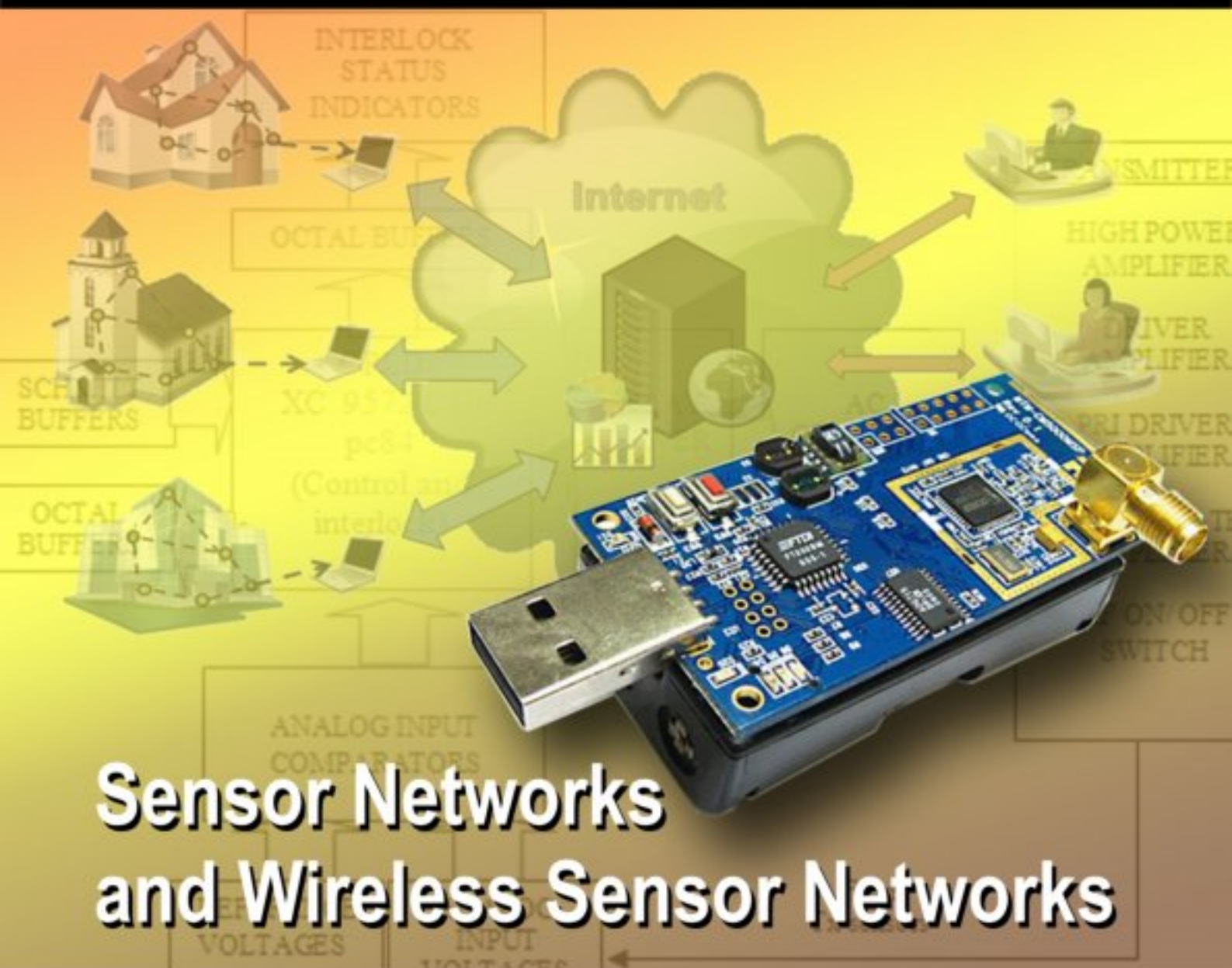


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## Wireless Remote Monitoring System for Cultural Heritage

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**Abstract:** Existing systems to collect temperature and relative humidity data at cultural heritage buildings require technical knowledge by people who are working with it, which is very seldom that they do have. The systems available today also require manual downloading of the collected data from the sensor to a computer for central storage and for further analysis. In this paper a wireless remote sensor network based on the ZigBee technology together with a simplified data collection system is presented. The system does not require any knowledge by the building administrator after the network is deployed. The wireless sensor device will automatically join available network when the user wants to expand the network. The collected data will be automatically and periodically synchronized to a remote main server via an Internet connection. The data can be used for centralized monitoring and other purpose. The power consumption of the sensor module is also minimized and the battery lifetime is estimated up to 10 years. *Copyright © 2010 IFSA.*

**Keywords:** ZigBee, Remote monitoring, Low cost, Low power, Long battery lifetime

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### 1. Introduction

Every old building is unique, consisting of construction and building material where a modern building-technician may not fully have knowledge about. The requirement of maintaining with old buildings and monuments is great. It requires a lot of knowledge from the building administrator. However, the knowledge on the field is often too poor for a person to take care of the buildings in a correct way. This leads to the fact that the risk on damaging the building increases. A data-collecting system can be used to collect varies data with different sensors. The collected data can be used for monitoring and controlling functions in the building such as heating and ventilation. Furthermore, the

collected data can be used for developing knowledge about the environment behavior of each specific building. With such a knowledge, a smart control-system can be built for the specific building based on the building properties and functions, e.g., controlling the interplay between the heating and the ventilation systems in a building with high relative humidity to avoid the moulds.

