The WISE-MUSE Project: Environmental Monitoring and Controlling of Museums based on Wireless Sensors Networks

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ABSTRACT: A major concern to all museums' managers is to properly conserve the artwork in museums and, for that to be achieved, it is fundamental to monitor the museum's environment. Therefore, it is critical to continuously measure some environmental parameters, such as temperature, relative humidity, light and, also, pollutants, either in storage or exhibition rooms. The deployment of a Wireless Sensor Network (WSN) in a museum can help implementing these measurements continuously, in a real-time basis, and in a much easier and cheaper way than traditional procedures. In this paper, we describe an experimental testbed deployed in a contemporary art museum that is located in Madeira Island, in Portugal, and it reveals the preliminary results of these experiments. For this purpose, we have developed a new wireless sensor node that brings some advantages when compared with other commercially available solutions. This work is being developed in the context of the ongoing project on museum environmental and structural monitoring using WSNs, the WISE-MUSE project.

KEYWORDS: Active tags, antennas, concrete, debris tracking system, ultra-wideband (UWB).

1. INTRODUCTION

The conservation of artwork in museums is a very well known problem, either in exhibition rooms or in archival collections. Their degradation is a result of being exposed to both human intervention and environmental variations. Monitoring the museum's environment is one of the most important tasks and concerns of all museums. In order to properly conserve the artwork it is critical to continuously measure and control some parameters, such as temperature, relative humidity, light and, also, pollutants (in terms of a museum's environment, pollutants can be: carbon dioxide, several types of acids, dust particulates, etc.).

It is also crucial to consider that the desired values for these parameters depend on the type of material or on the group of materials (typical in contemporary art) that constitute the artwork. So, depending on the type of works that are in exhibition or in storage rooms, different rooms may have different requirements regarding environmental conditions. The main goal of preventive conservation is to maintain the artworks under basically constant levels of, above all, humidity and temperature. However, in the case of rare objects and artefacts, the temperature and humidity levels must be controlled very precisely.

Today's museum managers are faced with the constant demand of gaining greater control of the indoor environment, under increasing budgetary constraints. Those in charge of historic buildings have the added complexity of preserving not only the existing artwork but also the building's historic structure. Besides, in this type of environments, it is very important to minimize the visual impact caused by monitoring systems for esthetical reasons. So, both kinds of protections must be accomplished with minimal intrusion from the new system being installed.

A Wireless Sensor Network (WSN) typically consists of a large number of tiny wireless sensor nodes (often simply referred to as nodes or motes) that are densely deployed (Akyildiz et *al.*, 2002). Nodes measure some ambient conditions in the environment surrounding them. These measurements are, then, routed to special nodes, called sink nodes (or Base Station), typically in a multi-hop basis. Then, the sink node sends data to the user. Depending on the distance between the user and the network, a gateway may be needed in order to bridge both, either through the Internet or satellite (e.g., in case of remote monitoring).

A sensor node typically consists in five components: sensing, memory, processor, transceiver (transmitter and receiver) and battery. Nowadays, nodes are intended to be small and cheap. Consequently, their resources are limited (typically, limited battery, reduced memory and processing capabilities). Moreover, due to short transmission range (caused by restrained transmission power), nodes can only communicate locally, with a certain number of local neighbours (Akyildiz et *al.*, 2002). So, nodes have to collaborate in order to accomplish their tasks: sensing, signal processing, computing, routing, localization, security, etc. Consequently, WSNs are, by their nature, collaborative networks (Gracanin et *al.*, 2006].

Taking advantage of wireless communications, WSNs allow for a wide range of applications: environmental monitoring, catastrophe monitoring, health, surveillance, traffic monitoring, structural monitoring, security, military, industry, agriculture, home, etc.

The deployment of a WSN in a museum can help implement these measurements continuously, and in a much easier and cheaper way. Besides cost and flexibility, the use of WSNs can bring several advantages: 1) it causes almost no visual impact in visitors due to the small size of sensor nodes and to the absence of cables, what is extremely important in a museum; 2) also, it eliminates the problems inherent to traditional measuring equipments, such as mechanical hygrothermographs, psychometers and hygrometers; there are no moving parts to break and it stays in calibration; 3) moreover, there is no need for specialized employees to implement these measurements, as occurs when traditional measuring equipments are used.

In this paper, we describe an experimental deployment of a small WSN in a contemporary art museum called Fortaleza São Tiago, located in Madeira Island. This WSN aims at monitoring the environment of the museum, both for artwork and building conservation purposes. We also present a new wireless sensor node that we have developed specifically to environmental monitoring applications, but considering the specific requirements of the museum, for example, reduced size and cost. This is one of the main contributions of our work. Moreover, we highlight all the problems identified at this initial phase, which will influence the final deployment of the complete WSN. This work is being developed in the context of the WISE-MUSE project, an ongoing project on museum environmental and structural monitoring using WSNs.

This paper is organized as follows. Section II describes the related work in the area of WSNs applied to the monitoring of museums or historical buildings. Section III presents the problem of environmental monitoring of museums and proposes the use of WSNs as a cheap and suitable solution. Still in this section, the objectives of the Wise-Muse project are outlined, a new sensor node is presented, and a practical testbed deployed in a museum is described as well as the respective network topology. Besides, the problems identified during these experiments are outlined and the results are described. Section IV describes a monitoring system that is being developed specifically for WSNs, whereas Section V and VI provide some conclusions and some perspectives of future work.

2. RELATED WORK

Nowadays, there are some works related to the deployment of WSNs in museums; nevertheless, the most common applications are, usually: to use WSNs for security reasons (Wang et *al.*, 2007; Onel et *al.*, 2006); or to monitor the number and distribution of visitors in the museum (Pai et *al.*, 2007); or for the creation of interactive museums [Pai et *al.*, 2007; Heidemman & Bulusu, 2001; Oldewurtel & Mähönen, 2006).

