Distributed Measurement Systems: Advantages and Challenges of Wireless Sensor Networks

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In general, a *distributed system* can be considered as an aggregation of several units which, even though physically located in different positions, are able to jointly carry out some specified tasks, communicating together by means of a suitable network infrastructure. This type of system was born with the introduction of the first communication networks, and it started growing quickly with the establishment of the first world-wide network: the Internet. As a matter of fact, the spreading of the Internet provided developers with a new and almost-ubiquitous network that is able to connect virtually any kinds of devices and make them operate together.

The idea of distributed systems can be successfully applied to the metrological field with the development of so-called *distributed measurement systems*, which are distributed systems whose units are able to perform some kind of measurement, to acquire data and to aggregate them in order to carry out a specified task. This article provides a general overview of distributed measurement systems and their applications, highlighting the unique advantages of such systems, while also discussing the actual technological limitations and challenges.

Distributed Measurement Systems

Several measurement applications require, due to their intrinsic nature, a distributed acquisition of information in several locations. As an example, to optimize the power distribution in electric grids it is required to measure specific parameters in specific grid nodes. Such nodes can be located at distances up to several kilometers, and the information acquired in each one of them should be aggregated and processed together to maintain optimal and safe conditions all over the grid. In these types of applications, the employment of distributed measurement systems is of great benefit and often compulsory.

The basic structure of a distributed measurement system is shown in Fig. 1. A set of instruments and sensors, called measurement nodes, are deployed in several locations and connected by means of a suitable network infrastructure. In general, each node is able to perform a specific task, such as acquire measurements, and optionally process the acquired data. According to the working protocol and the ultimate task of the system, the nodes either can be managed by a supervisor node or they can cooperate together (collaborative systems) for achieving a specified result. Depending on the application, the network can be either an existing infrastructure (such as the Internet and the mobile phone grid) or a specifically-designed communication network for hosting the measurement system. Sometimes, such as in the case of wireless sensor networks, the nodes themselves are responsible to create and manage the network infrastructure.

A distributed measurement system has several advantages over a traditional concentrated one [1]. First of all, it allows one to carry out specific measurements with several instruments placed in far away locations and to process the acquired data as if such instruments were concentrated in the same place. As a consequence of this, a number of hardware resources can be shared in the infrastructure, and it is not required to replicate the whole hardware in each location. Also, data processing can often be shared over all the nodes, and in general, this allows
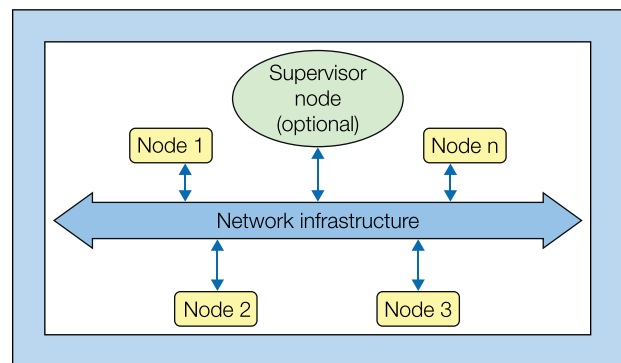

Fig. 1. General structure of a distributed measurement system.

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one to achieve high computing capabilities by using several low-cost processing units. Therefore, the capability which distributed systems have to share resources involves the reduction of the overall cost of the system. Moreover, distributed systems are intrinsically more robust and reliable than concentrated ones: generally, a distributed measurement system is able to work properly even though one or more nodes fail. This is something which, of course, cannot be obtained in a concentrated system.

Distributed measurement systems are also scalable and, in general, easily re-configurable. As an example, it is possible to add or remove a measurement node without changing the design of the whole system. In addition, nodes can be moved from their location and deployed in other points without impairing the function of the remaining part of the system. Such characteristics and features are extremely difficult, or sometimes impossible, to achieve with a concentrated measurement system.