Existing systems mostly used today are based on the deployment of sensors at the place where one wants to collect data from [1]. The sensors, also known as data-logger, are battery-powered and it can sense one or more types of data such as temperature and relative humidity. Each of the sensors has a flash memory where all the sensed data is saved. The user has to collect the information periodically via cables to a computer and the graphs over the desired period are converted using specially designed software provided by the sensor manufacture. The graphs give a clear picture of how the church was heated during different periods and the relative humidity prevailing in specific timeframe, when the sensors are deployed. This kind of solution requires some technical knowledge of the operator and time to manually collect data from the sensor devices, which can be very time consuming and not always feasible, since the sensor network does not locate at the same place as the operator is stationed. This requires long traveling distance to the site just for downloading the data to a computer and the collected data needs to be manually transferred to a computer for analysis. There is wireless monitoring solution today, but the sensors are connected with wires to a so-called base station for reporting sensed values through GPRS/3G/Ethernet connection [1]. However, the wired connection between the sensor and the base station is sometime limited to maximum 10 meters [1].

In this project, a wireless remote system monitoring for cultural heritage is developed and deployed. The wireless sensor network is based on the ZigBee protocol [2]. The network can automatically create a local sensor network and sensor deployed on site can automatically join the network when the radio is within range. The wireless sensor network is further connected to a remote main server via the Internet through a GPRS/3G/Ethernet connection for central storage, monitoring and maintenance. The goal with a wireless sensor network is to bring an optimal solution for each individual building with as little technical knowledge requirement by the building administrator and local users as possible. The network is modularly built so future expansion and improvement can be developed and included. However, since the main server is connected to the Internet, it also provides the possibility for the users to remotely access information. The data synchronization is done periodically so the administrator always gets the latest information from each building, which is also valuable for alarming in case of sudden change of the collected values. The data collection and synchronization between the wireless local wireless sensor network and the remote main server is done seamlessly so that the administrators and the users do not need to think about the technology behind the system [3].

## **2. System Overview**

Fig. 1 shows an illustration of the system overview. From the left hand side, there are a number of small local wireless sensor networks, which can be deployed at different types of buildings, such as churches, museums and/or any other buildings. Each local wireless sensor networks contain a local database where the local sensed data are stored. The database is further synchronized via a broadband or mobile Internet connection to a remote main server, where information from all the local servers that are connected is stored, as shown at the middle of the figure. The remote main server is the monitoring center of all local servers which are connected to it. Data stored in the main server can be used for monitoring and analysis of climate behavior at each individual building and further development of an adaptive control system of ventilation in the building.

## 2.1. ZigBee Wireless Sensor Network

A ZigBee wireless sensor network typically consist of low-cost, low-power and multi-functional sensor nodes that are deployed in a region of interest. These sensor nodes are small in size, but are equipped with sensors, embedded microprocessors, and radio transceivers. Therefore they have not only sensing capability, but also data processing and communication capabilities.

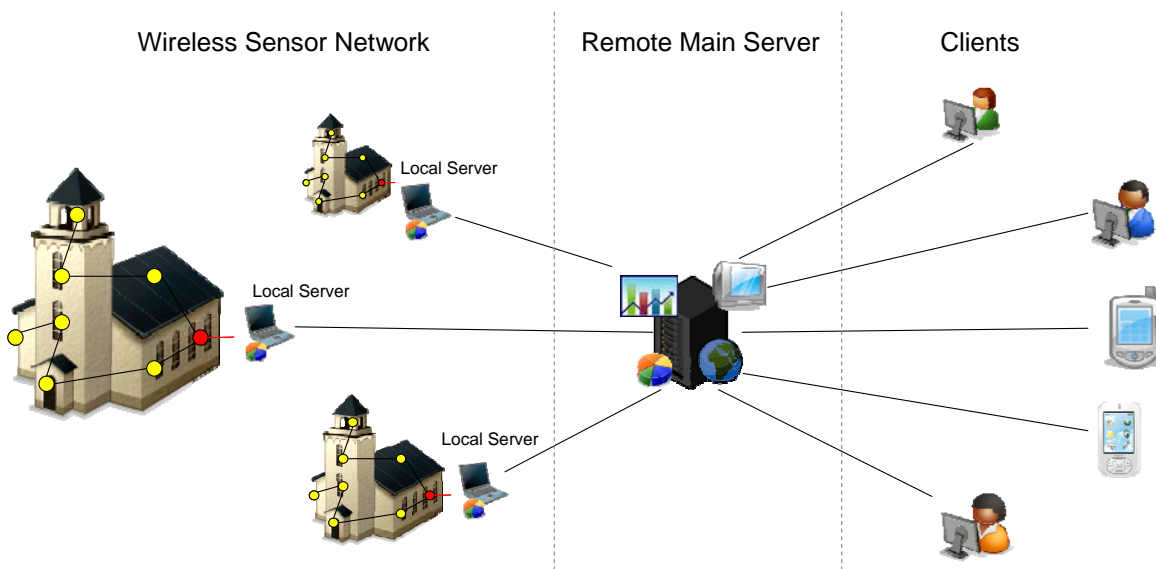


Fig. 1. Illustration of the system overview.

