

# MONITORING AND MODELING BUILDING ENERGY EXPENDITURE WITH SENSOR NETWORKS

Erwing R. Sanchez, Bartolomeo Montrucchio and Maurizio Rebaudengo  
*Politecnico di Torino, Corso Duca degli Abruzzi, 24, Torino, Italy*

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**Abstract:** Residential and commercial buildings constitute one of the largest energy consumption sectors in industrialized countries. This paper introduces a flexible commissioning system for maximizing energy usage efficiency in large and complex buildings. The system focuses on energy saving models to efficiently acquire and process sensor network data, thus reducing energy consumption and costs through the whole process. Novel protocol mechanisms are included in the implementation of the network to reduce its energy expenditure while maintaining a reliable communication. Special attention is placed in developing the performance monitoring interface, specifically designed for increasing personal energy consciousness of end-users. The overall system has been implemented at the Politecnico di Torino main site.

## 1 INTRODUCTION

Nowadays sustainability and green policies have become real drivers for industrial and economic projects in every modern country. Financial crisis, effects of pollution on human health and climate changes are only some of the biggest threats related to energy production, uses and wastes. For these reasons, the development of innovative concepts and systems concerning energy management has achieved increasing interest during last years. Furthermore, since residential and commercial buildings represent 20-40% of the total energy demand (Perez-Lombard et al., 2008), it becomes evident the importance of optimizing resources in buildings and the significant possible savings.

The aim of this paper is to describe the creation of an energy management system in large and complex structures, which represents one of the most interesting challenges concerning energy efficiency and ICT.

A non-intrusive, embedded technology was considered: Wireless Sensor Networks (WSN). WSNs constitute a pervasive and ubiquitous technology which may be deployed in the environment in order to gather information about a physical phenomena. Due to a combination of recent technological advances in electronics, nanotechnology, wireless communications, computing and networking, it is possible to design tiny, low-cost and low-power sensors.

The main contributions of this paper are described

in the following. Mainly, a commissioning system based on WSN was implemented in a large building structure. Particular concern was devoted to the efficient design and implementation of the WSN architecture. The system includes novel mechanisms to tackle down the energy expenditure problem of the network; improvements to traditional Medium Access Control (MAC) and routing protocols are introduced which leads to an energy-efficient system with a several-month lifespan. Furthermore, analysis of captured environmental data is presented, and a model is introduced based on cyclostationary processes.

The paper is organized as follows: Section 2 is devoted to the description of the data management by using wireless sensors networks and their optimized schemes for acquisition and data transfer. Section 3 presents a data analysis framework providing energy saving models for sensor networks, while Section 4 is devoted to the description of the envisaged humans-data interface, developed with the objective of creating awareness and a real perception of energy usage to the user. Results obtained from a sensor network deployed at Politecnico di Torino are presented and discussed in Section 5 and Section 6 concludes the paper.

## 2 DATA MANAGEMENT SYSTEM

Wireless sensor networks are exploited in rather diverse applications to continuously monitor a given environment. To this aim, the sensor network is frequently queried, i.e., acquisition from all sensors of measurements describing the state of the monitored environment (Gehrke and Madden, 2004; Madden et al., 2003; Yao and Gehrke, 2003) is performed. However, this approach is characterized by high energy consumption. Since main contributors to sensor energy consumption are communication and data acquisition (Deshpande et al., 2004), novel intelligent techniques for sensor network querying are needed. Hence, devising power-efficient architectures and models for energy saving during data collection is desired.

Raw measurements from sensor nodes are transferred to a central processing unit via the base stations, which constitute intermediate entities in mesh networking topology. This architecture increases network reliability, avoiding information losses, shrinking delays due to distances in communication and enabling fast response to events detected.

Raw data collected is stored in the DataBase Management System (DBMS), which in turn elaborates information to provide energy indicators for different networks areas. Moreover, information from different base stations are processed simultaneously, increasing the overall interoperability of the system. Results from the commissioning system are reported completely to trained staff responsible for pursuing buildings energy policy. In addition, information provided to non-technical users allows to increase their personal energy consciousness, possibly modifying some of their bad habits.

