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A Wireless Sensor Network Innovative Architecture for Ambient Vibrations Structural Monitoring

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Abstract. Wireless sensor networks can be beneficial for monitoring ambient vibrations in historical buildings where the installation of traditionally wired system may be either difficult due to wiring difficulties or forbidden due to prohibitive legislation. In this paper, a novel wireless sensor network architecture is presented that is focusing on efficiently monitoring ambient vibrations in historical buildings. Traditional wired monitoring technologies are often difficult to be installed in historical buildings either to high costs for installing the wires or to prohibitive legislations. Employing a wireless system could be beneficial. However, as there is no wireless system of high resolution available in the market, an innovative network architecture is proposed that efficiently combines the benefits of both the wired and wireless systems. The problem of synchronization that this novel architecture introduces, is also discussed in this paper along with a possible solution.

Introduction

Idiosyncrasies of historical buildings have been the focus of the civil engineering scientific community for decades, mainly to foresee structural changes and preserve them against natural disasters (mainly earthquakes, floodings) and most importantly time. Historical buildings normally carry with them an enormous historical, cultural and emotional burden since citizens leaving nearby get attached to them and proudly consider them as important elements of their life and tradition.

The financial aspects involved given the touristic industry, should not be neglected. Visiting historical buildings where important events have changed the roadmap of history in various levels, is a key part of a large percentage of tourists throughout history. Undoubtedly, Italy is markedly a country of a plethora of historical buildings and preservation is a key policy for the state as well as for the European Commission. Greece also posses a large number of historical buildings that need to be preserved for the same reasons, mostly in urban areas like the city of Corfu in the Ionian Islands.

The first step towards “understanding” a building, is monitoring its structure by suitably placing sensors capable to capture ambient vibrations. These sensors report the captured data and given some time, the scientists are able to derive a profile corresponding to the particular building. This profile can be useful in many ways such as foreseeing structural problems and/or understanding changes on the buildings' behavior and in any case, the usefulness of the approach is an open research problem in the civil engineering research community.

On the other hand, a historical building is very sensitive with respect to installing a monitoring system that requires some control equipment and wiring the building between the sensors and the control equipments. The latter is prohibitive in many historical buildings due to both structural as well as aesthetic reasons. Lately, some solutions have been proposed, e.g. [1], considering wireless links between the sensor nodes and the control equipments. Under the previous light, a cross-border program between Italy and Greece has been formed attempting to give innovative solutions to problems arisings by the peculiarities of the historical buildings in Corfu (Greece) and Bari, Trani (Italy) [5].

In this paper, the architecture of such a wireless sensor network system for monitoring ambient vibrations in historical buildings is presented along with a comparison against both the traditional wired and existing wireless technologies in the market. The proposed architecture has been installed in three different buildings and its performance has been investigated thoroughly.

Wireless Sensor Networks

Wireless sensor networks have been the focus of an increased research volume during the last decade due to their meaningful and diverse applications, like data gathering, monitoring, surveillance, etc. [2], [3]. A key issue in these environments is network lifetime, since after some time nodes exhaust their batteries and are no longer functional. As such, energy consumption efficiency is fundamental for extending network lifetime.

Sensor networks are composed of a number of small and comparably cheap devices, capable of sensing, computing and communicating, scattered in large numbers in certain areas of interest [2]. There are numerous applications for sensor networks: fire detectors (e.g., inside buildings or in forest areas), nutrition level monitoring in agricultural fields, etc. Sensor networks are considered to be stationary (even though this is not mandatory), at least after their deployment. The deployment of sensors in an area of interest can be either fixed when each node takes a predefined position (e.g., a fire detector in a building) or random when there are no predefined nodes positions.

After the deployment of a sensor network, nodes start sensing their surrounding environment. In case of a particular event of interest, the corresponding sensed information is conveyed to the sink node (the collector of information in sensor networks) over a multi-hop communication path composed of intermediate sensor nodes (i.e., nodes between the source node and sink node).

