A Low Consumption Real Time Environmental Monitoring System for Smart Cities based on ZigBee Wireless Sensor Network

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***Abstract*—Nowadays, there is an increasing interest in wireless sensor networks (WSN) for environmental monitoring systems because it can be used to improve the quality of life and living conditions are becoming a major concern to people. This paper describes the design and development of a real time monitoring system based on ZigBee WSN characterized by a lower energy consumption, low cost, reduced dimensions and fast adaptation to the network tree topology. The developed system encompasses an optimized sensing process about environmental parameters, low rate transmission from sensor nodes to the gateway, packet parsing and data storing in a remote database and real time visualization through a web server. A monitoring system integrating the outlined system has been deployed and tested for monitoring the level of dust particles in the air, acoustic levels in different places of a city, ambient temperature and relative humidity. A calibration process of a low cost audio sensor was performed to measure the acoustic level from different noise sources, hence, it is not necessary to use an expensive sound level meter at each node. Furthermore, experimental results show autonomy nodes can be about three months.**

***Index Terms*—Environmental monitoring, Smart cities, Wireless sensor networks, ZigBee**

I. Introduction

SMART city is a concept that brings together all the characteristics associated with organizational, technological, economics and social changes in a city. Smart city is currently supporting the provision of several services aimed at enhancing the quality of life in the city as it is described in [1]. On the other hand, WSN are one of the most powerful tools for remote controlling and monitoring, and hence, an active research area mainly due to the potential of their applications [2] such as healthcare, home automation, agriculture, industrial environments, etc. Development of the WSN has been achieved by advances in miniaturization and ubiquitous communication. Low cost and ability to function in real time make WSN success in civil environment applications. Furthermore, large distances between network nodes in these systems make wire connections impractical and often impossible. Therefore, this technology is appropriated for using in a smart city context.

WSNs can be implemented with different wireless protocols for data transmissions. In [3] is described a detailed comparative study of the different short range wireless protocols: Bluetooth (over IEEE 802.15.1), UWB (over IEEE 802.15.3), ZigBee [4] (over IEEE 802.15.4) and Wi-Fi (over IEEE 802.11a/b/g). It is found that ZigBee is an efficient protocol in field of automation. Furthermore, this protocol implements AODV routing protocol [5] so that intermediate nodes participate in routing by forwarding data to other nodes and new nodes have a real time adaptation to the network tree topology. Due to the fact that it is a reactive protocol and route tables are calculated just before information is sent, router nodes can go to sleep during idle time. Finally, due to Zigbee is implemented over a Low-Rate Wireless Personal Area Networks standard [6] it has low energy consumption. Taking this into account, WSN described in this paper uses ZigBee protocol for radio communication.

On the other hand, an important application for WSNs is controlling and monitoring of environmental parameters such as temperature, air pressure, humidity, wind speed, wind direction, etc. Those systems can be used in agriculture to improve plant growth conditions such as [7] where the authors describes a prototype of WSN for monitoring of greenhouse environmental conditions including temperature and soil moisture. It consists of measurement nodes powered from small-size solar cells to be autonomous platform. In [8] an environmental WSN is proposed to monitor environmental basic parameters such as temperature and an original water level for the Campus pond. The final aim is to monitor environmental parameters from the air, water and ground, and to become a generic platform that serves different purposes. In [9] the authors propose a WSN based framework for monitoring the water conditions such as the underwater luminosity and temperature, information necessary to derive the health status of the coralline barrier. The system is based on clusters relying on a star topology and hence, it requires a gateway for each cluster and it can raise the price of the global system.