Unfortunately, all of these advantages come with drawbacks and technological limitations. Some of such limitations are related to the network employed for connecting the measurement nodes. Specifically, the network infrastructure, either if already existing or created ad-hoc, has to be available in all locations where the nodes are deployed. Such a network should be reliable as much as possible, and often nodes should be able to operate even in case of network failure to guarantee a minimum level of service and function according to the application. Another important aspect related to the network is its throughput which is always limited by physical and technological factors.

Data amounts exchanged by each node can span from few bits to several million bits per second, depending on the sampling frequency and the type of the acquired data. Therefore, the total data traffic incoming from all the nodes can become an important constraint for the network design and the optimization of the communication protocol. Indeed, the cost of the network can significantly contribute to the cost of the overall system, especially when node locations are not fully covered by the network.

Despite the fact that distributed systems allow one to partially share resources, it is required that all the nodes embed a proper communication interface able to support a common protocol. Moreover, taking into account that protocols and control software for a distributed system can be significantly more complex than those found on a concentrated system, special care should be taken in order to optimize the node design and to minimize its cost. Often, node cost represents the most significant part of the overall system cost, especially for those systems featuring a large number of nodes.

Additionally, node power supply is another common limitation in a distributed system. As a matter of fact, a suitable and reliable power supply should be provided to each node. Unfortunately, there are applications where, either due to node locations difficult to reach or because of other constraints, it is extremely difficult to provide a stable power supply for all the nodes. In such situations, nodes should embed a sort of power backup, as an example, based on rechargeable batteries, which is able to provide a continuous power supply to all the nodes. All of these aspects make design and maintenance of distributed systems more complex and more expensive with respect to concentrated instruments.

Eventually, other two aspects, which are often underestimated, should be considered carefully: data security and quality of measurement. Data acquired from the system can be either sensitive or reserved, such as biomedical information of patients and access to restricted areas. Such data should be protected both from the access of unauthorized people and from any possible alteration. Therefore, these applications require suitable communication protocols and network infrastructures that are designed to guarantee the required level of data security.

Furthermore, acquired data can represent important information which is necessary to know accurately and effectively, as in the case of critical and life-related applications [2]. This aspect is rarely discussed in the literature, and assuring the required level of measurement accuracy for all nodes during all the system operative life can be extremely difficult. Therefore, this aspect should be carefully considered during the design of the system. As an example, during the system development, it is possible to foresee the possibility either to perform periodic calibrations of the sensing nodes or to periodically receive feedback on the current measurement accuracy. Preferably, such procedures should work remotely to decrease the maintenance cost, especially in those systems counting hundreds of nodes placed in distant locations.

Nowadays, distributed measurement systems find applications in several fields from scientific research to consumer services. Their size and extension range from few meters up to thousands kilometers, and they can feature from few tens of nodes to several thousands. For instance, the Square Kilometre Array (SKA) [3] is an international distributed radio telescope which, even though still under construction, will feature hundreds of thousand antennas. Approximately eight terabits per second of data will be synchronously collected by these independent antennas, mainly located in South Africa and Australia, and processed together to achieve unprecedented performance and resolution.

Despite such impressive systems, there are smaller distributed systems which find application in every-day life. From smart traffic light controllers and other smart city applications [4], [5], to home automation [6], environmental monitoring [7], [8] and health care [9], the applications of such systems are virtually unlimited.