It is assumed that sensor nodes use omni-directional antennas and not any other sophisticated modern technology (e.g., antenna arrays, MIMO), due to the necessity for the devices to remain small and cheap. Consequently, when a node transmits towards a neighbor node, the particular transmission may interfere with the transmissions of other nodes in the area resulting in a number of corrupted transmissions. If the rate according which data are sensed/generated in the network (i.e., the load of the network) is small, then data are expected to arrive at their final destination (i.e., the sink node) with a small probability to interfere with neighbor nodes. As the load of the network increases, some transmissions from neighbor nodes may take place simultaneously resulting in corrupted transmissions. The avoidance of corrupted transmissions and increment of successful ones per time unit, is the main objective of most Medium Access Control (MAC) protocols proposed in the area of wireless networks (e.g., local area networks, ad hoc networks, sensor networks).

Due to the multi-hop nature of WSNs, the traffic arriving at the sink node does not consist of packets belonging to the individual nodes only. Indeed, any node is expected to forward data packets, created by both itself and other nodes, towards the sink node. The volume of such traffic at a particular node, increases as its location is closer to the sink. As a result, nodes that are closer to the sink exhaust their battery resources sooner than others. Many research works have studied this problem, [4], and several ideas have been proposed, like employing multiple sink nodes, introducing a mobile sink that is able to move around the network or performing hierarchical data aggregation.

However, for the case considered here, single hop wireless transmissions from sensors directly to the particular node that collects the required information takes place, as opposed to multi-hop wireless transmissions.

Existing Approaches

The wired approach is a traditional one used for years by civil engineers and it is at mature level e.g., [6], [7], [8], [9], [10], [11]. Wires are installed between each sensor node and the acquisition point where data are gathered and stored to be further studied and analyzed.
Wireless technology regarding monitoring ambient vibrations, is a relatively new technology. The basic architecture consists of a Base Station (BS) and a number of end points or sensors. Depending on the particular building there can be only one BS in the building or more than one located at different floors.
Each BS, as also depicted in Fig. 1, is wirelessly connected to a number of sensors within its reach. The number of these sensors depends on the particularities of the building (e.g., big stone walls do not allow for good signal quality in order to achieve efficient wireless communication) and their location within the building. Each BS is connected to a series of other devices in order to accumulate data to a central point. Looking inside the end points (i.e., sensors are within these devices), a representative system architecture is the one presented in Fig. 3 which corresponds to imote3-SHM (alpha configuration) device by MEMSIC [1]. In this example system architecture a processor plays the role of coordinating all actions. There is a radio interface for wirelessly transmitting the sensed data and a selection of a number of possibilities for sensing the environment. The available options consist of a 3-axis accelerometer, another one for triggering the operation (useful for long periods of monitoring for saving battery), humidity sensor and a temperature sensor. For the case considered in this project, the accelerometer is of interest.

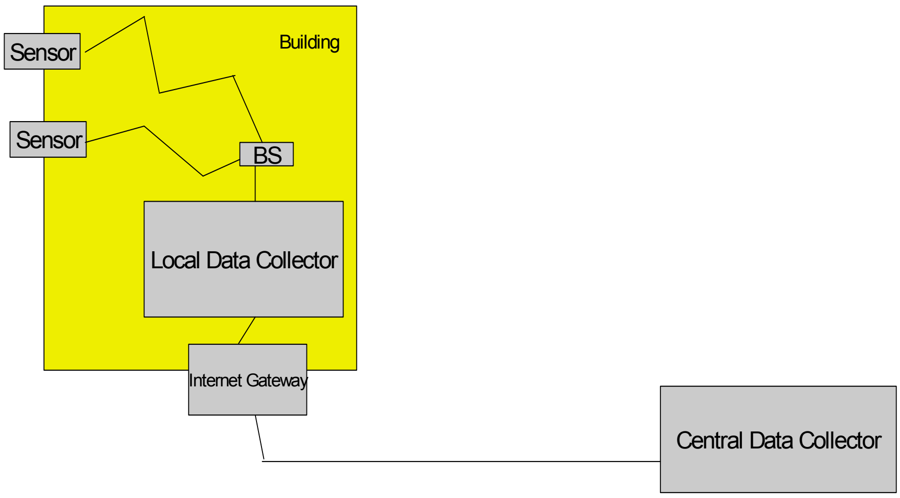

Fig. 1: Basic wireless network architecture.

This system architecture is representative to the majority of the existing systems in the area. The wireless interface ensures (e.g., through ZigBee protocol) that all the devices in the wireless network will be synchronized in order the collected information to have reference to a common time.

