Key Engineering Materials Vol 628 (2015) pp 225-230
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doi:10.4028/www.scientific.net/KEM.628.225

Submitted: 2014-05-15
Accepted: 2014-06-10
Online: 2014-08-28

Synchronization Issues in an Innovative Wireless Sensor Network Architecture Monitoring Ambient Vibrations in Historical Buildings

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Keywords: Wireless; Sensor; Network; Architecture; Vibrations; Monitoring; Data Acquisition; Accelerometer; Network Time Protocol; GPS; Synchronization; Historical Buildings;

Abstract. The problem of bridging the gap between the traditional wired monitoring systems and the wireless ones, was the objective of an innovative network architecture that elegantly combined benefits from both approaches. The monitoring focus is on historical buildings in which installing wires maybe range from difficult (e.g., fragile constructions) to impossible (e.g., prohibitive legislation). However, this innovative approach is vulnerable with respect to synchronization issues. In particular, all data sensed by different sensors need to have the correct universal time stamp. Since under this approach there is no central entity to take a synchronization role, in this paper the use of a local NTP server is proposed and as it is shown here using experimental results, this approach suffices for the particular monitoring needs. Thus, the claim that the innovative system can efficiently support the required monitoring of ambient vibrations in historical buildings.

Introduction

Wireless sensor networks [1,2] can be beneficial, when monitoring ambient vibrations in historical building is the aim of the wireless system. Even though this is a relatively new area for wireless sensor applications, a lot of consideration has been put in to it lately. In spite of the fact this is a research area traditionally dominated by civil engineering, the problems that historical buildings introduce require the assistance of the networking community.

In particular, historical buildings impose the problem of installing cables within its structure. This ranges from difficult to impossible depending on the case. In some cases, cables are allowed to be permanently installed and some times only in a temporary basis and for a short time period. However, for the majority of historical buildings, even a simple installment is prohibitive, often by hard rules such as legislation. Wireless sensor networks can provide the means for avoiding this problem by wirelessly transmitting the required sensed data.

Wireless sensor equipment already available in the market, e.g., [3], can be used when small resolution (i.e., up to 16 bits per sample) is adequate. Such systems employ a Base Station (BS) that controls the end terminals (the devices in which sensors are embedded). By controlling is meant handling the process of data acquisition/collection. The BS has absolute control and it is also responsible for synchronizing the clocks of the end terminal devices in order to make sure which samples are concurrently sensed. Several BSs may cooperate in which case one of them plays the role of the master/leader.

However, the digital world of wireless sensors has a number of limitations against the traditional wired systems (either analog or digital) and particularly on the number of bits per sample that can be dedicated. Since ambient vibrations are to be monitored [4,5,6,7,8,9], at least 24 bits per sample are required to make sure that the wireless system is capable of suitably monitoring the idiosyncrasies of the particular building category.

This problem brought together partners from both Greece and Italy under a cross-border program attempting to give innovative solutions to problems arisings by the peculiarities of the historical buildings in Corfu (Greece) and Bari, Trani (Italy) [10]. An innovative wireless sensor network architecture was proposed in order to bridge the gap between the traditional wired monitoring systems and the wireless ones, while at the same time maintaining the cost of the system as low as possible [10]. This architecture, consists of a number of comparably small traditional wired systems wirelessly interconnected. This simple and elegant approach, introduces a significant problem which is no other than synchronization. Since there is no base station installed to have control over all operation or any other entity of such capabilities, it is possible that samples concurrently sensed to be marked by different time stamps.

In order to overcome this synchronization problem, that may be proved vital in the consequent analysis, a solution based on the Network Time Protocol (NTP), [11], was employed. In particular, in every deployment a local NTP server was set up and by synchronizing from time to time various parts of the system, it made possible to achieve an acceptable synchronization level.

