A WSN-based Testbed for Energy Efficiency in Buildings

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***Abstract* — Residential and business buildings account for a large fraction of the overall world energy consumption. Despite the high energy costs and the raising awareness about the impact on climate changes, a significant part of energy consumption in buildings is still due to an improper use of electrical appliances. In this paper we propose GreenBuilding, a sensor-based system for automated power management of electrical appliances in a building. We implemented GreenBuilding as a prototype system and deployed it in a real household scenario to perform a prolonged experimental analysis. The obtained results show that GreenBuilding is able to provide significant energy savings by using appropriate energy conservation strategies tailored to specific appliances.**

Keywords – building energy efficiency; WSNs; energy awareness; building management system.

I. Introduction

It is estimated that the residential sector, which includes household and public buildings, accounts for approximately 20% of the overall world energy consumption [1]. The major causes of energy consumption in buildings are space heating and conditioning, water heating, lighting, and the use of computers and other electronic devices [2]. A significant part of this energy consumption is due to an improper use of such appliances and devices. Just eliminating energy wastes, without lowering the level of perceived comfort, would reduce the overall energy consumption in buildings by approximately 30% [3]. One of the main sources of energy waste is represented by electrical appliances in standby mode. It is estimated that the standby waste accounts for approximately 10% of the overall energy consumption in buildings, and this fraction is expected to increase up to 15% by 2030 [2]. However, while significant energy savings can be achieved by providing users with appropriate feedbacks on personal energy consumptions [4], only relying on people's willingness may not be an effective approach. A recent experimental study [5] has shown that more than 30% energy saving was achieved immediately after installing a monitoring system in a residential household, but the percentage reduced to less than 4% one month later. A more effective solution would be the use of an automated energy management system in addition to user cooperation.

In this paper we propose GreenBuilding, a system based on a network of sensors and actuators that is able to *monitor* and *control* the behavior of electrical appliances in a building so as to minimize the overall energy consumption without reducing the comfort level perceived by the user. GreenBuilding has two main goals: (**i**) making the user aware of economic (and environmental) costs caused by an improper use of electric appliances; (**ii**) providing automated solutions for energy efficiency through appropriate management of appliances. We implemented a prototype version of our system and deployed it in a real household scenario. We found that a significant amount of energy is wasted due to improper use of appliances, and could be saved just using a simple energy conservation rule for each specific appliance, or class of appliances.

The rest of the paper is organized as follows. Section II introduces the GreenBuilding architecture, while Section III describes its implementation. Section IV briefly summarizes the experimental results.

II. System Architecture and Design

We referred to a generic building consisting of a number of floors, each divided in rooms, containing electrical appliances/devices with different characteristics and energy consumptions (e.g., lamps, personal computers, printers, HVAC systems). The overall system architecture consists of two main components, namely a *monitoring subsystem* and a *control subsystem*. The *monitoring subsystem* is used to measure the energy consumption of each single electrical appliance. In addition, it also provides environmental and context information (e.g., temperature, light intensity, presence of persons). The *control subsystem* is aimed at controlling the behavior of each single appliance on the basis of information provided by the monitoring subsystem and on *energy conservation strategies* defined by the user.

A. Monitoring Subsystem

The monitoring subsystem, depicted in Figure 1, is composed by a number of electricity sensors, measuring the power consumption of each single electrical appliance in the building. In addition to electricity sensors, the monitoring subsystem also includes environmental sensors for monitoring parameters such as temperature, light intensity, human presence, and so on. Such information will be used by the energy manager application to minimize energy wastes, according to energy conservation strategies defined by the user(s). Data collected by both electricity and environmental sensors are communicated wirelessly to a base station located in the same floor (there is at least one base station per floor) and, then, conveyed to a central server. The communication between base stations and the central server typically occurs through a wired LAN (e.g.. Ethernet). The central server has the responsibility to collect and process data. It provides users with real-time and/or periodic reports on energy consumption and costs. The server also sends alert messages to notify specific events (e.g. a device active when it is supposed to be inactive) suggesting possible actions to save energy.