Regarding quality of life, some research based on WSN have been deployment for air pollution and acoustic level

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monitoring due to is becoming a major concern for the health of the population. In [10] the authors propose a system to monitor air pollution in Mauritius through the use of WSN deployed in huge numbers around the island. Simulation results showed short execution time for monitoring. Nevertheless, real implementation was not done and none mote sensor characteristics were described. In [11] is presented an approach for gathering noise pollution data by using mobile applications. The applications are designed following gamification techniques to encourage users to participate using their personal smartphones. Nevertheless, it requires a high periodic collaboration of people if real time constrains are needed. Recently, in [12] is presented a WSN design for monitoring emissions on construction sites in real-time. It is designed for monitoring disturbing emissions like air pollution, noise and hazardous ground vibrations. In order to sense the acoustic level a sound level meter is used. Hence, it is not a low cost system, the energy consumption is high and system size is large.

The main contribution of this paper is to propose an innovate and novel low cost and low energy consumption architecture for monitoring environmental parameters in real time. In order to minimize the energy consumption programable interruptions were used to wake up the node when only an event occurs. Hardware used for sensing information has small size and low cost sensors have been used to minimize price of nodes. In fact, to avoid expensive sound level meter utilization at each sensor node we use a low cost microphone on which a calibration process was performed to gathered correct values. Furthermore, new nodes have a real time adaptation to network tree topology because ZigBee protocol is implemented. As far as we know, our research is the first to propose and test a low cost and energy consumption real time environmental monitoring system for controlling parameters such as the acoustic levels in places of a city, the level of dust particles in the air, ambient temperature and relative humidity.

The paper is organized as follows: Section 2 explains the global architecture of our real time environmental monitoring system. Next, in Section 3, we describe the developed WSN to gather environmental data. In Section 4, we describe how the web data management has been developed. In Section 5, we show some experimental results. Finally, we sum up the conclusions.

II. Overview of Real Time Monitoring System

Fig. 1 shows the developed system for real time monitoring. WSN is formed for several devices, named motes, capable to sense information about ambient temperature, humidity, dust particles concentration in the air and acoustic level. The hardware of motes is based on Libelium Waspmote platform [13]. Besides, each mote has a GPS sensor to obtain its correct location. In order to minimize energy consumption, the code implemented in the motes has been developed using system on chip programmable interruptions. Concretely, time and accelerometer interruptions have been used, that is, the mote wakes up when an specific time expired or a fall is detected. This information is packed by each device and sent to the gateway or also named network coordinator using ZigBee protocol. The gateway module is a device with ZigBee radio interface and an USB port that enables wireless medium transmissions to be sent over the wired medium. An algorithm developed in Java and running at computer where gateway is connected is in charge of parsing the received packets and storing the information in a remote MySQL database. Finally, a web server has been developed with HTML5 and PHP publishing the information stored in database. Web site shows information about gathered sensor data by each mote and motes location in a map using Google Maps API.

Fig. 1. Overview of real time environmental monitoring system.

III. Environmental Wireless Sensor Network

In this section we describe the selected mote for implementing the WSN, the calibration process of audio sensor and the source code developed for programming the motes.

A. Mote Hardware

The main goal in designing the equipment was to obtain a product of small size, low cost, low consumption and versatile to allow its use for permanent monitoring deployments with fewer numbers of nodes, as for introducing monitoring of urban areas that require a massive expansion of these.

The selected device for deploying WSN is based on Libelium Waspmote platform [13]. It is a modular device that allows us to install different sensors of various kinds and also, different radio transceivers. Waspmote hardware architecture has been specially designed to be extremely low consumption. The WaspMote has an Atmega1281 running at 14MHz and it has sleep modes make Waspmote the lowest consumption sensor platform in the market (0.7uA in hibernate mode and 55uA in sleep mode). The selected technology of communication has been the ZigBee protocol where the modules used were XBee manufactured by Digi [14]. The whole set, formed by Waspmote and sensors, has a small size (85 x 75 x 35 mm, included battery) which is very useful to place at different positions in a discrete way. It is based on two electric boards:

- *The Mainboard*: This board has the most important basic components that allow its use in any application in the field of WSNs. The most important components are the System on Chip(SoC), Real Time Clock (RTC), accelerometer (ACC), the communication sockets and the analogs and digital inputs/outputs.
- *The Smart Cities Sensor Board*: It is an expansion board that enables the connection between different kind of