There are some commercially available wireless equipments that measure humidity and temperature (Omega, 2009; 2DI 2009), however they have bigger dimensions and they are more expensive than wireless sensor nodes.

Spinwave Systems offer a solution for preserving a building's architecture using WSNs (Spinwave, 2009). Spinwave claim to provide precise control and monitoring of environmental variables, such as temperature and humidity, in buildings where wired sensors are not feasible or are prohibitively expensive. However, they do not monitor light or pollutants. Besides, the nodes are expensive. They also claim to ensure minimal disruption to building occupants and improved indoor climate; but, nodes are quite big for being applied in an environment where the visual impact is of extreme importance.

Lee et *al.* (2008) present a scenario of applying WSNs to monitor the environment of art galleries, but focusing in measuring only humidity and temperature. However, the paper focus on a different problem, i.e., on evaluating the efficiency of the ALOHA protocol without retransmission, when transmitting from sensor nodes to a base station. Del Curto & Raimondi (2006) present a work where WSNs have been used for preserving historic buildings. Crossbow manufacturers (Crossbow, 2009) present two systems to be applied in museums and archives: a system that monitors humidity and temperature, the CLIMUS, and a system that controls the air conditioning unit, the REAQUIS. However, they do not use WSNs; sensors used are wired are much bigger than wireless sensor nodes commercially available.

Our main goal is to create a WSN for monitoring and control of the most critical environmental parameters, which are humidity, temperature and light, in museums (exposition rooms and storage rooms). We are also using smaller and cheaper wireless sensor nodes than the ones used by Spinwave, (2009). These factors are the basis that makes our solution more suitable to the environmental monitoring of museums or historical buildings. As pollutants are also are a major concern for museum managers, we aim at monitoring pollutants, but in a subsequent phase of the WISE-MUSE project.

Data collected by these sensor nodes is sent to another node, the sink node and, then, to the user who is responsible for this monitoring system. The user will be able to consult the collected data in real time, in a computer (via graphs, tables, colour gradients, etc.); he will also be able to consult the data historic whenever needed. Additionally, we intended to integrate the visualization of data in a 3D representation of the building.

Furthermore, we are connecting the WSN monitoring system to the air conditioning and dehumidifying devices in order to automatically control the temperature and the humidity of both the exhibition and storage rooms.

3. APPLYING WSNS TO MUSEUMS' ENVIRONMENTAL MONITORING

Today's museum managers are faced with the constant demand of gaining greater control of the indoor environment for preventive conservation of art purposes, under increasing budgetary constraints. In the particular case of Fortaleza São Tiago, in Madeira Island, Portugal, environmental measurements are performed in a very rudimental way, using traditional and very expensive measuring equipments, such as mechanical hygrothermographs, psychometers and hygrometers. These measurements take too long to be performed in the all museum and require a specialized person for this purpose. Besides, these equipments require calibration and cause visual impact on visitors and on exhibition rooms. For all these reasons, these measurements haven't been performed as often as they should, which means numerous times a day. In contrast, measurements are usually carried out once a day. Besides, the administration choice regarding a more flexible and practical solution is limited by severe budgetary constraints.

The deployment of a WSN in a museum can help to implement these critical measurements automatically, continuously, and in a much easier and cheaper way. It causes almost no visual impact due to the small size of sensor nodes and to the absence of cables, what is extremely important in a museum. Also, it eliminates the problems inherent to traditional measuring equipments; there are no moving parts to break and it stays in calibration.

Our goal is to create a WSN for monitoring not only humidity and temperature, but also light and some pollutants, in a museum, for art conservation purposes. This work is being developed in the context of the WISE-MUSE project, an ongoing project that aims at the application of WSNs to museum environmental and structural monitoring and control. Some of our preliminary work has been published (Brito et *al.*, 2008), but it refers to tests that were conducted using a commercial sensor. All the results presented in this paper refer to tests performed with our prototype.

Our initial deployment at the museum of contemporary art, Fortaleza São Tiago, serves as a proof-of-concept and consists of a small group of wireless nodes capturing environmental data continuously. Data collected by sensor nodes is sent wirelessly to a database, through the sink node that is connected to a PC. Data can be visualized, in real time, through a web page, in different ways: tables, graphs, colour gradients, etc., or through data reports.

Figure 1 illustrates the phases involved in the environmental monitoring of a museum. There are, essentially, five phases: it starts with the monitoring of temperature, humidity, light and pollutants; then, collected data is sent to a data repository; after that, this data can be visualized in different formats (graphs, tables, colour gradients, etc.); afterwards, data is analyzed to verify its compliance with the art conservation rules; if not, alerts are sent to the Museum's staff; finally, the environment conditions are automatically controlled and, therefore, optimized accordingly to the analysis results.

3.1 The WISE-MUSE Project

As main goals, the WISE-MUSE project includes: 1) to create a WSN for monitoring the most critical environmental parameters in museums (exposition rooms and storage rooms); 2) to monitor pollutants as they also are a major concern for museum managers; 3) to give the users of this monitoring system the possibility of consulting the collected data in real time, in a computer (via graphs, tables, colour gradients, etc.); 4) to consult the data historic whenever needed; 5) to visualize data integrated in a 3D representation of the building; 6) in order to increase the efficiency of this environmental monitoring system, to automatically send an alert to the user if a significant variation (below or above the required levels) on at least one of the measured parameters occurs, through a mobile phone (text message) or by e-mail; and 7) to install a system based in wireless video cameras that improves security by sending alerts in case of intrusion or robbery.

As the architecture for all the components of the project is an ongoing work, in this paper we will just present the basic ideas and the architecture of a 3D awareness and monitoring tool that is being developed specifically for WSNs.