Sometimes, it is not possible to employ wired networks either due to the necessity of avoiding wires or to mobility constraints. In such situations, a Wireless Sensor Network (WSN) can be employed with success. Such a solution allows one to connect several sensing nodes by using a suitable radio link as network infrastructure. The advantages of such technology are relevant, and this explains why in recent decades, most of the research carried out in such fields involves the development of new technologies and protocols for WSNs.
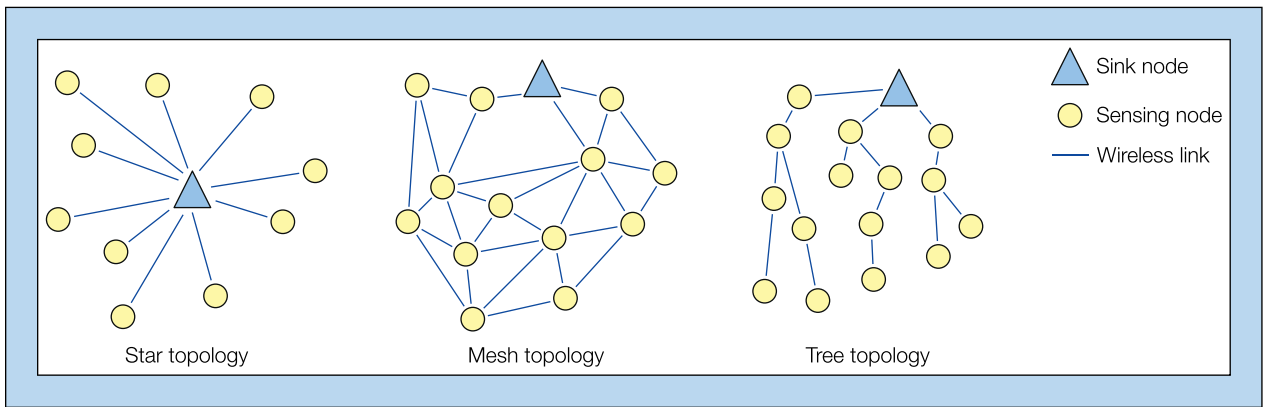
Fig. 2. Three main topologies employed in wireless sensor networks.

Basics of Wireless Sensor Networks

A wireless sensor network is an infrastructure consisting of a set of sensing nodes connected together by means of a specified wireless link and forming a network where data packets are exchanged according to a specified network protocol. Each sensing node, depending on the specified application, embeds one or more sensors employed for acquiring specific information and data from the environment. Therefore, each node can be considered as an independent measurement system that operates according to a specified protocol. Nevertheless, since each node is connected to the others, the whole WSN can be seen as a distributed measurement system that is able to acquire data both in different positions (spatially distributed) and different time moments (temporally distributed).

Several possible configurations have been developed for arranging and connecting the sensing nodes inside a WSN, and usually, such configurations can be grouped in three basic topologies: *star networks*, *mesh networks* and *tree networks* (Fig. 2). Star topology is the simplest, composed by a *central node*, or *sink node*, operating as network manager and data collector, and a set of several *sensing nodes* connected exclusively to the central node. In such a configuration, a sink node is always required since the data packets are exclusively exchanged between each sensing node and the sink node itself.

An opposite situation occurs, instead, with the mesh topology. Here, all of the nodes can communicate together, creating links according to the position of each node. The presence of a central node is optional and data packets travel along the mesh links from node to node (*multi-hop links*) until they are gathered according to the network protocol. In such a case, there is not any prefixed link among nodes, and several protocols allow the nodes themselves to configure links, finding the most convenient route for each data packet traveling in the network. Therefore, such a topology is characterized by a much higher flexibility and link reliability compared to the star topology.

As an example, Fig. 3 shows a typical situation where a link is broken for any reason (i.e., an obstacle blocks the wireless signal). In such a situation, a star topology would irremediably lose the connection with the related nodes. Nevertheless, the mesh topology still fully operates in such a situation: the links are properly re-arranged so that all data packets can be routed over unblocked links. However, this higher flexibility and reliability come at the cost of a more complex network protocol which typically requires higher computing capabilities for the sensing nodes.