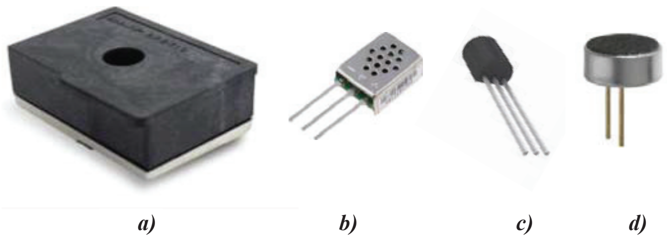

Fig. 2. Sensors: a) Dust particles, b) Humidity, c) Ambient temperature, d) Audio.

sensors [15]. In our deployment we have used the following low cost sensors: ambient temperature, humidity, dust particles and audio. This board is connected to the Mainboard through the expansion connector.

Next, we describe the sensors used in WSN deployment of which are showed in Fig. 2:

- *Dust particles sensor (GPY21010AU0F)*: It is an optical sensor whose principle of operation is based on the detection of the infrared light emitted by an ILED diode, reflected by the dust particles and captured by means of a phototransistor. The range of output values is between 0 and 0,8 mg/m^3.
- *Humidity Sensor (808H5V5)*: It is an analog sensor which provides a voltage output proportional to the relative humidity in the atmosphere. The range of output voltages is between 0,8V (0,1% Relative Humidity) and 3,9V (99% Relative Humidity) at 25°C.
- *Temperature Sensor (MCP9700A)*: It is an analog sensor which converts a temperature value into a proportional analog voltage. The range of output voltages is between 100mV -40°C and 1,75V 125°C, resulting in a variation of 10mV/°C, with 500mV of output for 0°C.
- *Audio Sensor (POM-2735P-R)*: It is an omnidirectional condenser microphone with an almost flat response in the whole frequency range of human hearing, between 20Hz and 20KHz. Because the output of analog digital converter is not correlated with the received sound pressure level we have to calibrate it to return an output in the range between 50dBA and 100dBA. In the next section, we explain how the audio sensor calibration was performed.

The communication between motes is carried out through ZigBee radio module. The chosen topology is based on tree mode, so sensors nodes or end-devices send data to a coordinator node. Since the distances to covered can be relatively large, we have considered using intermediate nodes between the coordinator and end-devices nodes. These nodes are called routers-devices and their mission is to route data packets from end-devices nodes to coordinator. As it was above mentioned, ZigBee implements AODV routing protocol and it is used to know the best route to destination. Router-devices can be also configured to sense information about environment.

B. Audio Sensor Calibration

In order to monitor the acoustic level produced by the different existing noise sources of a city, a previous audio sensor calibration was performed to achieve a correct functionality device and obtain correct values. The audio sensor or microphone was calibrated by comparison method, making a direct comparison with a previously calibrated microphone, that is, a sound level meter. The procedure used to calibrate the audio sensor consist to use a loudspeaker with integrated amplifier of 150W, called BARRISTER BAMP-10, a signal generator and a sound level meter NL-31 from Rion manufacturer.

Fig. 3. Devices in the calibration process.

The process to calibrate the microphone was the following. The signal generator was connected directly to the speaker. Then, a white noise was generated by the signal generator. The noise intensity was changing between 50dB and 90dB. The white noise is a random signal, which is characterized by the fact that signal values at two different times do not keep statistical correlation, and consequently its power spectral density is a constant, that is, the frequency response is flat according to the amplitude of the signal. Both the mote and the sound level meter was one meter away from the noise source to reduce the interference in the acoustic field, that means, interferences from external sources or air system will not influence in the measure. Fig. 3 shows the location of the devices in the process of calibration.

The sound level meter collected the generated noise level by the signal generator and showed it in a digital display, in decibels. Simultaneously, the coordinator received from the mote (previously programmed) the output values of the Analog-to-Digital Converter (ADC). Microphone output was connected to ADC via Smart Cities Board. Once the process was completed, a table that relates the sound pressure level to the value at the output of ADC was obtained. In order to obtain consistent data 1000 samples were collected at each noise level and three sampling rates were used: 1 KHz, 10 KHz and 20 KHz. Table I shows the average value of the output values of the ADC with different sampling rates and at each sound pressure level.