The data acquisition stage relies in different mechanisms and protocols which performance affects the overall operation of the network. The sensor architecture establishes the foundations of a reliable acquisition regarding, mainly, energy efficient applications. Energy-saving and reliable strategies are considered for relevant layered protocols, e.g., MAC and routing. A preamble sampling approach is adopted for MAC, while an improved energy-aware collection tree algorithm is implemented for the routing protocol.

### 2.1 WSN Architecture

WSNs are mainly deployed to monitor and report physical measured data to a central device or base station. Therefore, their main concern is to collect this data from the environment, by means of sensor nodes, and route it to the base station which perform

appropriate analysis of the collected information. In a *centralized* architecture, there is only one base station which handles all the incoming messages from the nodes and take the decisions related to the analysis to perform. Other alternative, based in this approach, may be adopted such as *multi-tree* architectures.

In a multi-tree approach, networks are created according with the area they cover. Hierarchical trees are formed individually one from another. Every tree is constituted by several sensors nodes and a base station. Thus, each tree is a single network that interacts with other networks in the building by means of their mutual database. This approach presents many advantages for large buildings for several reasons. First, by having multiple base stations, sensor measurements do not have to be propagated through large paths, therefore overall energy is saved because just a few nodes are involved in data propagation each time. Another advantage of multiple base stations is related to networks responsiveness to detected phenomena; since sensor measurements converge faster to the analysis maker entity, i.e., the base stations, then, analysis of data is performed earlier and, consequently, reacting mechanisms such as alarms can be triggered faster.

### 2.2 Collection Tree Protocol

The routing protocol designed is a *tree-based* collection protocol (CTP) where several number of nodes are able to announce themselves as roots of the tree. The routing protocol is *address-free*, which essentially means that the data is not sent to a particular root, instead the destination is, implicitly, chosen by sending the message to the next hop in the upper level of the tree. The main metric used by the protocol to select next hops in the routing tree is the *Expected Transmissions* (ETX), which produces a routing gradient to allow generating the path towards one root. While the initial conditions for a root establish its ETX equals to zero, all other nodes have

$$ETX(n_i) = ETX(n_i^p) + ETX(\mathcal{L}(n_i^p, n_i)),$$

where node  $n_i^p$  is the parent of node  $n_i$ , and  $\mathcal{L}$  is the function to obtain the link between two nodes. As a result, the routing protocol performs the selection of the path with minimum ETX between the source node and the root node.

To improve the behavior of traditional CTP, a new mechanism to compute the metric was developed. Reducing the number of packets transmitted provides an efficient manner to reduce energy expenditure due to the high energy cost of the radio operation. Even if, in CTP, the number of protocol packets decreases in

time, a large quantity of these flows in the network. A solution to reduce the number of protocol packets consists on perform the metric calculation based on the quantity of energy available to the node. Thus, the node with larger energy available is responsible for sending the packets to measure the metric. The receiving node only sends one packet to update the sending node. With this simple mechanism, nearly half of the packets used for the routing protocol are reduced and, in consequence, the overall energy usage of the network is reduced as well.

### 2.3 Preamble Sampling Protocol

Preamble sampling is a protocol designed to avoid sharing sleep/wake up schedules among nodes, i.e., every node chooses independently a schedule without synchronizing it with other nodes.

An optimization to the traditional preamble sampling protocol was introduced in (Sanchez et al., 2009) and was implemented in this deployment. High-traffic nodes are normally closer to the sink due to their behavior to forward others packets to their destination in a network without aggregation mechanism. Most of the energy used to send is due to the waiting period of sending nodes before the receiving nodes wake up. This time can be reduced by following an adaptive mechanism which reduces the sleeping time according to the closeness of the nodes to the sink. The base station is always listening i.e., sleeping time equals to zero, thus, reducing to the minimum the sending time of high-traffic nodes which are in the first level of the routing tree. The sleeping time of those nodes is less than the nominal value in order to help second-level nodes to send their packets without too much waiting. Second-level nodes' sleeping time is higher than first-level nodes' sleeping time. This mechanism goes on until the nominal sleeping time is achieved by nodes that are far from the sink and do not have to forward others packets.