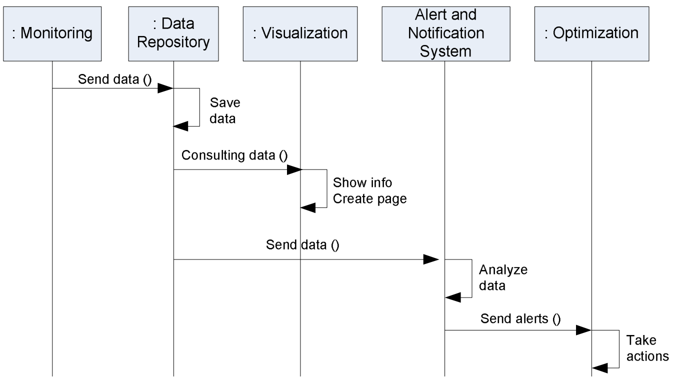

Figure 1. Phases involved in a museum's environmental monitoring.

3.2 Development of a new wireless sensor node

We have developed a new wireless sensor node, which is shown in Figure 2. It is designed specifically for environmental monitoring applications, but also considering the specific requirements of the museum, for example, reduced size and cost. This device emerges as the element that collects the environmental parameters, such as temperature, humidity and light. In addition to these three parameters, it is possible to send the battery status (internal voltage) and the RSSI signal. The sensor node transmits the captured data to the base station, via radio frequency (RF).

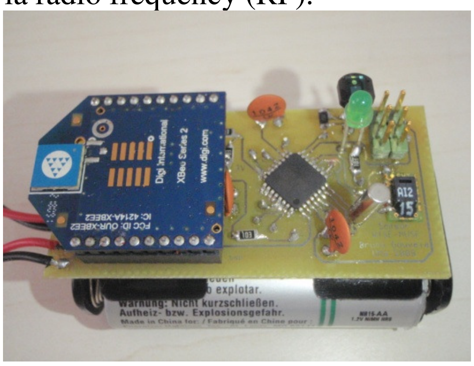

Figure 2. New Wise-Muse sensor node.

The radio module used is the XBee or the XBee PRO, from the Digi manufacturer (Digi, 2009), which operate according to the ZigBee protocol (ZigBee Alliance, 2004), i.e., it is designed according to the IEEE 802.15.4 standard and to support the specific requirements of WSNs (above all, low cost and low power). The ZigBee protocol allows the creation of PAN (Personal Area Networks) networks, supporting several network topologies, namely star, mesh and cluster-tree.

To meet the requirements of the museum in terms of the physical location of the rooms that needed to be covered by the WSN and, consequently, in terms of transmission range (please consult section 3.3) we had to employ a cluster-tree topology. As a result, the type of nodes we needed to deploy were some end devices, some routers and one coordinator. The end devices and the routers were developed by us, whereas the coordinator was acquired to DIGI manufacturer. Nevertheless, the router created can also act as an end device whenever needed; in our experiments, it was used as both a router and as an end device. The differences between the end devices and the routers, at the hardware level, reside in the power supply module since it has to be connected to an electricity socket; the router can never be turned off or go into the sleep mode. At the software level, there are also some differences since it has to be programmed as a ZigBee router, i.e., it has to receive data from the end devices that are wirelessly connected to it (i.e., end devices that are not under the range of the coordinator), and forward this data to the coordinator (sink node).

The WISE-MUSE sensor node, which corresponds to the ZigBee end device, was designed and built from scratch, with a set of components to meet the proposed requirements. This is a node of small dimensions, which causes minimum impact in the Museum. Its low cost is one of the strengths of this sensor node (less than 70€). Another advantage is its low energy consumption.

To be more precise, the WISE-MUSE sensor node has four main blocks:

- The power unit, which is composed of two AA batteries and a step-up circuit that allows to guarantee the supply of a constant power (3.3V) to the microcontroller Xbee and to the sensors;
- The microcontroller that is the "brain" of the node. It receives data from multiple individual sensors, processes it and, then, sends it through an Xbee radio frequency card;
- Two specific sensors: a light sensor that measures the brightness in the rooms of the Museum, and a sensor that measures both temperature and humidity;
- The transceiver module that transmits the collected data.

As just mentioned, the microcontroller is the sensor's core. To guarantee an easy programming of this component, it was designed to be easily connected to a programmer, using the AVR-ISP500 protocol[1]. Using this connection, the code can be easily updated whenever necessary. The chosen microcontroller is the Atmega 168 (Atmel, 2009), since it presents a set of characteristics that fits almost perfectly all our purposes; its low cost, low consumption and high performance are the main reasons for this choice.

The sensor elements chosen are the SHT15 humidity and the temperature sensor, from the Sensirion Company (Sensirion, 2009), and the S1087 photocell, from the Hamamatsu Company (Hamamatsu, 2009). The photocell captures the sunlight and returns a value of voltage to the microcontroller, which is then converted to the intensity of sunlight (LUX) unit values. The SHT15 sensor calculates the relative humidity and the temperature values. This is a CMOS industrial device, totally calibrated, that allow for good stability at low cost. Its accuracy is much appropriated considering the requirements of the project (+/-2% for humidity and +/-0.3Cº for temperature).

In order to meet the power autonomy requirements of a sensor node, each node is powered by two AA batteries (1.5V each) that feed the microcontroller, the Xbee module and the sensor STH15. These batteries have a capacity of 2450mAh and an output voltage of 1.5V. Their technology is the Nickel Metal hydride and they weight only 28g. Our goal is that the batteries last between 2 and 3 months, but this is still being tested.

Finally, we describe the modules for radio transmission frequency (Xbee or Xbee-PRO from Digi manufacturer). These modules were chosen because they require minimal power and because they provide a real and consistent delivery of information between devices, operating at the 2.4GHz ISM frequency band. Although there are other brands for radio transmission modules with lower power consumption, the popularity and the characteristics of Xbee modules determined our choice.

Table 1 presents a comparison of sensor nodes that could be used in the environmental monitoring of museums. We have considered the nodes' characteristics, as described in the manufacturers' datasheets. It is important to highlight that, in the current market, there are several RF modules separated from the sensing modules. Therefore, we attempt to look beyond the prototype created in the project, by analysing other solutions that perform the collection and transmission of data in these indoor environments.