The wireless sensor network can exist as a star, a tree or a mesh network topology, as illustrated in Fig. 2.

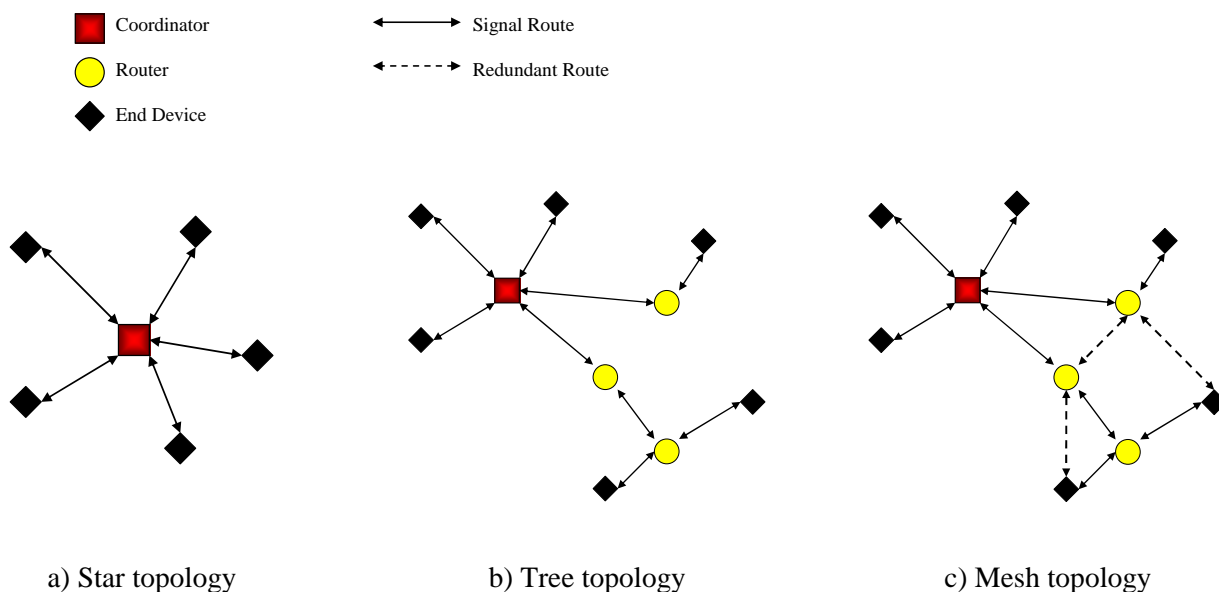


Fig. 2. Illustration of different network topologies.

Depending on the environment, different network topologies can be used with the cost of network complexity, reliability and signal latency. The star network is the simplest topology with point-to-point connection and has the lowest signal latency. Since the end devices communicate directly with the coordinator, the risk for a network failure is kept to the minimum. The network fails only when the coordinator fails, but the wireless network coverage is limited by the radio range between the coordinator and the end device. The wireless network coverage can be extended with a so-called tree or mesh topology, by adding routers between the end devices and the coordinator. The tree topology still uses point-to-point communication between the devices, which makes the connection predictable and the complexity of the network is moderate. The drawback is that if one of the routers fails, all the devices which have a signal path to the coordinator via that router will also be disconnected from the network. A mesh network can be used to avoid this problem by self-repair of the network, i.e., by reconnect of the disconnected devices to another in-range neighboring router and rejoin to the network. This self-healing function provided by the mesh topology provides robustness to the network, but at the cost of increased complexity and data latency time.

## **2.2. Local Server**

A local server (see Fig. 1) is a computer located at the building where the deployed wireless sensor network is located. The main task of the local server is to store all the local sensed data into a database. The local server also serves as a gateway between the wireless sensor network and the Internet so that the local database can periodically synchronizes with a remote main server. Simple tasks like adding new sensor modules and alarming the local user when any system failure occurs are done by the local server.

## **2.3. Remote Main Server and Monitoring**

A remote main server (see Fig. 1) is a computer server with a main database where all the local servers synchronize their local database to it. The main server is installed with web service and all the tasks that can be issued by the local server should also be able to handle with the main server. In this way the remote user will have full control over the system as he/she was at the local building. The main server can furthermore have additional functions as real time graphical display or download of the collected data with a selectable time frame.