As you can see, it is detected that the analog values obtained for each sampling frequency does not change sharply with different sampling rates. Hence, the values used to calibrate the audio sensor were taken from the 10 KHz sampling rate. The audio sensor is able to capture acoustic level settings between 50dB to 100dB. Nevertheless, values above 90dB can not be obtained when the sampling was done. This is because the

TABLE I
ADC OUTPUT AVERAGE VALUES VS SOUND PRESSURE LEVEL

Sound Pressure Level (dB)	1 KHz	10 KHz	20 KHz
50	42,01	42,11	42,17
55	42,48	42,22	42,28
60	43,37	43,52	43,77
65	49,49	48,67	49,32
70	61,67	60,6	61,63
75	88,49	90,89	90,01
80	142,41	140,35	145,73
85	197,63	197,97	198,87
90	256,83	250,20	250,85

signal generator has not more ability to achieve or generate noise above 90dB. To calibrate the audio sensor with values above 90dB, it was made an interpolation curve from the ADC output values of the previous table. The interpolation curve to acquire the corresponding ADC output values with a sound pressure level between 50 dB and 100dB is shown in the Fig. 4. Polynomial of fourth order that fits the interpolation curve to obtained values is Equation 1 with a coefficient of determination $R^2 = 0,99938$.

$$y = -0,0004x^4 + 0,1009x^3 - 10,338x^3 + 458,66x - 7.431,7 \quad (1)$$

C. Mote Source Code

Fig. 5 shows the flow diagram of source code implemented in motes. First, the RTC, GPS and ACC modules are initialized and enabled. When GPS is connected and synchronized with satellites network it will adjust the internal clock of the SoC and data about mote location are sent to gateway. Next, RTC and ACC programmable interruptions are enabled and the mote goes into sleep mode waiting for the detection of some two implemented interruptions. The RTC interruption is used to awaken the mote periodically. Microprocessor internal clock gives us the option to program the alarm and it can be triggered from 1 second to 24 hours. It is fixed when mote is programmed. On the other hand, the mote has built in an accelerometer that offers insight into the X, Y and Z in which is positioned. The ACC interruption is used to detect if the mote has experienced a fall. If RTC interruption is gathered ambient temperature, humidity, dust particles concentration, acoustic level, battery level, internal temperature and datetime data are gathered and sent to coordinator. Due to ZigBee frame payload is 72 bytes, all data can be sent in a unique packet. If ACC interruption is detected a packet with datetime information and a payload field set to one is sent to gateway. Application level acknowledgment is required from coordinator to confirm the successful delivery. If it is not received within a certain time the packet is re-sent. After some interruption is managed the mote goes into sleep mode again.

IV. Web Data Management

The implementation of the Web Data Management is made up of three different modules:

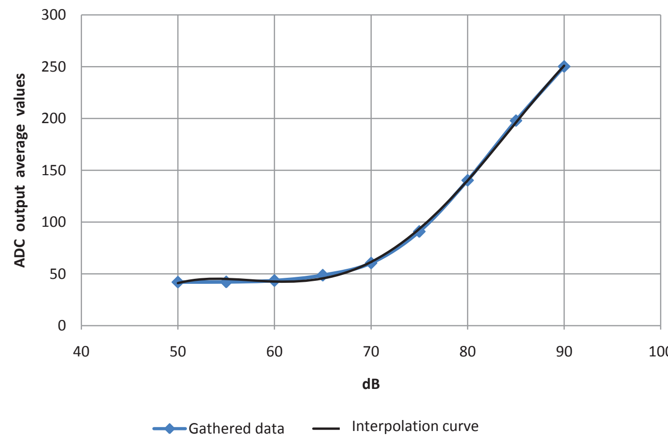

Fig. 4. Gathered data vs Interpolation curve.