Analysing Table 1, there are several advantages and disadvantages of each solution proposed for monitoring environmental parameters. At the sensing module level, the sensors presented are quite similar. Most of the modules use the SHT15 or STH11 sensors, by Sensirion, and their accuracy does not vary much, about +/-0.3ºC for temperature and about +/-3% for relative humidity.

Almost all sensor nodes collect light, temperature and humidity, with the exception of the Mica2 Sensor Board MTS101CA that can't measure the humidity. The Mica Z reads other kind of data, but this is not necessary in the specific case of the Museum. Besides, Mica Z has the disadvantage of a higher cost.

Regarding the microcontroller there are some considerable differences. Most microcontrollers are manufactured by Atmel, with the exception to the Tmote Sky sensor, which is manufactured by Sentilla (Sentilla, 2009). Atmega devices have many features in common with our prototype; The WISE-MUSE prototype presents a smaller flash memory; however, this factor should not be seen as a disadvantage since it conducts to a reduction on the amount of code programmed into the microcontroller. Consequently, the microcontroller has to process less amount of code what leads to a lower power consumption of the node. Therefore, it is not necessary a bigger flash memory. We verified that the energy consumption of our prototype can be reduced when operating at a frequency of 1MHz. In these conditions, its consumption can be decreased to 0.3mA, a value smaller than for the other devices.

The Mica motes (Crossbow, 2009) must be programmed through a base station, which involves an additional cost. The Tmote Sky and the WISE-MUSE nodes offer an advantage over the others; they are more easily programmed. The Tmote is programmed using USB, while the Wise-Muse prototype is programmed using the Olimex programmer that uses the AVR-ISP500 protocol.

In relation to the transceivers of each sensor node, all of them use the IEEE.802.15.4 protocol, which is the most appropriate protocol for WSNs. The Mica 2 operates in the 868/916Mhhz, 433MHz or 315MHz ranges, while the others use the 2.4GHz range.

We believe that the Xbee module used in the WISE-MUSE prototype is well ranked due to its higher power transmission. Using the Xbee-PRO which allows an even higher transmission range what is one advantage when comparing to the other nodes. Its disadvantage regards the energy

[1] AVR-ISP500 is USB low cost in-system programmer for AVR microcontrollers. It implements the STK500v2 protocol as defined by Atmel. ISP means In-System Programmable.

consumption; however, the Xbee is designed to enter in the sleep mode, waking up only in pre-defined intervals to send data; in this way, the problem of energy consumption is minimized.

Looking to the sensor nodes as a whole, they all have similar dimensions, and the WISE-MUSE mote presents a very low cost when compared to the Mica motes.

Table 1 - Comparison between the WISE-MUSE mote and other commercially available motes

SENSOR NODES					
Characteristics		**WISE-MUSE**	**Mica 2 (MPR400CB) + Sensor Board (MTS101CA) [13]**	**Mica Z (MPR2400CA) + Sensor Board (MTS400CB) [13]**	**Tmote Sky [18]**
Produced by:		The authors at the UMa	Crossbow	Crossbow	Moteiv Corporation
Sensors	*Ambient parameters*	Light, relative humidity, temperature and battery level.	Light, temperature, and prototyping area	Light, relative humidity, temperature, 2-axis accelerometer, and barometric pressure	Humidity, temperature, and light
	Temperature and humidity sensors	SHT15	Termistor	SHT11	SHT11 or SHT15
	Accuracy	Temp: +/- 0.3Cº Hum: +/- 2%	Temp: 0.2 Cº	Temp: +/- 0.2ºC Hum: +/- 3.5%	Temp: +/- 0.2ºC or +/- 0.3Cº Hum: +/- 3.5% or +/- 2%
	Light Sensors	S1087 by Hamamatsu	CdSe photocell	TLS2550, by TAOS	S1087, by Hamamatsu
Transceiver	*Module*	Xbee or Xbee PRO, both by Digi	Chipcon Wireless Transceiver	TI CC2420 802.15.4/ZigBee compliant radio	Chipcon Wireless Transceiver
	Frequency	2.4GH	868/916 MHz, 433 MHz or 315MHz	2.4Gh	2.4GHz
	Standard	IEEE.802.15.4/ Zigbee	IEEE.802.15.4/ ZigBee	IEEE.802.15.4/ ZigBee	IEEE.802.15.4/ ZigBee
	RF Power	0dBm to 18dBm (PRO)	-20 to 5dBm	-24 to 0dBm	0dBm
	Outdoor range[2]	100mt to 1200m (PRO)	150mt	75 to 100mt	50 to 125mt
	Current Draw (Tx)	35mA @ 0dBm[3]	27mA @5dBm	17,4mA @ 0dBm	17,4mA @ 0dBm
Processor	*MCU*	Atmel, Atmega 168	Atmel, ATmega128L.	Atmel, ATmega128	Texas Instruments MSP430 microcontroller
	Current Draw (in Active mode)	0.3mA @1MHz 1.9mA @4MHz 6.8mA @8MHz	5mA @4MHz 17mA @8MHz	5mA @4MHz 17mA @8MHz	2.4mA @ 8MHz
	Flash Memory	16Kb	128kb	128kb	48kb
	Programming access	ISP	Base station	Base station	USB
	Serial Communication	UART	UART	UART	UART
	Physical dimensions (mm) (Excluding battery pack)	(58x28x12)	(58x32x10)	(58x28x10)	(65x32x22)
Sensor Node Price		70€	352€	[4]	82€

[2] Considering an outdoor environment without obstacles.

[3] The consumption of the Xbee´s module in RF transmission is certainly a little below than 35mA, because this value is not totally expensed with the RF transmission, but also includes some processing activities.