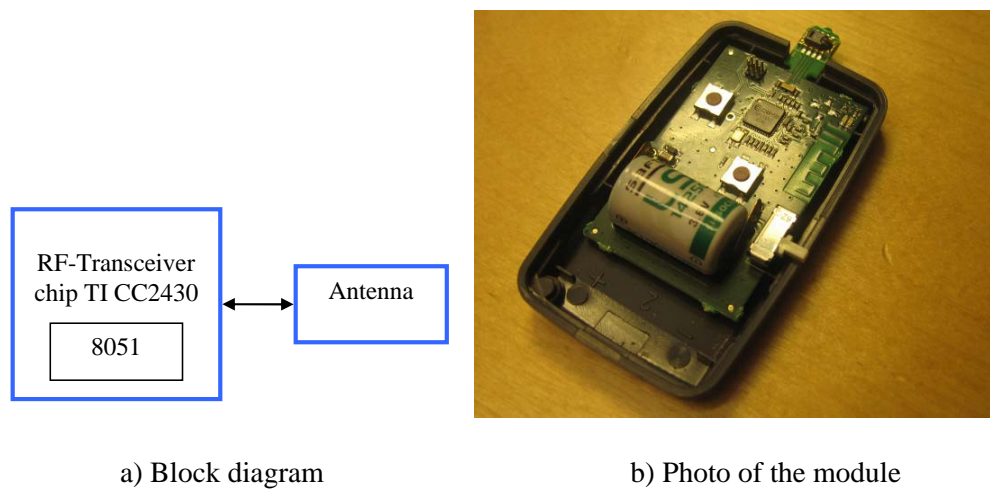
## **3. Hardware Implementation**

Two different types of ZigBee modules were developed for the wireless sensor network. The first module is so-called ZigBee sensor module, which will sense the temperature and relative humidity data and act as an end device in the network. The second module is a ZigBee radio with external power amplifier (PA) and low noise amplifier (LNA). With extra adapter boards, the module can be used to act as a router or a coordinator. Furthermore, the module can also be used to connect to other types of sensor and act as an end device.

### **3.1. ZigBee Sensor Modules**

Fig. 3 shows a block diagram and photograph of a ZigBee sensor module. The RF part utilizes the Texas Instruments (TI) CC2430 system-on-chip solution for IEEE 802.15.4 [4] and ZigBee applications. The TI CC2430 RF transceiver includes an industrial-standard 8051 microcontroller unit for signal processing [5]. The sensor used is a temperature and relative humidity sensor SHT15

provided by Sensirion Inc. [6]. The sensor device is powered by a 3.6 V lithium battery. Table 1. shows the electrical characteristics of the ZigBee sensor module [3].



**Fig. 3.** ZigBee sensor module as end device powered with a 3.6 V lithium battery.

**Table 1.** Electrical characteristic of the sensor module.

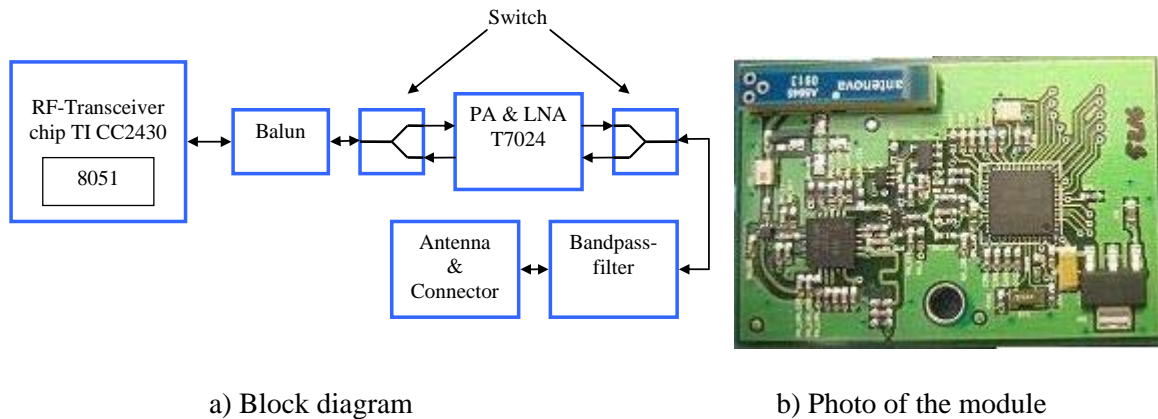
Parameter	Min	Typ	Max	Unit	Condition
Supply voltage	2.4	3.6	3.6	V	
RF frequency	2400		2483.5	MHz	
Radio bit rate		250		kbps	
Current consumption Rx mode		34		mA	
Current consumption Tx mode		32		mA	0 dBm output power
Power mode 2		0.0008		mA	
Radio range		144		m	Outdoor line of sight

### 3.2. ZigBee Coordinator and Router

Fig. 4 shows a block diagram and a photograph of the ZigBee module with a power amplifier and a low noise amplifier. The PA implementation in Atmel T7024 is a three stage amplifier with an analog input control (ramp) for control of the signal output power. The same control signal can also be used to switch the PA to power-down (standby) mode when the module is not in transmitting mode. The PA can deliver up to 23 dBm (200 mW) output power. Typical noise figure of the LNA is 2.1 dB at the frequency range between 2.4 and 2.5 GHz. Two extra switches are added to switch the PA and LNA between transmit and receive modes [7]. This module can be used as a coordinator or a router, where extra range to the sensor device is needed or where extra robustness to the connection is needed. Table 2 shows the electrical characteristics of the ZigBee module with external PA and LNA [8].

## 4. Software

The local wireless sensor network is programmed to such that the coordinator will form a local network as soon the power is switched on. All the other devices will automatically join the network when power is turned on and a network is found. To reduce the data traffic load on the network, the devices are programmed to remember which address it was connected to latest so a fast connection can be established. This is useful in case of a power failure and a reset is needed [9].