The aim of this paper is to show how synchronization with respect to the innovative architecture was achieved. So in the following section the particular wireless sensor architecture is briefly presented and in the next the deployment scenarios. Synchronization issues regarding these deployments as well as results are presented afterwards. Finally, the conclusions are drawn in the last section of this paper.

Ambient Vibrations Monitoring Using an Innovative Wireless Sensor Networks 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. 1.

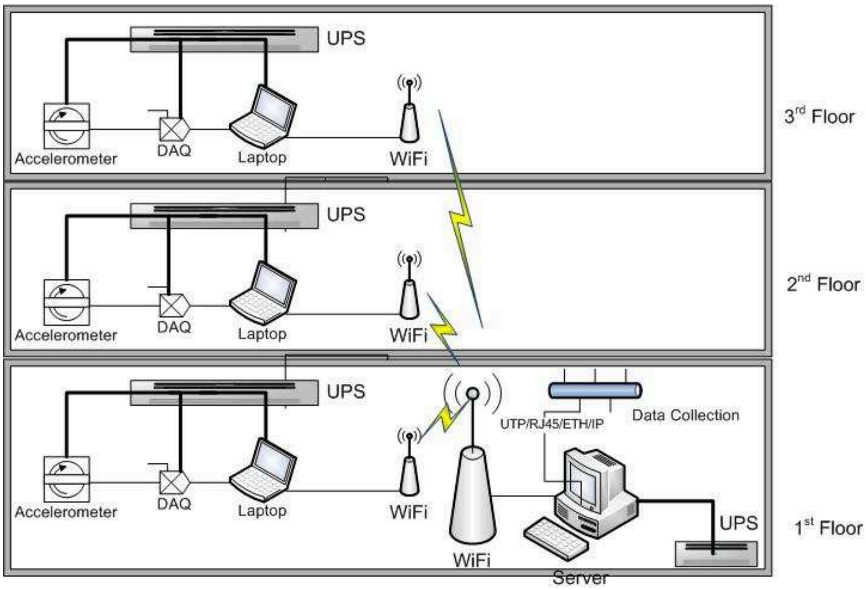

Fig. 1: A possible implementation of the proposed network architecture.

Under this approach, an accelerometer of the desired range and accuracy is used (i.e., capable of sensing ambient vibrations that is the focus here). It 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. 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 one floor in the building and several floors can also be considered accordingly.

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 computers (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, [11], is installed in the premises in order to synchronize the devices.

Due to the nature of the wireless networks, the transmission latency between the BS and each device varies. The main benefit of NTP is that synchronizes devices over variable-latency data networks and can achieve better than one millisecond accuracy in local area networks (LANs). NTP uses a 64-bit packet that consists of two parts. The first 32-bit part is used for the seconds elapsed since 1/1/1900 while next 32-bit part is for second fraction giving a resolution of 2^{-32} seconds.

Servers providing the time synchronization service are typically organized under a hierarchical structure. The levels of this structure are called *Stratums*. On the top level (*Stratum 0*) belonging the reference clock servers which are synchronized with a high precision clock (atomic, gps, etc). *Stratum 1* consists of servers that are synchronized with a Stratum 0 server. In general each *Stratum N* server is synchronized with one or more *Stratum N-1* servers.

When a device tries to synchronize its clock with the server, it must compute the *roundtrip delay time* (δ) and the *offset* (θ). These values are given by Eq. 1 and Eq. 2 respectively

$$\delta=(t_{c\_res\_r}-t_{c\_req\_t})-(t_{s\_res\_t}-t_{s\_req\_r}). \tag{1}$$

$$\theta=\frac{(t_{s\_res\_r}-t_{c\_req\_t})+(t_{s\_res\_t}-t_{c\_res\_r})}{2}. \tag{2}$$

where $t_{c\_req\_t}$, $t_{s\_req\_r}$, $t_{s\_res\_t}$ and $t_{c\_res\_r}$ are the timestamp of the client when the request packet transmitted from client to server, the timestamp of the server when the request packet received by server, the timestamp of the server when the response packet transmitted from server and the timestamp of the client when the response packet received by client respectively.