[3] No information has been obtained so far on this feature, however as the sensing module of the Mica Z is superior than the Mica 2, the total cost of the module will be higher.

In conclusion, it is important to note that the module created was designed and built for the specific indoor environment monitoring at the Museum, presenting a number of advantages that may be attractive for this monitoring application, where its skills are within the requirements of the final client. Moreover, this new sensor node brings some advantages when compared to other commercially available solutions, such as low cost, small size, low power consumption, and higher transmission range.

3.3 Field Deployment

With this experimental testbed, we aim at testing the behaviour of the new wireless sensor nodes, created in the context of the WISE-MUSE project, and at identifying some problems regarding both the nodes and the application scenario.

These experiments were conducted in two storage rooms, since these rooms are the most affected by humidity and, consequently, where automatic environmental monitoring and control is more urgent.

To evaluate the signal propagation indoor and outdoor, extensive signal measurements were performed (using the Received Signal Strength Indicator – RSSI - parameter) in the two storage rooms, located in the first floor, in the office (where the Museum's staff works), located on the second floor, and in the outdoor space that stays in between these three places. This allowed us to characterize the signal propagation, the obstacles and other factors that restrict its propagation, and to evaluate the transmission range and, therefore, to decide where to locate the sensor nodes.

We have conclude that it was necessary to deploy five end devices, two routers and one coordinator, as Figures 3 and 4 illustrate: two end devices in storage room 1, three end devices in storage room 2, which is bigger than the other, one router in each storage room, and one coordinator (sink node) located at the museum's office.

Currently, this WSN measures the most important parameters, which are temperature, humidity and light; however, internal voltage is also monitored so that the user is aware of the state of the nodes' batteries. The sensor nodes are programmed to measure and send data once each 10 minutes.

3.4 Network Topology

The network topology of the experimental WSN created is illustrated in Figure 5. As mentioned before, the topology created is the ZigBee Cluster-Tree topology.

Its representation is based in the WSNSCW (Wireless Sensor Networks Supported Cooperative Work) model, published in Brito & Rodríguez (2008).

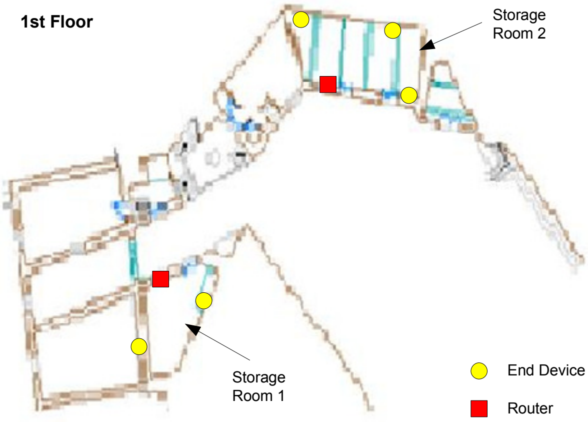

Figure 3. Experimental WSN deployment in Museum Fortaleza São Tiago, more precisely at storage rooms 1 and 2.

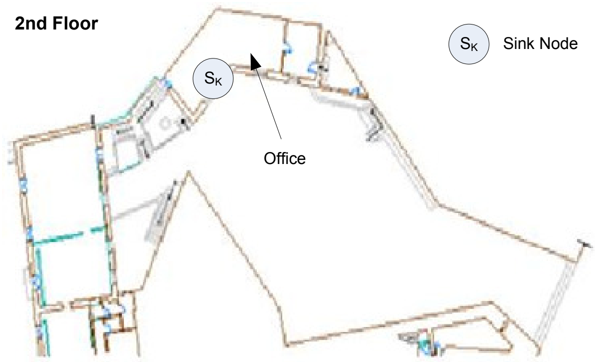

Figure 4. Experimental WSN deployment in Museum Fortaleza São Tiago, more precisely at the manager's office.

WSNSCW is a formal model of collaborative work created specifically to WSNs. However, WSNSCW allows not only the modeling of collaborative work (based in CSCW concepts), but also the modeling and visual representation of all the entities that can constitute a WSN, as well as its properties, which is fundamental to completely represent a WSN. The network hierarchy (from the collected data to the user) can be visualized, as well. Moreover, it is a generic model because it can be applied to heterogeneous networks (any type of nodes, any size, any hardware characteristics, any types of signals, etc.). The symbol, concept and description of all the entities included in the model are illustrated in Table 2. Note that we define entities as all the components that might exist in a WSN.

According to the WSNSCW model definitions, the specific case of the WSN deployed in the museum can be represented as deployed in Figure 5. The set of all nodes forms a cluster (represented by the dashed circle) or a PAN network using the ZigBee terminology. Nodes N_1 and N_2 act both as end devices and routers and each one is located in a different storage room. Nodes N_3 and N_4 are the end devices located in storage room 1, whereas the three nodes N_5, N_6 and N_7 are the end devices located in storage room 2, which is bigger than the other room and, therefore, needs more end devices to guarantee that the whole storage area is covered. There is one coordinator (sink node) located at the museum's office.

Data collected by nodes N_3 and N_4 is sent to the router N_1. Accordingly, nodes N_5, N_6 and N_7 send collected data to the router N_2. The routers N_1 and N_2, in turn, send data to the coordinator. Note that communication occurs on a one-hop basis, since the XBee modules do not allow for multi-hop communication. The obstacles (in this case, artworks shelves) existent between the nodes are also represented in Figure 5; a picture of this type of obstacles is shown in Figure 6.