Tree networks, instead, can be considered as a modification of the star topology. Even though tree networks support the multi-hop link strategy, this topology is characterized by
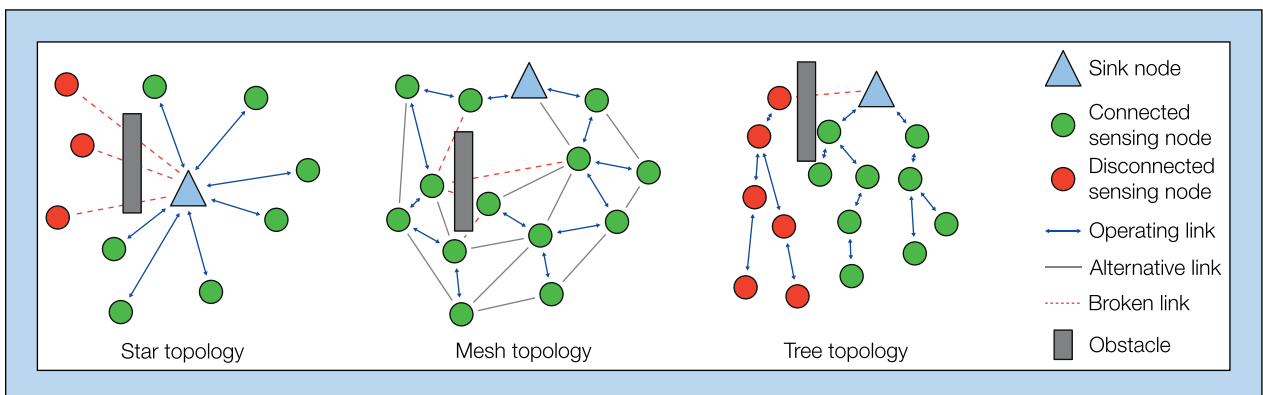

Fig. 3. Data packet routing example for the three different network topologies; mesh networks demonstrate to be more robust, allowing all nodes to be properly connected even when there are obstacles and broken links.

a fixed routing scheme which limits flexibility and reliability. Fig. 3 shows what can happen in the case a link breaks in a tree network. In such a situation, all nodes of the interested branch disconnect from the sink node. For this reason, tree networks can be even less robust than star ones, and they are used rarely only in specific applications.

A WSN, independently by its topology, can operate either as a stand-alone distributed system or as part of a wider infrastructure which typically employs the Internet as the global network for connecting multiple WSNs or sharing the acquired data on a world-wide level. In the latter case, a suitable Internet connection is required at least for the sink nodes.

In some special applications, and especially if the size of the network exceeds a few tens of nodes, the WSN can feature multiple central nodes which provide more flexibility on the data routing and, at the same time, an enhanced robustness against possible node failures or connection issues.

Virtually, any kind of sensor can be embedded in a sensing node, and this makes the WSNs an almost universal solution in all applications which require a continuous, and often autonomous, distributed monitoring of specific parameters over a defined location or territory. Among the possible employments of WSNs, surely there are: environmental monitoring, surveillance, industrial manufacturing, food and agriculture applications, scientific research, military applications, health care, transports, home automation and smart cities. Such applications differ significantly in the interfaces for the end-users, the working constraints and the physical parameters which are measured. Nevertheless, all of them can be successfully addressed by employing a suitable WSN and a specific protocol.

Node Structure

Fig. 4 shows the basic block diagram of a typical sensing node. One or more *sensors* acquire specific information from the environment. An *Analog-to-Digital Converter* (ADC) is usually necessary to convert the analog signal coming from the sensor to a digital signal which can be properly processed either by a *processor* or by a *micro-controller*.

An *analog interface* circuit is sometimes required to adapt the sensor signal to the input specifications of the ADC. In some special cases, a *biasing block*, basically composed of a Digital-to-Analog Converter (DAC) and an analog conditioning circuit, is necessary to provide the sensor either with a specific supply or set specific working parameters of the sensor. As an instance, some gas sensors work properly only at specific temperatures, and therefore, they require a suitable heating system to stabilize their working conditions. Such components compose the measurement chain of the sensing node. Indeed, they are responsible for the metrological performance and the accuracy of the sensing node.