More specifically, as already mentioned, Fig. 1 schematically presents an example network architecture when a wireless sensor network is considered for vibration monitoring in a building, as the one presented in Fig. 2. In Fig. 1, a sensor corresponds to a device capable of sensing vibrations and transmits this information through the radio interface to BS. This sensor component actually corresponds to the system depicted in Fig. 2 or any other similar. The important part is the connection to the BS. The BS is responsible for handling the wireless communication and provides a common clock for all sensed data. Note that the location of the sensors and the BS should be such that connectivity is ensured. The range of connectivity of the wireless medium is not always predictable, especially in old buildings that normally have huge stone walls.

The example architecture depicted in Fig. 1 normally corresponds to the installation on one particular floor. This is mainly due to the range of the BS. It is expected that there will be at least one BS on each floor if not more. Certainly, and depending on the building, more than one BS may be required for each floor. One important aspect is that all BSs are synchronized between them, otherwise the sensed data will be tagged with different time stamps.

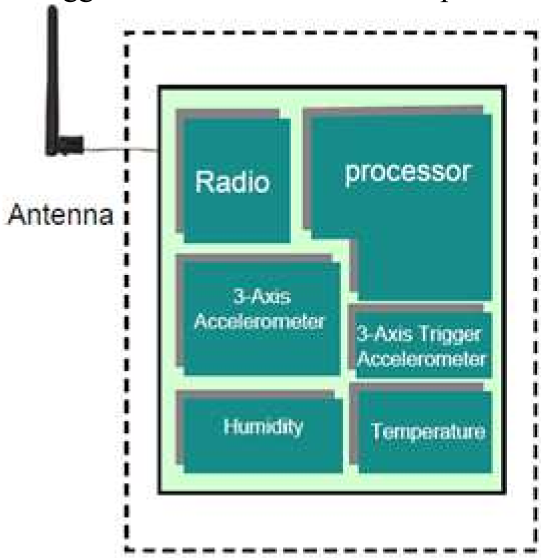

Fig. 2: End point for imote3-SHM from MEMSIC (alpha configuration) [1].

The BS collects the sensed data and forwards them to a local data collector unit. The latter can be a simple computer (e.g., a laptop) that is responsible for storing all data of the particular BS. Note that this unit is unique in the building and also receives data from any other BS in the building.

Depending on the building, the local data collector unit may forward the sensed data to a central data collector unit at another place where the actual data process will take place (e.g., in a lab). This can be possible if the building has a broadband connection. Otherwise, there is a need to receive the accumulated data manually (e.g., a person to copy them in a hard disc from time to time).

This description of the most important parts of the existing wireless network architectures that are suitable for monitoring ambient vibrations in historical buildings does not reveal some important issues and particularly the resolution in terms of bits per sample of the sensed data. Given that the type of the accelerometer is capable of capturing the particular level of vibrations (rather sensitive), the analog-to-digital converter (ADC) is responsible for the quantization of the analog signal produced by the accelerometer. In the majority of the systems investigated a 16-bit ADC is used, that is not a suitable choice for the under consideration application in this project. What is needed is at least 24-bit resolution. There is a possible solution by the so called beta configuration of the imote3-SHM of MEMSIC [1] that was not available at the market at the particular time when this study took place.

Investigations of Possible Approaches

When monitoring ambient vibrations is the key objective of the system to be designed, a close look on ambient vibrations is needed in order to ensure that monitoring is efficient and captures the required data. Ambient vibrations correspond to mild vibrations in the nearby area of the building caused by human activities like vehicles passing nearby, pedestrians etc. as well as activities within the building (people moving in the corridors, stairs etc.). Even though this system will be able to monitor large scale vibrations (e.g., earthquakes), this is not the main purpose of the system. Further details on further aspects about ambient vibrations can be found in [6], [7], [8], [9], [10] and [11].

In order to capture ambient vibration using digital technologies, there is a need for a system capable of monitoring a wide data range, or equivalently, the bit resolution to be significantly high. For the time being, wireless systems are of 16-bits per monitored sample which is not suitable. There is a need for at least 24-bits per sample.

The previous gives a guidance with respect to the design in the sense that wired technologies should be used in order to satisfy the increased bits per sample requirement. On the other hand, the need for wiring the building should be decreased in order to lower the cost of installment (fewer cables and less alterations on the buildings).