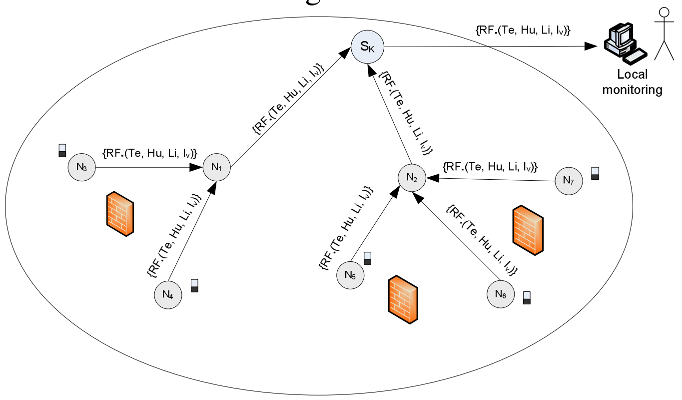

Figure 5. Representation of the WSN created in Fortaleza São Tiago, using the entities and notations defined in the WSNSCW Model [13].

Figure 5 also represents the type of signal that is being used (RF) to transmit the collected data (Te – temperature, Hu – humidity, Li – light, and Iv – internal voltage). The battery level of each battery-supplied node, which corresponds to the internal voltage parameter, is represented near each node. Note nodes N_1 and N_2 do not have any battery symbol associated since they are being supplied by an electricity socket.

3.5 Problems Identified

Several problems were identified during this experimental phase. These problems are essentially related with the type of building where the WSN is being deployed but, also, with the hardware characteristics and resource limitations of the wireless sensor nodes.

Type of building - Fortaleza São Tiago was built in the 17th century as a military fortress. Therefore, the width of the walls is very large (from 0,5 to 1m, with 1m being the predominant width). The building has double doors and windows. It has an irregular shape and its rooms and terraces are distributed among three floors, as shown in Figure 7. All these factors influence and difficult the signal propagation and, consequently, the transmission range of sensor nodes.

Location of the building - The museum is located by the sea, as can be seen in Figure 7, what obviously influences the humidity and temperature levels of the building.

Location of the sensor nodes - Sensor nodes must not be placed near to the visitors' passageways, in order to avoid the risk of being stolen or damaged. Besides, nodes need to be located in rather discrete places. This will also help to minimize the visual impact caused by the nodes.

Figure 6. Shelves that are used to store artworks in storage rooms, and that impose some restrictions to signal propagation between nodes N_3 and N_4, and between nodes N_5, N_6 and N_7.

Transmission Range - The transmission range of sensor nodes (XBee modules) is not as good as described in the manufacturer's datasheets, even in line-of-sight conditions. In order to increase the transmission range of sensor nodes, we had to use the XBee PRO modules that have a higher transmission power than XBee modules. So, equipping the nodes with a better radio device increases the transmission range, but this obviously affects the energy consumption, which is a typical problem of WSNs. To minimize this problem we have decreased the number of measurements and transmissions per time period. Using a more efficient antenna can also help to decrease the energy consumption.

Type of antenna – Nodes are equipped with omnidirectional antennas. Thus, the location of the nodes near the walls can cause signal reflections. Changing the type of antenna to a more efficient one (directional) will improve the signal propagation characteristics and, consequently increase the duration of the batteries.

Obstacles – In the storage rooms, not only the shelves where the artworks are stored influence indoor signal propagation; its propagation is also influenced by wooden doors, glass windows and, above all, the walls. In the case of the exposition rooms, not only these factors influence the signal propagation, but the visitors themselves can also act as obstacles.

3.6 Results

In the deployed WSN, all data collected was centralized in a PC. To implement these tests and to capture data using a point-to-point connection, we used the WISE-MUSE prototype and an Xbee module as the coordinator. To visualize data we applied the program X-CTU provided by Digi. Data was collected each 10 minutes and, based on that, our system generated graphs every hour. The monitoring period for the environmental parameters started at 9:00am and ended at 5:00pm, per day. If this monitoring period had been extended to the night period, we would naturally notice an increase of humidity and a decrease of temperature.

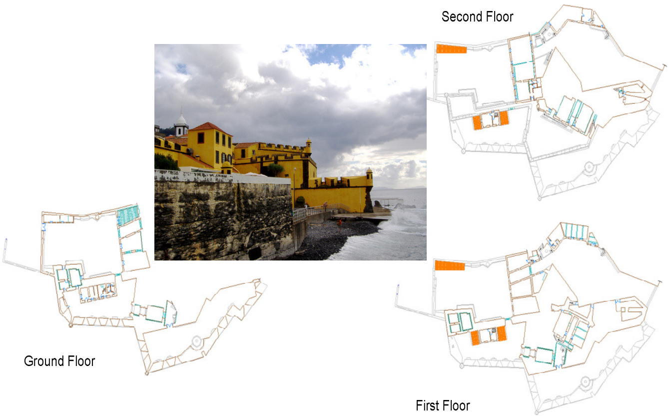

Figure 7. Museum Fortaleza São Tiago and correspondent floor plants.

Figure 8 shows the results that refer to the environmental data captured by the WSN deployed in the Museum (considering the average of all nodes), namely the graphs for temperature, humidity and light. Graphs were built from samples collected by the own nodes. After analysing collected data, it was possible to achieve some conclusions about the behaviour and the type of variations of temperature and humidity throughout the day, in the storage rooms of the museum. Considering the obtained graphs, we verified that temperature varies about 2ºC whereas humidity varies about 10% RH. According to the museum's staff, these variations are typical during the summer in this museum; however, these parameters usually vary less during winter. Figure 8 shows that light values increase throughout the day, as expected. We also noticed that the light value varies when the lights are turned on or off, even though these variations are not visible in Figure 8. In general, the results of the environmental parameters meet the expected values.

Figure 8 also shows the battery status of the two AA batteries that are used on the WISE-MUSE prototype. We have collected samples during several days to get an estimated battery lifetime. Analysing the graph, we can observe that the batteries' level follows a typical behaviour: in the first 10 days, the battery level dropped from 2.8 to 2.6 volts; however, from then on, its decrease was much lower, since in the consequent 30 days, the battery level only dropped 0.1V. Therefore, after 40 days, the sensor node remains operational. Even though the decrease of the battery level is not a linear function, we think that the battery level will remain stable for some more days. We will go on performing more tests, but we can guarantee that the WISE-MUSE prototype will have at least 1 month of autonomy being very likely that batteries can last for 2 months. These tests were performed on one node only, but in the future we will test the battery of all nodes.