- *Database*: It is a MySQL database where the collected information by environmental sensors is stored.
- *Gateway Algorithm*: It is an application charge of parsing the received data from WSN and storing in the remote database.
- *Web Platform*: It is an web site where users can observe the data from environmental sensors.

A. Database

The storage system is composed of a relational database implemented in MySQL. Database is formed by six tables and all the information sent by the motes such as mote location, temperature, humidity, dust particles concentration and acoustic level are stored. Fig. 6 shows the tables relationships in the database.

Waspmote_t table includes the corresponding data to the mote identifier (Serial_ID field) which is defined as primary key and its value is fixed by the manufacturer, an mote description (Waspmote_ID field) and GPS location (float values), latitude and longitude of every mote. *Status_t* table includes maintenance data such as battery level (integer value), internal temperature (float value) of the each mote (Mote_ID field) and a boolean value (Fall field) to register if a fall has been detected. *Temperature_t* table stores collected data by each ambient temperature sensor as float number (Temperature field) of the each mote (Mote_ID field). *Humidity_t* table stores gathered data by each humidity sensor as float number (Humidity field) of the each mote (Mote_ID field). *Dust_t* table stores collected data by each dust particles sensor as float number (Dust field) of the each mote (Mote_ID field). *Noise_t* table stores gathered data by each noise sensor as float number (Noise field) of the each mote (Mote_ID field). Finally, in each table, except for *Waspmote_t* table, are stored date and time when each register was saved.

B. Gateway Algorithm

The Gateway module is a device with ZigBee radio interface and an USB port that enables wireless medium over the wired medium. All ZigBee received packets are forwarded to USB interface. In order to process the packets sent by each

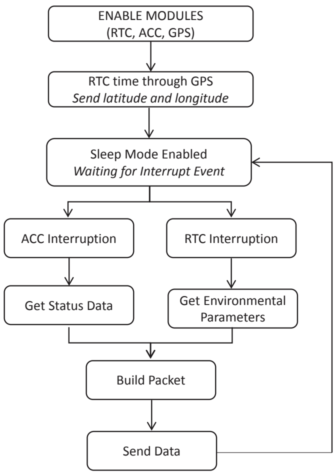

Fig. 5. Mote flow diagram.

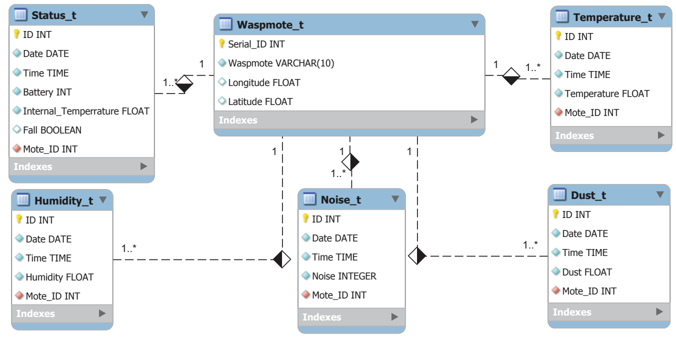

Fig. 6. Database scheme.

mote of wireless sensor network, it has been implemented an algorithm which runs at computer where the gateway module is connected. The algorithm enables the USB port where the module is connected. After that, the algorithm remains waiting for data until a data packet is completely received. The received packet is parsed to extract the sent data from motes. Finally, data are sent to remote database. Fig. 7 shows the flow diagram of gateway algorithm which it has been implemented in Java language.

C. Web Platform

A Web site has been developed to display the content stored in the database. Web site has not established any restricted access system, which means that the publication of data collected by the wireless sensor network is available to any user, and it can be requested at via http protocol. The web application is implemented using HTML5 and PHP. The HTML5 allow us to use objects for enriched data visualization, and on the other hand, the PHP code has been used to connect to the remote database and make appropriate inquiries. The most relevant views are the following and they are shown in the Fig. 8.