During the synchronization, a sufficient number of such packets are transmitted and received in order the client to estimate a fair average for δ and θ values. Finally client sets its clock to a value that minimizes its difference from the server's time.

System Deployment in Historical Buildings

This particular network system was deployed both in four historical buildings both in Greece and Italy. Fig. 2 depicts the deployment of the sensor nodes in the Annoutsiata campanile. Anountsiata is a historical and interesting building of Corfu, located in the busy shopping and commercial center of the city. What remains after the second world war bombing is campanile. It was used to be a catholic monastery and in its surroundings the dead of the naval battle of Lepanto (1571) were engraved. This naval battle was one of the most significant ones in the world history with paneuropean consequences. The inside of the Annoutsiata consists of three floors but since it was difficult for safety reasons to install the system on the second and third floor, it was installed on the first floor.

Each sensor corresponding to the end point has a particular identification number (ID) as depicted in Fig. 2. The four corners of the building were covered both on the ground and on the wall.

Similar deployments took place at two floors of San Giaccomo and at the Trani Cathedral campanile. San Giaccomo is another historical building in the city of Corfu. It used to be the loggia of the nobles during the Venetian period, then it became theater and since the beginning of the twenty century it serves as the main building of the town hall. Today it hosts the Mayor's office and some departments of the municipality's services. The wireless system was also installed in Trani, at the campanile of the city's cathedral. This building is an exceptional one of Romanesque style and its campanile is as high as 60 meters.

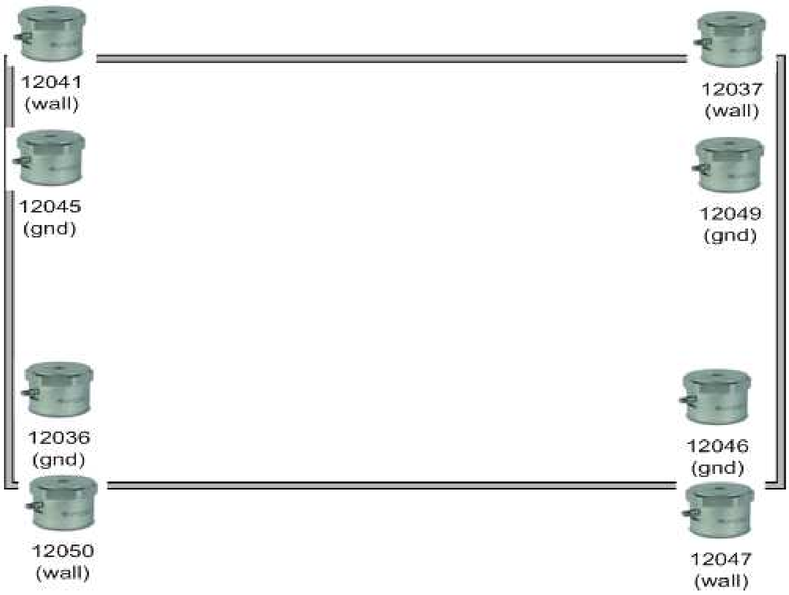

Fig. 2: Annountsiata example deployment configuration.

Synchronization Issues and Results

One big challenge of using this network approach is the time difference between the clients (laptop) clock. Assuming a wired setup the acquisition boards are synchronized with each other with the use of special synchronization signals generated by a particular acquisition board that plays the role of the master board. These special signals generally provide access to synchronization, and counter/timers and are available through hardware-timed digital input and output modules. In this way the recorded data output from each sensor are synchronized to the master board time with a synchronization signal trigger originated by the master board with a minor loss of a few nanoseconds. This way the recorded samples from the accelerometers can be compared and evaluated.