We verified that these environmental parameters are not as constant as they ideally should be. Therefore, it is very important that the WSN is connected to the air conditioning and dehumidifying systems in order to automatically control, above all, the temperature and the humidity of these rooms.

These results have an error skew, which is associated with each sensor; nevertheless, we believe that these first results show us a good performance of the WISE-MUSE prototype. Some more adjustments will still be carried out in order to avoid some peak values that may occur.

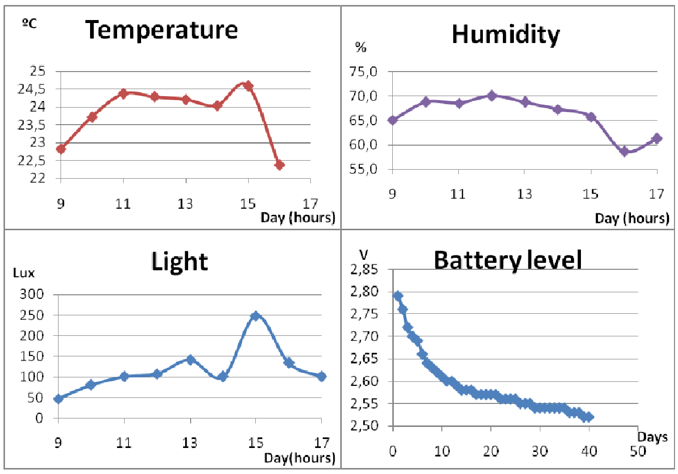

Figure 8. Data collected by the deployed WSN.

4. MONITORING SYSTEM FOR WSNS

We are developing a monitoring system for WSNs that includes a web-based monitoring platform and a 3D awareness tool. Both tools are being developed separately, but they will be integrated soon.

Opposing to traditional networks, WSNs are only useful if sensor nodes are aware of the environment surrounding them. This means that the great potential of WSNs lies in its ability to correlate collected data in time and in space (Broxton et *al.*, 2005; Hu & Servetto, 2005). This is one of the reasons why we are developing a 3D web-based awareness tool for WSNs visualization, which will be applied to the specific case of this museum's environmental monitoring.

One of the most important properties of the awareness tool is the 3D representation of the network. This is very important so the user can have a more realistic view of the network, becoming more aware of the surrounding environment (different types of terrains, different types of rooms, which obstacles might interfere with the collaboration established between nodes, etc.). This tool will allow for the visualization of different granularities: fine-grain (sensor nodes), middle-grain (clusters) and coarser (sessions) modelling level. Also, it will allow for an interactive navigation in the map of the network. Some screenshots of the preliminary implementation of the awareness tool is presented in Figure 9.

The web-based monitoring platform complements the 3D visualization of the WSN with the visualization of collected data in several different formats (tables, graphs, colour gradients, etc.). It will allow the visualization of data in a real-time basis or through data historics. Since we will apply this monitoring system to this specific project of a museum's environmental monitoring, the data visualization will be enhanced by integrating it in a 3D representation of the museum, giving the user a much more realistic view of the network.

The basic modules of the implementation of the monitoring system are represented in Figure 10. The first module transforms the raw data collected by wireless sensor nodes into international system (IS) measuring units; this module sends the RSSI (Received Signal Strength Indicator) parameter to the module that is responsible for implementing a localization algorithm that will compute the positions of sensor nodes[5], and sends environmental data to the module that is responsible for the automatic control of air conditioning and dehumidifying devices. The automatic control module is composed of a power transformer, an XBee radio and a relay. When the humidity values go outside the normal values, a command is sent by the sink node to the XBee radio (activating one of its pins); this activates the relay, which in turn connects or disconnects the dehumidifier. For the time being, the automatic control has been implemented only for dehumidifying devices, since the Museum does not have air conditioning devices. Nevertheless, the procedure would be exactly the same.

The data output from the first module is saved into a database and, then, exported to an XML file. The XML files are used not only as an input for the awareness tool but, also, for the web-based monitoring platform.

WSNs are extremely dynamic systems, both in the sense that their characteristics change over their lifetime and for the fact that sensor networks' technology (hardware and software) is subject to fast changes. To overcome this issue, any changes that might occur in the deployed WSN, obviously besides a new set of collected data, will be sent to the monitoring system, via a new XML document. This way, the collection of XML documents created during the network lifetime will represent an historical of both the data and the network evolution. Moreover, the historical will be available to be consulted whenever needed.

And, last but not least, this is a collaborative system for web-monitoring of WSNs, since it may be used, on a real-time basis, by several users that may be located in different places. This system will provide awareness, perceptibility in data monitoring, and visibility for problems detection and resolution. In essence, it will make the WSN monitoring more interesting and more intuitive, conducting to more successful decisions regarding the network maintenance.

5. CONCLUSIONS

In this paper, an experimental WSN for automatically and continuously monitoring and control the environment of a museum was presented. This solution was compared with related solutions, being outlined its advantages.

Besides being a simpler solution, the use of WSNs for environmental monitoring of a museum is, indeed, a more reliable solution. It is also less expensive than manual data collection or than a wired central monitoring system. Several problems were identified during the experiments, but they can be classified in two types. The problems related with the type of building where the WSN is being deployed, because it affects the signal propagation; and the problems related with the hardware characteristics and resource limitations of the sensor nodes, with the battery being the most limited resource. Equipping the nodes with a more efficient antenna and using a higher number of nodes will lead to the need of a lower transmission power, increasing the duration of the batteries. Also, programming the nodes so that they perform less frequent measurements and transmissions will allow for high energy savings.