- *Map*: In this web page the position of the active sensors in the wireless sensor network is displayed. Google Maps API was used to show the exact location of each node.
- *Data*: This web page is responsible for displaying the gathered data by sensor motes. The data are displayed in graphs and can make an individual choice of each sensor showing the data that it has been collected.

V. Experimental Results

Our monitoring architecture was tested in an environment composed by two motes, a gateway connected to a computer with Internet connection and web server was deployed at http://wsn.ulpgc.es/EnvironmentalMon/. Each mote was equipped with a 3.7V 6600mAh battery, a GPS, a ZigBee radio interface and four mentioned sensors. RTC interruption was enabled to be trigger each hour. Experiments were developed for 96 hours and were focused to test the proposed architecture and demonstrate long life of battery.

Initially the battery of each mote was charged at 99% of capacity. Upon the motes were powered GPS took about four minutes to synchronize with satellite network. After that, gateway received a packet with position information from each mote and it was updated in *Waspmote_t* table at remote database. Next, and until the experiment finished the gathered information by the sensors was successfully stored in the corresponding table each hour. None packet was dropped. At time, http request were completely carried out to web server for visualize the collected information. Upon the experiment ended battery capacity was 95%. That is, only 4% of capacity was used in four days. It is about 66mA per day. Hence, we can infer autonomy mote is about 100 days under experiments conditions. It is an excellent result because large WSN can take a battery replacement long time. Besides, battery life could be extended if GPS module is not used and location information is fixed at mote firmware upload time.

VI. Conclusion

As was discussed in this paper, recent technological developments in the miniaturization of electronics devices and sensors and wireless communication technology have led to the emergence of WSN. Furthermore, environmental monitoring is becoming a major concern to people. In this paper was described the design and development of a real time system for environmental monitoring based on WSN. It was given an overview of the network architecture and communication principles, as well as a detailed description of the hardware and software implementation. The system is capable of monitoring ambient temperature, relative humidity, acoustic levels and concentration of dust particles in the air as well as status information of mote. To minimize the energy consumption ZigBee protocol and programable interruptions were used to wake up the mote when only an events occurs. Results show autonomy nodes can be about three months. Unlike other research where expensive sound level meters are used and hence large size motes are designed, low cost and small size mote was implemented for sensing activity. In order to use low cost microphone we performed a calibration process to achieve correct functionality. AODV routing protocol was used to allow real time adaptation to the network tree topology.

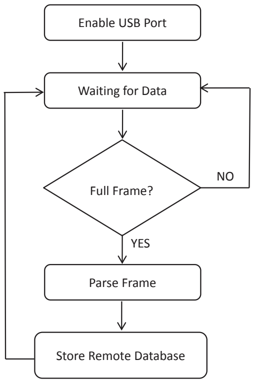

Fig. 7. Gateway flow diagram.

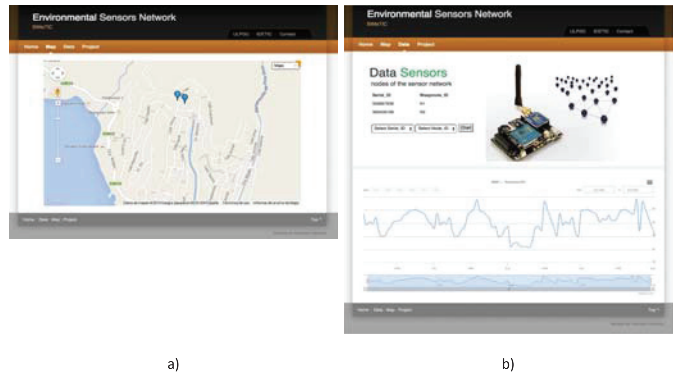

Fig. 8. Web Data Management, a) Map, b) Data.

Furthermore, an application to parse received information from motes and store in a remote database and a web server to visualize the gathered information in real time were designed and implemented.

In our ongoing work we are planning to perform a signal processing of audio captured by the noise sensor. This treatment seeks the acoustic footprint noise being produced and identifying the noise kind in the measuring points such as crowds of people, traffic, train, etc.

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