In the considered setup, the limitations of the clients clocks offset were measured and eliminated in order to get a reference dataset. For this purpose the network time protocol service running on the server handles the synchronization of all the client computers system clocks. The server in this configuration acts as the local *Stratum-1* time server. Although the time reference of the server's clock is enough to compare and evaluate results, the server is synchronized through GPS to the GMT acting as a *Stratum-0* server (1); to allow the observers to manually record or keep notes of the environmental conditions trivial for the evaluation of the dataset (sounds – vehicle vibrations etc.)

While the server's real time clock is synchronized with an average accuracy of 50 microseconds, various other factors like network delays and high cpu loads on the clients introduce an additional delay to the reference clock.

In Fig. 3 the results of the time difference before and after immediate time synchronization are recorded between the server and two clients with CPU load 20 percent (Client 1) and 50 percent (Client 2) respectively, for a time period of 100 seconds. Clients appear to have a time difference after synchronization of a few milliseconds for the high-loaded client and microseconds for the one with the 20% average load.

In Fig. 4 is recorded the time difference of a client with CPU load 50 percent after immediate time synchronization for a time period of two hours (each sample is recorded every ten seconds). It is proved that this client had a maximum time difference of 250 milliseconds. In this case and since a difference of a few milliseconds is acceptable for the nature of the experiments and measurements, a scheduled synchronization of the clients with the server's clock with an interval of 1 minute will ensure that the offset of the measurements will be no more than 1.5 milliseconds in any case.

Additional overhead from the software used to record the chassis input of the accelerators measurements is not existent since software timer functions use the operating system timers. The time resolution of these timers depends on the operating system.

Overhead and other factors as the client's cpu load or network delays are not an issue since in the first case the cpu load is always below 20 percent (cost of running the particular software for gathering and storing measurements) and in the latter NTP clients and in general the NTP protocol is sophisticated enough to compensate for any network delays (if any since in the worst scenario ping reply delay of the server to the client through WiFi does not exceed 0.4 msec).

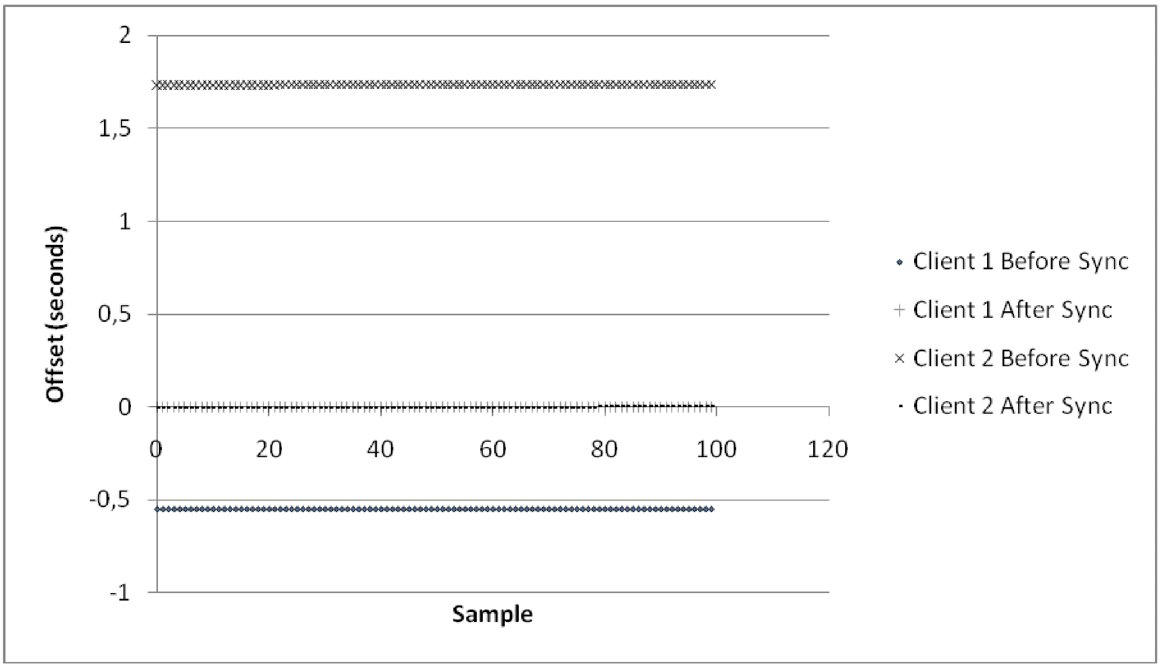

Fig. 3: Time offset of two clients with CPU load 20% and 50% before and after synchronization.