Alternatively, several digital sensors are available on the market. Such sensors directly provide the acquired data in a digital format, and therefore, they do not require any additional analog circuit or converter.

Once the acquired information is available in a digital form, it can be processed by the micro-controller according to the specific application and the operating protocol of the WSN. Of course, a wireless transceiver and a suitable antenna are required to establish a radio link between the nodes and exchange data and control information.

The recent development of electronic technologies and the introduction on the market of new ultra-low power processing devices are making it easier and more straightforward to develop small and power-efficient node architectures. New complex Systems-On-Chip (SOCs) which embed in a single device all of the principal blocks of a sensing node (processor, analog circuitry, ADCs and wireless transceiver) are becoming widely available on the market. Such devices allow developers to reduce the number of external components of a node with the benefits of both reducing overall dimension and cost. Moreover, the processors embedded in such devices are quite powerful and are able to operate at a few hundred micro-amperes per megahertz. This paves the way for the development of more complex and intelligent protocols which feature very low power consumption, higher data rate and improved link reliability. As a result, several WSN applications, which were extremely challenging until a few years ago, are rapidly becoming available at a quite low-cost.

The last fundamental module in each sensing node is the power management block. This module, which is responsible for providing a reliable power supply to the node, is extremely important because most of the WSN architectures employ battery-powered nodes, and therefore, power consumption and battery management are key points of a sensing node design.

The simplest node designs just employ batteries with optionally a dedicated power converter. In such a case, the sensing node has
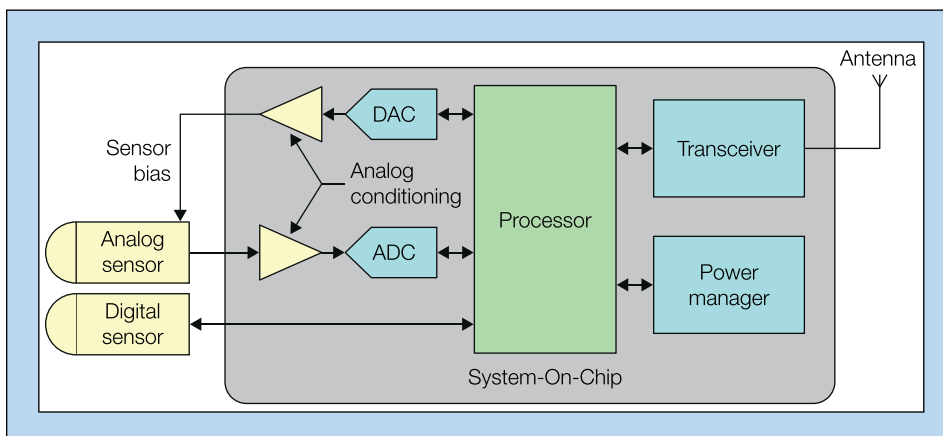

Fig. 4. Generic block diagram of a sensing node.

a limited operating life, and when the battery discharges, it is required either to replace the node itself or its battery. However, more advanced designs are also available which employ rechargeable batteries with optionally some sort of energy harvester, so that such nodes are able to recharge their battery autonomously without any maintenance.

The design of the node enclosure is also a critical part in some applications. Sometimes, sensing nodes are exposed to harsh environmental conditions, such as low/high temperatures and humidity, dust and aggressive gases. Extreme working conditions can negatively affect the performance and the operative life of a sensing node, and therefore, particular care should be devoted to the enclosure design, also considering that sensors often require openings on the enclosure itself.

Size and weight are important factors as well. In fact, some specific applications require small and light sensors. All such factors are often competing together, and therefore, it is extremely difficult to optimize the design of these devices.

Sink Nodes

In some network architectures, sensing nodes and sink nodes are identical. This means that all of the nodes are interchangeable, there is no specific sink node and the network itself can be considered self-organized. Nevertheless, sink nodes can slightly differ from normal sensing nodes for several reasons. First, the number of sensing nodes is much higher than the number of sink nodes. Consequently, most of the design effort is dedicated to optimize as much as possible the cost of sensing nodes.