**Fig. 4.** ZigBee module with external power amplifier and low-noise amplifier

**Table 2.** Electrical characteristic of the ZigBee module with external PA and LNA.

Parameter	Min	Typ	Max	Unit	Condition
Suppy voltage	4.5	5.0	7.5	V	
RF frequency	2400		2483.5	MHz	
Radio bit rate		250		kbps	
Current consumption Rx mode		53		mA	
Current consumption Tx mode		182		mA	0 dBm output power
Radio range		1600		m	Outdoor line of sight

#### 4.1. Battery Consideration on ZigBee Sensor Module

In order to keep the battery lifetime as long as possible on the sensor device, the devices are programmed to enter sleep-mode when there is no task to operate [10]. This is a proven method for saving energy consumption. The following operation modes are implemented in the module [11]:

- Sensing data
- Send sensor data
- Status check
- Send data request

At the sensing data mode, the module is programmed to enable the sensors and collect the data. The collected data is stored in an onboard flash memory and compared with previous stored value. If the sensed value is the same as previous stored value, there is no need to send the data to the local server for storage. If the collected data are different from the previous stored value, the module will switch to Send Sensor Data mode and send the newly collected data to the local database on the local server.

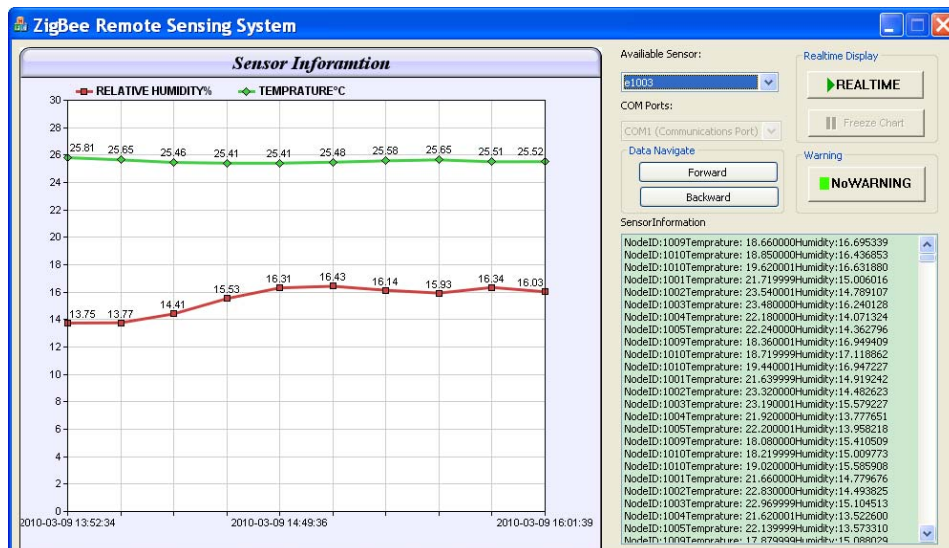
The Status Check mode is implemented to let the end device notify the network that it is still available. This mode is necessary due to the implementation of Sensing Data mode. If the sensing data is stable for a long time, the network will not know if the sensor device is malfunctioned, communication is blocked or the end device has run out of battery. At Send Data Request mode the end device will check if there is any command to be taken from the network. Table 3 shows a summary of which part of the module is enabled/disabled at different operation modes.

**Table 3.** Operation modes with different parts of the module enabled/disabled.

Operation Mode	Sensor	Microcontroller	Radio	32 MHz OSC	32.768 kHz OSC
Sensing Data	Enable	Enable	Disabled	Enable	Enable
Send Sensor Data	Enable	Enable	Enable	Enable	Enable
Status Check	Disabled	Enable	Enable	Enable	Enable
Send Data Request	Disabled	Enable	Enable	Enable	Enable
Sleep Mode	Disabled	Disabled	Disabled	Disabled	Enable

## 4.2. Data Display on Local Server

Fig. 5 shows a screenshot of a Windows-based user interface at the local server installed in a Netbook. From the user interface, the local user can monitor any sensor deployed in the local wireless sensor network. The navigation buttons will let the user navigate through the collected data in different time frames. A warning button is implemented to notice the local user if there is anything in the system that needs extra attention.

**Fig. 5.** Local server user interface.

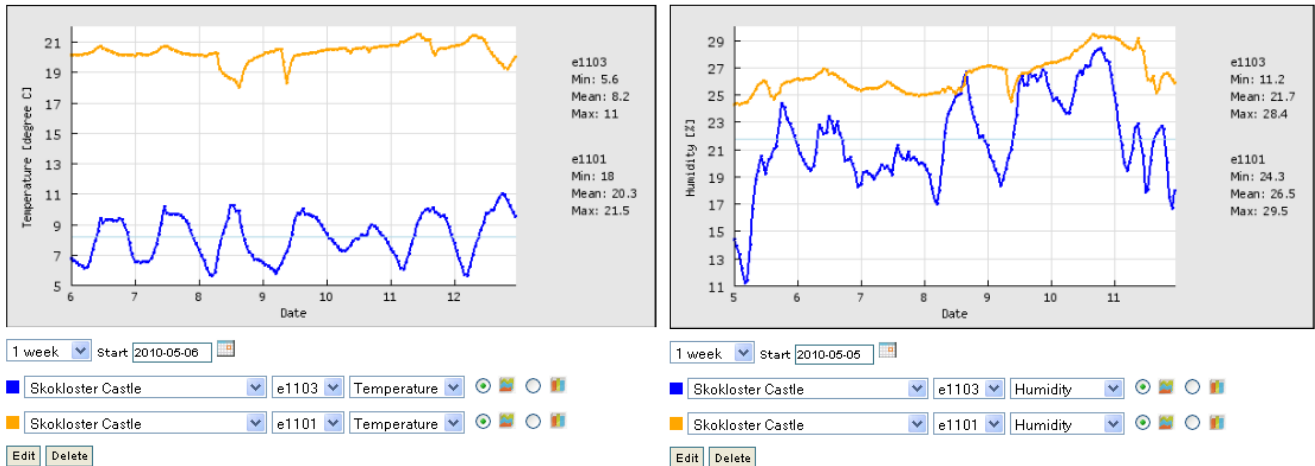
Behind the surface, the local server software has the following additional tasks:

- Serve the local wireless sensor network and store the collected data in a local database
- Issue a warning when the battery indicator from a sensor end device is low
- Issue a warning when the onboard radio chip temperature is abnormal
- Issue a warning if the sensed data is outside of a predefined acceptable value frame
- Synchronize the local database with a remote main database located at the main server
- Check the Internet connection stability before starting the synchronization process
- Periodically back-up the local database

## 4.3. Main Server (Remote Data Monitoring)

Fig. 6 shows two screenshots of the temperature and relative humidity measurements from a wireless local sensor network deployed in the Skokloster Castle in Sweden [3]. The graph shows a comparison

of two sensed data curves collected from two different sensors, one located at an indoor exhibition room and the other one is located at an outdoor environment. From the graphical user panel, the user can select results from other deployed local sensor network and also select the data from other interested time frames. Moreover, the user can also find the minimum, average and maximum data values within the selected time frame. There is also the possibility to download all the data stored on the main server.



a) Temperature comparison

b) Relative humidity comparison

**Fig. 6.** Temperature and relative humidity monitoring at Skokloster Castle.

Since all the local servers are periodically synchronized with the main server, the online user can always be sure that the available data is the latest synchronized ones. This also gives the possibility for future implementation of control and alarm functions at the main server for a centralized maintenance.

Behind the webpage, the main server should also provide the following tasks:

- Checking for abnormal synchronized data
- Issue a warning when attention to the system is needed
- Send an SMS and Email to the administrator when an emergency warning is issued
- Log the data traffic information
- Maintain the user authority for access to different area of the homepage
- Periodically back-up the main database

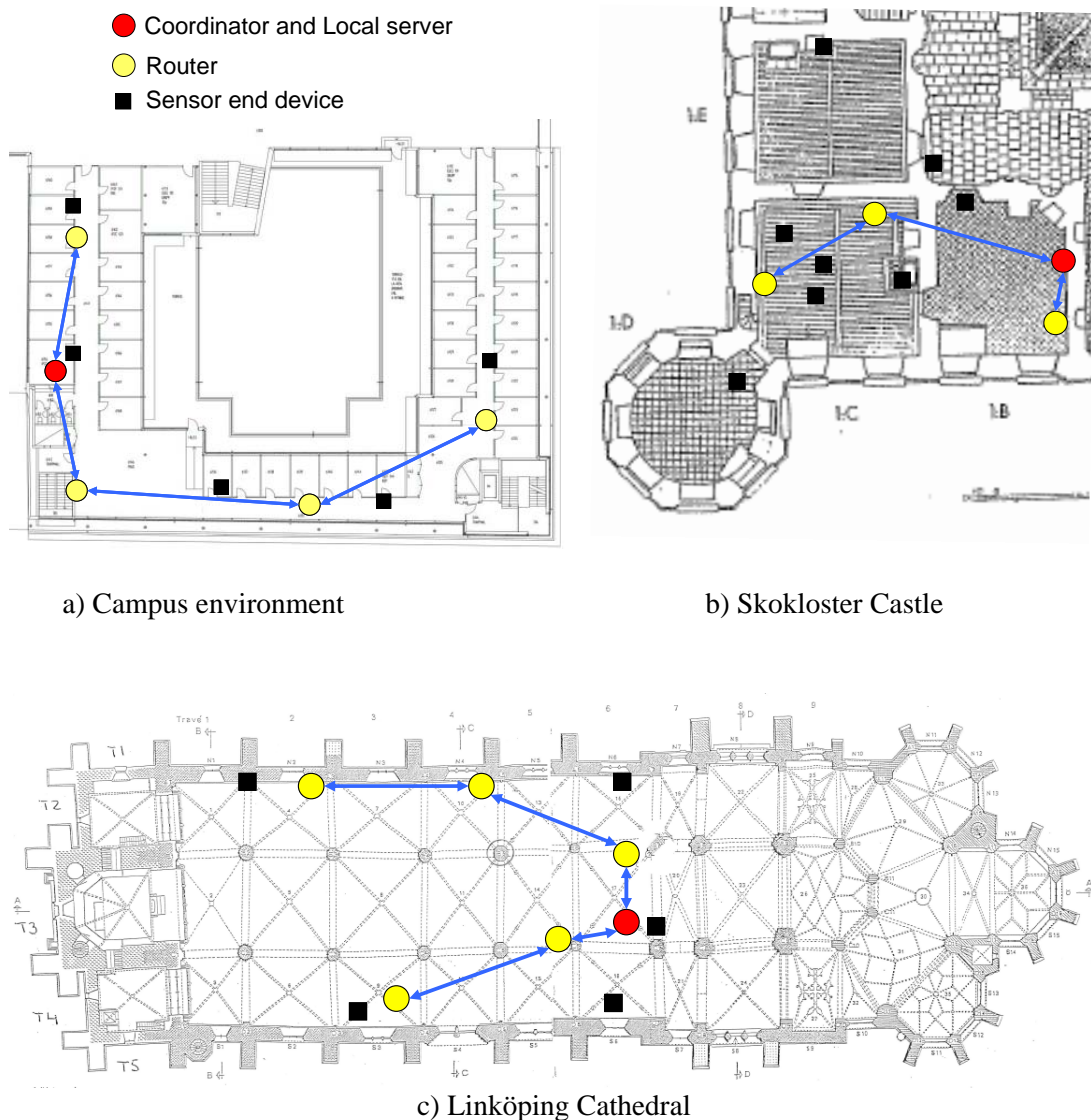
To handle all the tasks, the main server is installed with Apache and a PHP script interpreter to provide the dynamic webpage with monitoring, analysis and data manipulation. The installed database solution is MySQL, but for the future deployments, any other database solution can be used. The graphical representation of the graphs is done with Java scripts.