We also analyzed the graphs of collected data, what allowed us to understand the behaviour and the type of variations of temperature, humidity and light, throughout the day.

One of the main contributions of our work is the development of a new sensor node created for environmental monitoring applications, which is still a prototype since it is currently being tested. Nevertheless, even at this stage, we have already demonstrated that it brings some advantages when comparing to other commercially available solutions.

[5] The reasons for choosing a RSSI-based localization algorithm are outside the scope of this paper.

Furthermore, in order to increase the efficiency of this environmental monitoring system, we have implemented a system that automatically controls the dehumidifying devices, maintaining the humidity at more constant levels.

Moreover, we are implementing a solution to automatically send an alert to the museum's manager if a significant variation (below or above the required levels) on at least one of the measured parameters occurs. These alerts will be sent to a mobile phone (text message) or by e-mail. Besides, a system based in wireless video cameras will be installed to improve security by sending alerts in case of intrusion or robbery.

6. FUTURE WORK

We have to plan the deployment of the complete WSN that will coverage all the museum's exhibition rooms, storage rooms and library. The number of nodes and its location must be planned according to their transmission range and the existence of obstacles between them. That is to say, we are going to apply the lessons learned in these experiments to create the whole WSN. We also have to extend the WSN to monitor some pollutants, in particular the carbon dioxide (CO_2).

Regarding the monitoring system, data visualization will be enhanced by integrating it in a 3D representation of the museum, giving the user a much more realistic view of the WSN.

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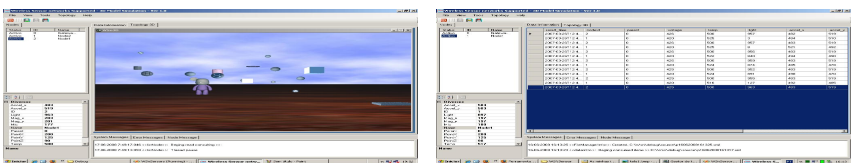


Figure 9. Preliminary implementation of the 3D awareness tool.

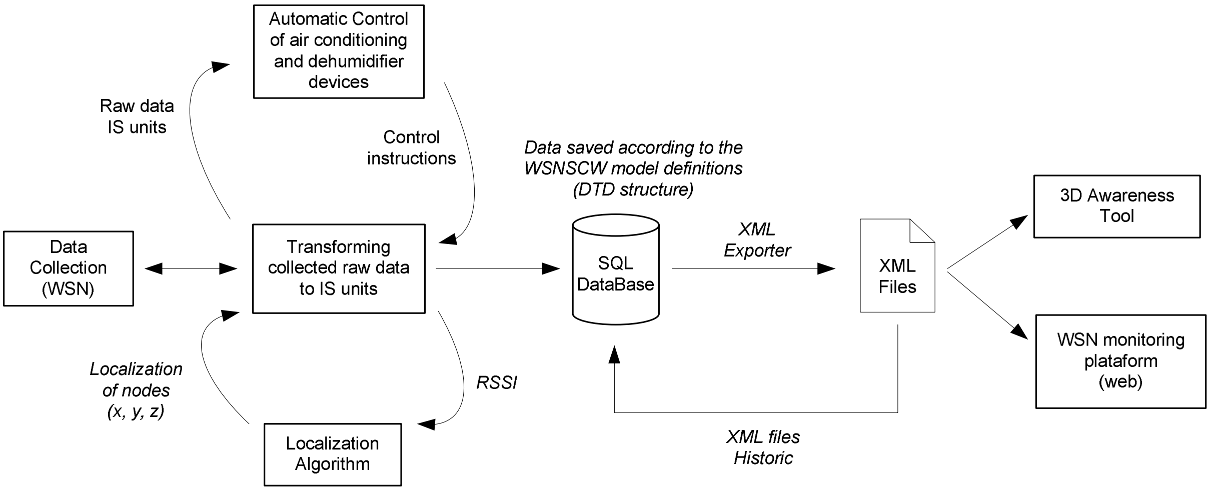
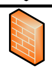
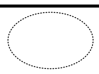
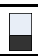
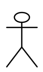


Figure 10. Basic Architecture of the Monitoring System for WSNs.

Table 2 - Entities of the WSNSCW Model (Brito & Rodríguez, 2008)

Symbol	Concept	Description
	Sensor node	Wireless sensor nodes, typically with limited resources. These nodes can be either stationary or mobile. Also, they can be in one of three possible states: active, sleep mode (in order to save energy) or inactive.
S_K	Sink node/ Base Station	Node to which data collected by ordinary nodes is sent; being responsible to send data to the gateway.
A	Anchor node	Node with known localization.
	Cluster	Group of nodes, created according to: geographical area, type of sensor, type of phenomenon, task, etc.
CH	Cluster Head	Sensor node to whom all sensor nodes in the cluster send the collected data; it is responsible for sending the received data to the Sink node.
A → B	Relationship	The arrow represents a relationship between nodes A and B. It also represents and adjacency relation between nodes A and B (see section 3.2); nodes A and B are neighbours. A relationship can be established based on: localization, phenomenon, type of sensor node, etc.
{TypeOfSignal.Data} →	Data flow	This label identifies both the type of signal being used (radio frequency, ultrasound, acoustical or light) and the type of data being transmitted between nodes (temperature, humidity, light, sound, video, internal voltage, etc.).
	Gateway	Device responsible to send the data to the user, through the Internet.
	Obstacle	An object (building, tree, rock, etc.) which obstructs line-of-sight between two or more nodes, not allowing for direct communication between them.
	Session	In a certain moment, there may be several collaborative sessions in a WSN. A session can be established based on the objective (type of phenomenon to monitor, geographical area to monitor, etc.) of the WSN.
	Battery	It represents the percentage of the sensor node's remaining battery.
	User	Person that interacts with the WSN, querying the network, visualizing data, etc. The user customizes the work of the sensor nodes; the data collected by sensor nodes is used by the users' application.