It should be also noted that the ultimate task of a sink node is typically the management of the network and the collection of data coming from the sensing nodes. Therefore, sink nodes do not usually require measurement capabilities. On the other hand, sink nodes usually need either a storage support to store the collected data or a connection to the Internet to deliver them.

Eventually, sink nodes usually connect to a large number of sensing nodes (especially in the star topology), and as consequence, their transceivers must be more complex and reliable than those employed in a sensing node.

Network and Wireless Protocols

The communication network is an important item in a distributed measurement system because it allows nodes to communicate together. As a matter of fact, the quality of node communication principally depends on the network reliability and its effectiveness.

In the WSNs, the network is implemented by means of radio links between nodes that operate in a specific frequency range. The available band can also be divided in sub-channels so that more links can operate at the same time, avoiding channel contention and data throughput reduction. Such an option can become a necessity for networks that feature a lot of nodes which are deployed in a small geographical area.

Several limitations can occur in a wireless channel: limited bandwidth and data rate, interference, noise, obstacles and losses are only few of them. Moreover, such limitations are often challenging to manage as they are unpredictable and uncontrollable. Therefore, the selection of the most suitable frequency band, modulation, encoding scheme and network protocol is extremely important to achieve a reliable and robust node communication.

WSNs can be designed to operate according to either a standard protocol or a custom protocol developed ad-hoc for a specific application. Typically, the former choice provides developers with a defined solution characterized by well-known performance and limitations. The latter one, instead, provides a more optimized solution but with higher development costs and time. Therefore, standard protocols are commonly employed in all cases except those applications which, due to specific constraints, require a more optimized solution.

The selection of the most suitable protocol depends on several factors. Among them, surely topology of the network, size, number of nodes, required data rate and security are the most important. Table 1 provides some basic information about some standard wireless protocol commonly employed in WSNs.

It is worth noting that most WSNs work on the Industrial, Scientific and Medical (ISM) bands due to the fact that they are freely usable without any authorization in many countries.

Several protocols are designed to operate on a short-medium range going from a few tens to hundreds of meters. The

Table 1 – Basic information regarding some standard wireless protocols employed in WSNs					
PROTOCOL	**TOPOLOGY**	**RANGE**	**BIT-RATE**	**MODULATION**	**BAND**
Bluetooth Low-Energy	STAR, MESH	~50 m	2 Mbps	GFSK	2.4 GHz
Ant/Ant+	STAR, MESH, TREE	~30 m	60 kpbs	GFSK	2.4 GHz
Zigbee	STAR, MESH, TREE	~100 m	250 kbps	QPSK	2.4 GHz, 915 MHz, 868 MHz
Z-Wave	MESH	~100 m	100 kpbs	FSK	915 MHz, 868 MHz
LoRa	STAR	~40 km	50 kbps	Spread-Spectrum Chirped FSK	915 MHz, 868 MHz, 433 MHz
SigFox	STAR	~50 km	600 bps	UNB DBPSK/GFSK	915 MHz, 868 MHz

Bluetooth Low-Energy (BLE) [10], is a standard wireless protocol employed by billions of devices in the world. The BLE is mostly employed for connecting consumer electronics and devices (such as smart phones, smart watches, fitness end medical devices). However, this protocol can also be successfully employed in the field of WSNs due to its very low power consumption and high performance [11].

Many other protocols are available with similar characteristics. As an example, Ant is a protocol specifically developed for the implementation of short-range WSNs which is able to support hundreds of nodes to maintain an ultra-low power consumption [12]. Also, ZigBee is employed in similar applications [13]. However, it may be used on a longer range than Ant, with a higher bit-rate, but at the cost of a higher power consumption.

Other protocols are, instead, designed only for specific applications. As an example, Z-Wave is a proprietary protocol employed almost exclusively in the home automation field [14].

