cdot 10^3$	$86.40 \cdot 10^3$	770.00
Raspberry Pi 2 shutdown	$80.00 \cdot 10^3$	0.00	0.00
Raspberry Pi 2 idle	$320.00 \cdot 10^3$	$86.38 \cdot 10^3$	$7.68 \cdot 10^3$
Raspberry Pi 2 running core (100% load)	$540.00 \cdot 10^3$	25.00	3.75

Table 6
Energy requirement for the custom gateway configuration.

Description	Current (μA)	Daily time (s)	Daily energy (mAh)
Micro. St STM32L476 sleep + RTC	0.42	$86.28 \cdot 10^3$	$0.10 \cdot 10^{-3}$
Micro. St STM32L476 stop + RTC	1.40	100.00	$0.39 \cdot 10^{-6}$
Micro. St STM32L476 active @16 MHz	$1.60 \cdot 10^3$	20.00	$8.89 \cdot 10^{-3}$
RF Texas Inst. CC1101 sleep	1.00	0.00	0.00
RF Texas Inst. CC1101 act. + trans.	$32.00 \cdot 10^3$	$86.40 \cdot 10^3$	770.00
Raspberry Pi 2 shutdown	$80.00 \cdot 10^3$	0.00	0.00
Raspberry Pi 2 idle	$320.00 \cdot 10^3$	2.00	0.18
Raspberry Pi 2 running core (100% load)	$540.00 \cdot 10^3$	26.00	3.90

estimated, 20 working nodes transmitting data every hour (i.e. 480 wake-up operations) for typical CH monitoring scenario.

The energy requirement of an standard gateway built around the components utilized for our custom gateway, are summarized in Table 5. The standard configuration will be the amount of energy required by a typical configuration (i.e. RF module + Raspberry Pi) always turned on. In this case, the daily estimated energy requirement is around 8.45 Ah for the standard configuration.

In order to obtain the power saving ratio, we compared the amount of energy required by a typical configuration (i.e. RF module + Raspberry Pi) always turned on (running or idle) with respect to a cycling schema where the Raspberry Pi is turned on and off when required. Table 6 summarizes the estimation of time required in each state for each configuration assuming two daily transmissions of data to the cloud (data synchronization). The Linux start-up time has been fixed in 8 s, and has been measured using an stock Raspbian Jessie Lite 4.0 distribution. The total amount of daily energy is around 0.72 Ah. Compared with the standard configuration, this configuration saves around 90% of energy, allowing the use of energy harvesting mechanisms (e.g. solar panels, wind generator, etc.) for powering the gateway.

6. Conclusions and future work

In a preventive conservation campaign of artworks, evaluating the environmental conditions in a building provides an overall perspective that allows specific actions to be implemented in spaces according to their climatic conditions, the possibilities of applying passive control actions, and to assist in designing a subsequent follow-up strategy. The present work has studied the viability of applying IoT technologies to CH by analysing the requirements and proposing the appropriate cloud and field systems for these requirements.

Since the sensor node is the most critical element, different RF technologies were analysed for their viability. The standard de-facto LoRa and Sigfox in the ISM of 868 MHz band were found to be suitable for monitoring artworks.

The elected wireless technology copes with the need of reaching relative long distances and pass through thick walls that are typical scenarios in artwork containers or open archaeological sites.

The energy requirements were then calculated based on the typical RH and temperature measurement requirements at a rate of one sample per hour. Using a small 1.7 mAh lithium-thionyl battery it is possible to achieve a node life-span of over 20 years with no maintenance for LoRa and 1.5 years for Sigfox. The Sigfox technology is useful for monitoring widely dispersed artworks and, hence, it should not be ruled out. With other strategies such as carrying more than one sample per transmission to optimize the energy transmitted, it would be easy to extend node life-span to 5 years. LoRa technology is clearly ideal for a CH scenario, but Sigfox can be considered if there is a good trade-off between node maintenance and gateway needs.

We propose using Infrastructure Manager and EC3 combined with cloud technologies to make the architecture open and reproducible so that anyone could deploy an equivalent virtual infrastructure on a public or on-premise cloud. Moreover, this choice enables us to design an elastic and scalable architecture in terms of storage and compute, which could adapt to the workload demand. On top of the cloud resources, we propose using containers for application delivery, as this is the most convenient way to embed users specific software configuration. This will help users defining and building their predictive models to use their preferred legacy data analytics software.

Since the results achieved were excellent we are at present working on integrating the electronics of a small node to be installed in the Santo Tomás and San Felipe Neri Church.

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