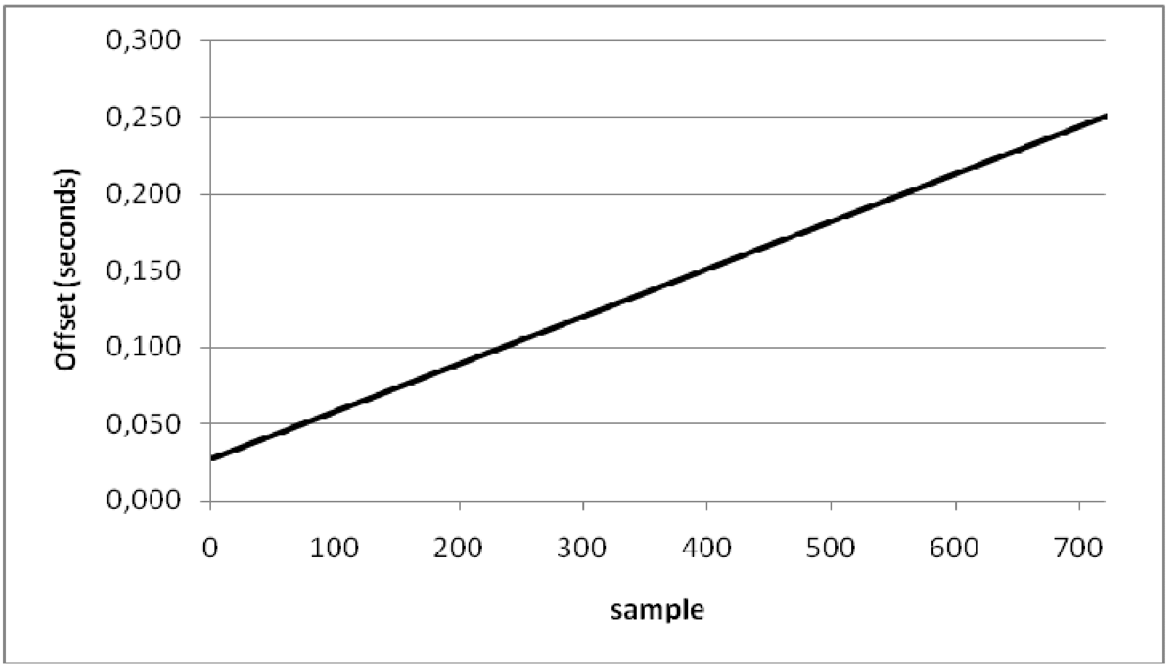

Fig. 4: Time offset of a Client with 50% CPU load after synchronization.

Summary

There was an open issue regarding the novel wireless network sensor system that was proposed to bridge the gap between the traditional wired approach and the existing on the market wireless systems for ambient vibrations monitoring, which was studied in this paper. The approach followed was to setup a local NTP server in each deployment and periodically synchronize clocks. This worked remarkably well and it allowed for the efficient operation of the system and data collection.

Acknowledgement

This paper is partly funded by S.M.ART.BUIL.T. (Structural Monitoring of ARTIstic and historical BUILding Testimonies), a European Terrestrial Cooperation Programme, Greece-Italy 2007-2013 (Investing in our Future), co-funded by the European Union (ERDF) and by National Funds of Greece and Italy.

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Structural Monitoring of ARTistic and historical BUILding Testimonies

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