Completely different approaches are developed for long range communications up to a few tens of kilometers. Here, signal integrity, noise and error rate become extremely challenging factors, and different modulation schemes have been designed and optimized for such applications. As an example, LoRa [15] and SigFox [16] are two protocols which allow nodes to exchange quite low amounts of data over very long distances (up to 50 km) while still maintaining quite low power consumption. LoRa has been successfully employed in several applications during the last few years [17].

Hundreds of protocols are available which feature innovative communication schemes and specific synchronization algorithms. Choosing the most appropriate protocol is a key factor in the design and optimization of a distributed measurement system because, together with power consumption, the network limitations are the most constraining issues in such applications.

Case Study

As an example of possible application of distributed systems in the instrumentation and measurement field, a solution for environmental monitoring recently developed at the Polytechnic University of Turin is briefly discussed here. Such a solution has been employed with success in several monitoring campaigns carried out both in Italy and abroad. The proposed solution consists of small battery-powered wireless sensing nodes, a suitable data collector, a dedicated cloud infrastructure where all measurements are stored, and several user clients. Two different versions have been developed: one that employs a dedicated protocol for the node communication [18] and the other, instead, that employs BLE [8].

Fig. 5 shows the architecture of the monitoring system, highlighting the data flow from the sensing nodes to the final user clients. Detail of the sensing node implemented for the BLE version is shown in Fig. 5b.
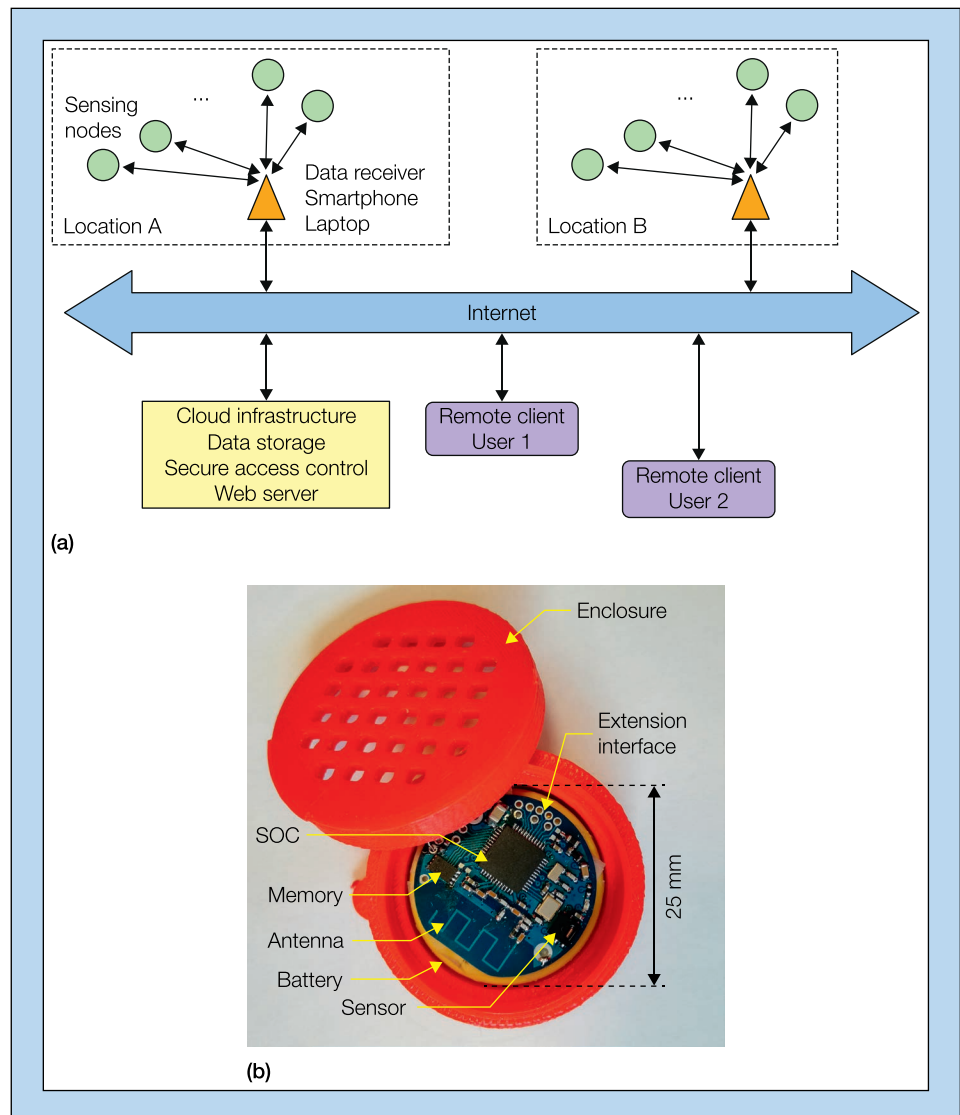