## 5. Results

Three separate local wireless sensor networks have been deployed at Campus environment, Skokloster castle and Linköping cathedral in Sweden as shown in Fig. 7. The three locations have been selected since they have different environment scenarios.

- Campus environment: the walls made of light materials with wood and plaster. The frame and floor of the building are made of steel and concrete. The office rooms have all large windows to the outside and small windows near the ceiling to the corridor. The whole campus environment is covered with the WLAN 802.11b/g wireless connection which cannot be deactivated. Bluetooth are also present.
- Skokloster Castle: the thick walls (up to 1 m) are made of bricks and stones. The building does not have any heating system except the bottom floor so the environment at the castle can have extreme changes during winter and summer periods. Human activity is most of the time low at the castle [12].
- Linköping Cathedral: the church is one of the largest in Sweden and has a large open area in the chapel. The floors and walls are made of thick stones and the roof is covered by copper plates. The amount of human moving around in the church is depending on the daily activity [13].

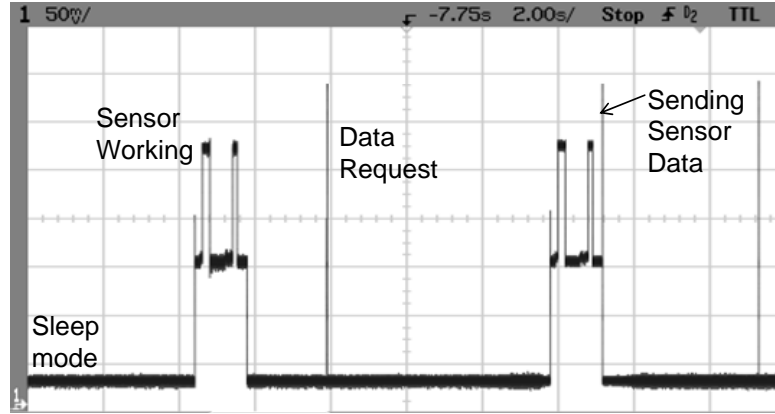
The stability of the Internet connection at the different destinations varies from very good to instable connection. To make sure that no data will get lost on a synchronization process, the local server will check the stability of the Internet connection before starting the synchronization process. The remote main server stores all the collected values from the wireless sensor networks. The results are presented as graph as shown in Fig. 6, which also can be found at the [www.culturebee.se](http://www.culturebee.se) homepage.



**Fig. 7.** Local wireless sensor network deployments at three different environments.

## 5.1. Current Consumption

Fig. 8 and Table 4 show the current consumption measurement result for each of operations on the ZigBee sensor module. The values are measured and calculated to give an idea of how much currents each operation modes consume.



**Fig. 8.** Screenshot of a typical current consumption measurement result with an oscilloscope.

**Table 4.** Power consumption in different operation modes.

Operation mode	Current consumption [mA*ms]	Operation time [ms]
Sensing Data ( $S_d$ )	23907	1380
Send Sensor Data ( $S_{sd}$ )	207	7.8
Status Check ( $S_c$ )	186	8.59
Send Data Request ( $S_{dr}$ )	186	8.59
Sleep Mode ( $S_m$ )	0.0008*t	t

Since the operation interval of the above four operations can be configured, the total power consumption of the module and the battery lifetime can be calculated according to different interval configurations for  $S_d$ ,  $S_{sd}$ ,  $S_c$  and  $S_{dr}$ . With the data from Table 4 and 5 the power consumption for each hour can be calculated according to (1) assuming the power consumption during  $S_m$  is so small it can be neglected.

$$P[\text{mA} * \text{ms}] = 3600 \left( \frac{S_d}{A} + \frac{S_{sd}}{B} + \frac{S_c}{C} + \frac{S_{dr}}{D} \right), \quad (1)$$

Consequently, the total battery lifetime can be estimated with

$$Batt_{lifetime} [s] = 1000 * Batt_{capacity} [\text{mAs}] / P, \quad (2)$$

where  $Batt_{lifetime}$  is the estimated total battery lifetime and  $Batt_{capacity}$  is the energy capacity of the battery. Table 5 shows an example of different operation interval scenario with corresponding battery lifetime.