## 3 DEPLOYMENT CONSIDERATIONS

The commissioning system described was implemented at the Politecnico di Torino main site. WSNs for data collection were developed by using Cross-Bow's Telos rev. B (Polastre et al., 2005) nodes compliant with IEEE 802.15.4 and Zigbee standards (Tsang et al., 2009). Telos nodes were provided with sensors for environmental parameters (temperature, relative humidity, light). In addition, customized no-

des were implemented in parallel for acquiring occupancy indicators (human presence and CO<sub>2</sub> levels). Up to 67 nodes were deployed concurrently within several measurements campaigns that were performed through one year.

Due to the measurement campaigns deployed in different buildings and the dimension of the covered areas, mesh networking strategies were limited to less than four hops by adopting the multi-tree network architecture. The routing protocol was address-free and represented an optimized version of CTP (Gnawali et al., 2009) where only the nodes with higher energy evaluated the link quality, as described in Section 2.2. The optimal solution was therefore designed on a 15-minutes sampling time and the improved Low Power Listening (LPL) MAC protocol (Polastre et al., 2004), presented in Section 2.3. This low-power, real-time data acquisition enabled fast response to perturbing situations with controlled network traffic and power consumption, providing improvements on the average lifetime of nodes.

The employed framework consider an end-user in charge of defining the energy saving strategy based upon consumption data and comfort of building users. To facilitate decision making, the processing stage performs statistical and comfort computations. By exploiting the presence sensors, the system is able to statistically single out isolated or weakly-populated areas. Additionally, the termo-hygro-metric comfort of the considered environment can be computed by utilizing the PMV index (ISO 7730, 2005).

Fig. 1 presents an area of the deployments: the Hydraulic and Transport Department. We deployed sensor nodes throughout two floors in an area of roughly 250 m<sup>2</sup>. We selected one corner of the area as placement for the base station. Sensors were placed in different environments of the department; several were positioned in offices, while others were placed inside facilities mainly used by students, such as a small library and small laboratories. One sensor was placed in the main hall as a reference for the other measurements. Another department, the Energetic Department facility was also chosen for deployment, mainly, because it has a large laboratory area with different equipment that may affect temperature or humidity, and may represent an interesting focusing area for energy-saving strategies. The area covered by sensors was about 250 m<sup>2</sup>, as well.

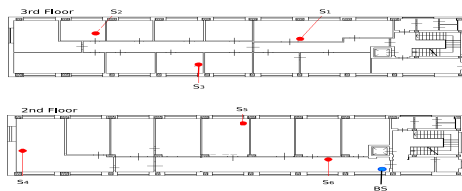


Figure 1: Sensor deployment at Hydraulic and Transport Department.

## 4 MEASUREMENT AND ENERGY-SAVING RESULTS

The reliability of the WSN acquisition system was more than 97% of delivery ratio, which is higher than other approaches (Gnawali et al., 2009). The adaptive preamble approach exploited for the MAC protocol provides a fairer distribution of the energy expenditure of the network by reducing the cost burden of high-traffic nodes towards low-traffic nodes. The optimization of CTP allows for a reduction of almost 50% of the control traffic in the network, which leads to a decrease in power consumption and an increment in the average lifetime of nodes to approximately six months.

The PMV computations shows that high thermal comfort level is guaranteed even in isolated areas, where usually users do not benefit of that situation, resulting in an inefficient energy usage. Fig. 2(a) shows the temperature measurement of an isolated area of the building on January 2010. By hypothesizing a reduction of heating power during working hours and a subsequent modification of the internal temperature by  $-1.5^{\circ}\text{C}$ , a decrease of up to 270 DD (DegreeDay) is obtainable during the whole heating period (180 days per year).

The same reasoning may be applied to summer period, when cooler are activated for air conditioning. Decreasing the internal cooling of isolated areas allows to obtain a further energy saving still guaranteeing an acceptable thermal comfort. The overall theoretical energy saving obtainable may be up to 15% of total annual energy consumption.

## 5 DATA TRENDS AND AUTOCORRELATIONS IN TIME

From the obtained data, autocorrelations functions (ACF) of temperature, humidity and illuminance are presented in Fig. 2(a), 2(b) and 2(c), respectively.

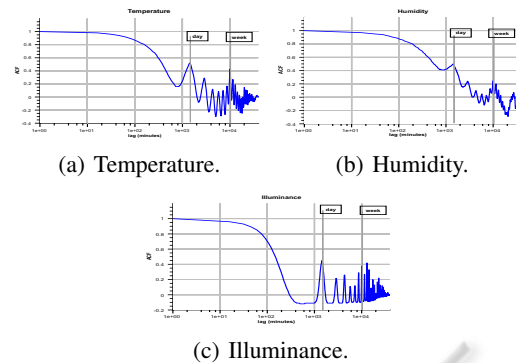


Figure 2: Autocorrelation functions.