Fig. 5. (a) Block diagram of the monitoring system showing how data are exchanged by the system components; (b) Implementation detail of a BLE sensing node (reprinted with permission, © 2018 IEEE).

Both versions feature sensing nodes that are designed to monitor the micro-climatic conditions in museum environments, even though other quantities can be conceived. The nodes, whose dimensions including the battery are 25 mm diameter and 15 mm thickness, are able to periodically measure temperature and relative humidity (RH) with an accuracy of 0.3 °C and 2% RH, respectively.

These nodes are also capable of storing on an internal non-volatile memory more than 135,000 measurements in case no sink node can be reached. Each node can be individually calibrated and the calibration data can be stored both on the sensor itself and on the cloud, so that each measurement can be automatically corrected.

The version employing the custom protocol is characterized by an ultra-low power consumption which allows each sensor to operate with a measurement period of 15 min for more than three years without any maintenance. This solution requires a dedicated data receiver, and it features a quite long data latency (up to 15 min) due to the deep-sleep mode employed to reduce the power consumption.

The BLE version is more recent. It is compatible with any standard BLE device, including smart phones and laptops, and features a much lower data latency (about 5 s). Nevertheless, its operative life can still reach about three years under equal operative conditions.

Both versions are able to transmit in real-time the acquired data when a suitable receiver is deployed in the node range. Additionally, the receiver can automatically upload the received data on the cloud infrastructure when an Internet connection is available. Thus, all of the acquired data can be remotely accessible by authorized clients.

Such a solution has been developed specifically for applications related to cultural and artistic artifacts, carrying out several optimizations:

◗ node size has been minimized, and shape and color of the enclosure can be selected to reduce the visual impact on the museum exhibitions;
◗ power consumption has been reduced as much as possible to limit the maintenance of the system and prolong its operative life;
◗ data are securely stored on the internal memory so that no data can be lost even in case of missing connection or system failure;
◗ periodic calibrations can be carried out to maintain an accuracy suitable to the application;
◗ a cloud infrastructure has been integrated so that data can be accessed remotely and in real-time if an Internet connection is available.

Of course, the solution can be employed in several other fields by changing the quantities to be measured and/or the data storage solutions.

Conclusions

Several applications can require a distributed acquisition of data and environmental parameters. In such applications, the employment of distributed measurement systems and wireless sensor networks can be of great benefit. During recent decades, such systems have experienced rapid development due to both the development of new efficient communication protocols and the introduction of highly-integrated and performing chips, which are progressively increasing computational capabilities while decreasing size and power consumption.

Nevertheless, the design of a distributed measurement system still requires great effort due to optimize the system to counteract both technological limitations and application-specific constraints. It is compulsory to undertake a multi-disciplinary approach which includes informatics, telecommunications, electronics, analog and digital processing, sensor and battery technology. Furthermore, such systems should be properly framed with a measurement approach, and therefore, special care should be always devoted to address aspects such as accuracy, stability and traceability which are fundamental to guarantee the reliability of the acquired data.

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