As an immediate consequence, a hybrid system can be considered that will combine the main benefits of both the wireless (no need to deploy cables) and the wired (high resolution) systems. These are the main lines along with the system in the sequel is proposed to be designed. It should be noted that one main of the factors regarding the design of the in the sequel proposed architecture, was to keep cost as low as possible since expensive prototype systems can always be proposed in the nowadays abundance of technologies.

Note that one of the main problems of wireless sensor networks is no longer a problem in this study, since within buildings power supply is expected to be available. If this is not the case (e.g., the under monitoring structure is a bridge), then this should also be taken into account. However, this study is beyond the scope of this paper.

The Proposed Architecture

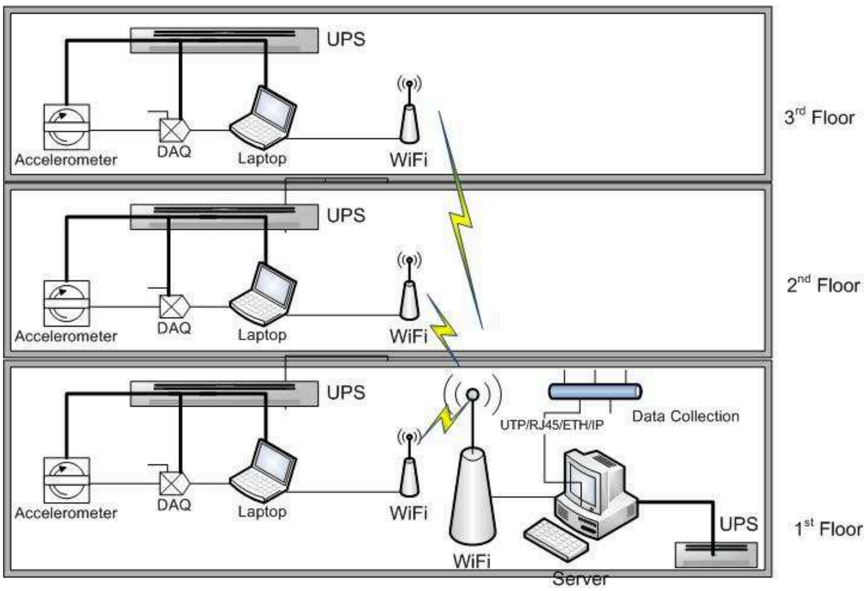

Fig. 3: A possible implementation of the proposed network architecture.

In order to overcome the aforementioned problems of resolution (24-bits as opposed to 16-bits) a novel network infrastructure is proposed in this section. A possible implementation of the under consideration system is depicted in Fig. 3.

Under this approach, an accelerometer of the desired range and accuracy will be used (i.e., capable of sensing ambient vibrations that is the focus here). This is connected (wired connection) to a data acquisition unit (DAQ) that is capable of quantizing the analog signal received from the accelerometer using 24-bits resolution. This DAQ is connected to a nearby device (e.g., a laptop) through an Ethernet interface. This device is wirelessly connected to a server in the building that plays the role of the local data collection unit. The previous setup refers to only one floor in the building. Three floors in total are expected to have installed this system.

This approach, even though it also avoids installing wires in the building and solves the resolution problem, introduces a certain problem with respect to synchronization. In particular, all three devices (laptops in the figure) that are connected to the DAQ are required to have the same time; otherwise time stamps of the sensed data will be different. In order to overcome this problem, a local network time protocol (NTP) server [12] can be installed in the premises (most likely the local data collection unit will be capable of supporting this server) in order to synchronize the devices.

Summary

In this paper, a novel wireless sensor network architecture is presented that is focusing on efficiently monitoring ambient vibrations in historical buildings. Traditional wired monitoring technologies are often difficult to be installed in historical buildings either to high costs for installing the wires or to prohibitive legislations. Employing a wireless system could be beneficial. However, as there is no wireless system of high resolution (e.g., >=24 digits per same) available in the market, a particular network architecture is proposed that efficiently combines the benefits of both the wired and wireless systems. The problem of synchronization that this novel architecture introduces, is also discussed in this paper and a possible solution using a local NTP server is also proposed.

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