**Table 5.** Example of different operation interval scenario with the battery lifetime as result.

<b>A (Sensing Data) (s)</b>	360	1800
<b>B (Send Sensor Data) (s)</b>	60	3600
<b>C (Status Check) (s)</b>	1800	3600
<b>D (Send Data Request) (s)</b>	3600	1200
<b>Power consumption per hour (mA*ms)</b>	252048	47654
<b>Batt<sub>capacity</sub> (mAh)</b>	1100	1100
<b>Batt<sub>capacity</sub> (mAs)</b>	3960000000	3960000000
<b>Batt<sub>lifetime</sub> (s)</b>	15711	81205
<b>Batt<sub>lifetime</sub> (days)</b>	654	3383

## 6. Discussions

The placement of the sensor devices is resulted in different indoor radio ranges. The best position to get a radio link between sensor devices and router/coordinator is when the radio part of the sensor device is placed some distance above the ground and if possible away from the walls. The antenna polarization has also been noticed that it will affect the radio range. For future improvements, none polarized antennas can be used on the routers and the coordinator, but the end device should be kept as simple as possible to minimize the physical size of the device and cost.

The control function can be added to the sensor network in the future to control the radiators and ventilation systems, based on the sensed data from the wireless sensor network. This will give a better comfort to people who are working at the area where the sensor network is deployed and also to avoid the mold infestation.

The energy consumption on the sensor module can further be lowed to prolong the battery lifetime by lowering the supply voltage to the radio and sensor chip. The switching power dissipated by a chip using static CMOS gates is given by [10], [14]

$$CV^2f, \quad (3)$$

where  $C$  is the capacitance being switched per clock cycle,  $V$  is voltage, and  $f$  is the switching frequency. As the equation shows, the power consumption decreases with the power of two of the voltage. As shown in Fig. 3 and Table 1, the sensor end device is today driven by a 3.6 V lithium battery without any voltage regulator. The power consumption from the CMOS chip and the temperature and relative humidity sensor can be lower by lowering the supply voltage and the frequency, as shown by (3). For example, if the supply voltage is lowered from 3.6 V to 2.5 V, the power consumption of the sensor module can be lower by

$$1 - 2.5^2 / 3.6^2 = 51.7\%, \quad (4)$$

Furthermore, since the microcontroller can operate with a 16 MHz or a 32 MHz oscillator, the lower frequency oscillator should be used as often as possible to conserve the battery, i.e., when the radio part is not active since it needs the higher frequency clock to operate.

## 6. Conclusions

A wireless remote sensor network based on the ZigBee technology has been presented in this paper. Robust local wireless sensor networks have been deployed at three different building environments to

sense temperature and relative humidity. The local wireless sensor networks are further connected via the Internet to a remote main server with synchronized measurement. Remote user can easily access the latest data stored in the remote main server and download the data for further analysis. Furthermore, the battery lifetime of the sensor device has been estimated up to about 10 years with a sensor sampling interval of 30 min.

## Acknowledgements

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## Guide for Contributors

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### Aims and Scope

*Sensors & Transducers Journal* (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In addition, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

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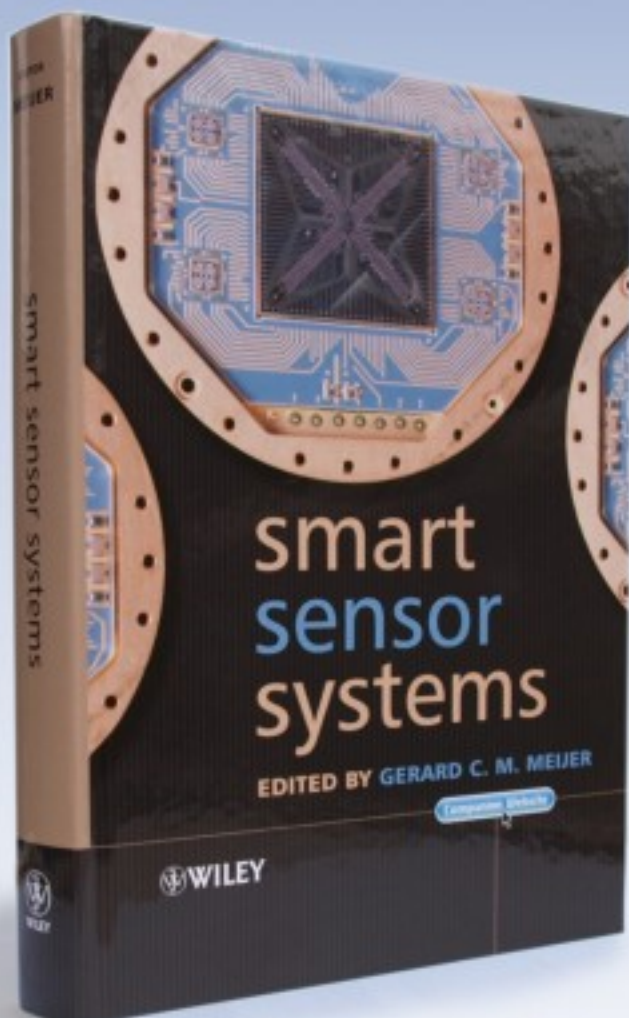
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