The particular node chosen corresponds to  $S3$  in the Hydraulic and Transport Department which is considered as a representative sensor.

Temperature and humidity present specific time trends in two particular periods: daily and weekly. As part of an in-door office scenario, the daily periodicity is consistent due to the clear drift of a day. The weekly frequency behavior becomes clearer by analysing the differences during the weekend, i.e., an office generally behaves differently in the weekend than in workdays in terms of temperature and humidity because fewer individuals are present, thus, generating a weekly periodicity that in other scenarios is negligible.

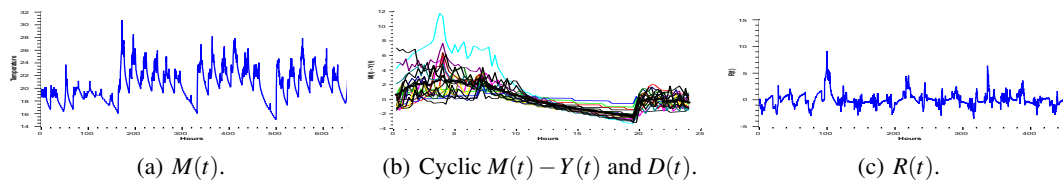
The autocorrelation is highly influenced by these periodicities. A more precise analysis of the energy consumption and behavior of a particular area of a building can be achieved by analysing the fluctuations of the autocorrelation once these cyclic trends and the seasonal trend are removed. To that end, a model of the data based on its decomposition is developed. The decomposition is constituted by three components: the yearly trend, a daily effect and a residual short term fluctuation.

For every time series  $M(t)$ , the addition of the three modes produces the following model

$$M(t) = Y(t) + \sum_n D(t - nT_d) + R(t),$$

where  $T_d$  represents the time period of one day,  $Y(t)$  is the yearly trend,  $D(t)$  represents the daily behavior and  $R(t)$  is the residual fluctuation.  $Y(t)$  is defined as the smoothed average over one day of data, in order to reduce the influence due to daily variations.  $D(t)$  is estimated as the daily trend, after taking out  $Y(t)$ . To address the different behavior of the weekends and workdays, the computation of  $D(t)$  considers merely the workdays.  $D(t)$  is produced by subtracting the yearly mode and taking the cyclic mean over a period of one day:

$$D(t) = \text{mean}(M(t) - Y(t)); t \in \{\text{workday}\}.$$

Figure 3: Decomposition values for node  $S3$ .

For the node  $S3$ , the result of this decomposition is depicted in Fig. 3(a), 3(b) and 3(c). Fig. 3(a) shows the complete time series,  $M(t)$ , for the temperature sensor of the node. After subtracting  $Y(t)$ , the cyclic daily values for working days are presented in Fig. 3(b). For convenience, the mean value  $D(t)$  is also shown in bold. Finally, the resulting  $R(t)$  is shown in Fig. 3(c).

When a day does not follow closely the usual cyclic pattern,  $R(t)$  presents peaks. The analysis of the different measures can be performed considering only  $R(t)$  which isolates the differences of the sensor from the usual trend. Energy managers may utilize this information to single out problematic areas or unusual behaviors in the different areas of the building. While  $Y(t)$  and  $D(t)$  tend to be similar among different nodes,  $R(t)$  represents small fluctuations which can be used to compare against a reference measurement.

## 6 CONCLUSIONS

Commissioning buildings represents usually a huge investment for tenants; however significant savings may be obtained by optimizing energy usage and reducing wastes. Flexibility and interoperability can be increased considerably by exploiting wireless sensors networks which reduce also deployment time and cost of the monitoring system. Optimized protocols play an important role on the savings and sustainability of the sensor network. A model for analyzing sensor networks data allows significant improvements and its exploitation helps to minimize energy consumption for data collection. The experimental results obtained at the Politecnico di Torino case study demonstrated the feasibility of the approach and may serve as a preliminary reference model in developing the monitoring/controlling framework of an On-going Commissioning system.

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