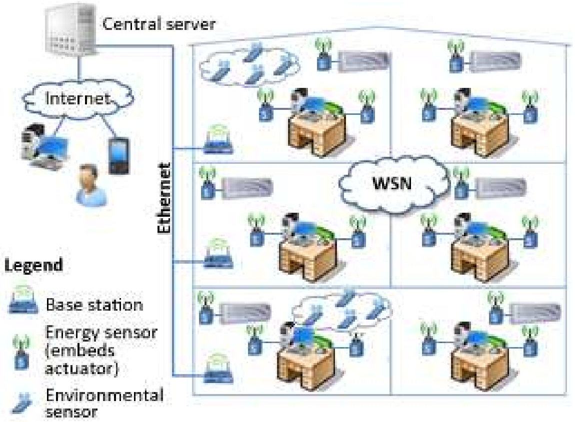


Figure 1. GreenBuilding architecture.

B. Control Subsystem

The control infrastructure consists of a number of actuators – one actuator for each single electrical appliance – and a set of controllers that coordinate the actuators. Controllers are connected to a central server, through a wired LAN technology (i.e., Ethernet). The server generates commands for a specific appliance in the building that are sent to the corresponding actuator through the appropriate controller. Possible commands are “switch on”, “switch off”, or “regulate the amount of current provided to the appliance”.

The monitoring and control infrastructures are conceptually different as they have different objectives. In practice, however, the sensing and actuation functionalities could be integrated in the same device, i.e., the electricity sensor could also act as actuator for the associated appliance. Actually, several integrated wireless sensor/actuator platforms are currently available on the market, e.g., Plogg [6] and WiSensis [7]. Obviously, when taking this approach one sensor/actuator per appliance must be used. It is not possible to use a single sensor/actuator for a group of appliances if we want to control each appliance autonomously. As an alternative, we could use two different infrastructures for monitoring and control (obviously, the latter approach is the only viable solution when electricity sensors do not provide actuation capabilities). For example, X10 products can be used for control. When using this technology, an X10 controller sends commands to X10 actuators controlling electrical appliances through Power-Line Communication (PLC). The main advantage of this approach is that the X10 technology is reliable and cheap. Instead, electricity sensors are typically more expensive (at least currently). Therefore, limiting the number of electricity sensors (e.g., using a single sensor for a group of appliances) may be convenient. The system architecture when using a dedicated (X10) control infrastructure is depicted in Figure 2.

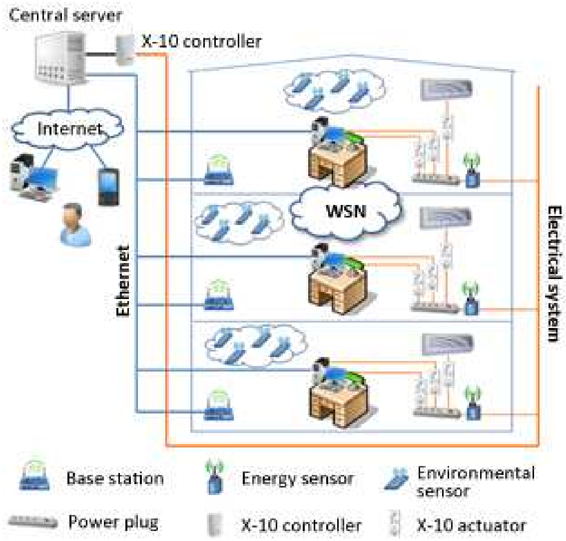


Figure 2. GreenBuilding architecture with a dedicated (X10) control infrastructure.

C. Energy Conservation Strategies

The system architecture described above allows a flexible and efficient management of each single appliance and, hence, provides the potentials for implementing appropriate energy conservation strategies for each appliance (or class of appliances). In the following we provide a (non exhaustive) list of possible strategies.

- **Energy awareness.** User awareness about energy consumptions is the primary form of building energy efficiency. According to a number of studies, providing appropriate feedbacks to building occupants can significantly reduce the overall energy consumption, in the order of 5-20% [4]. To this end, GreenBuilding allows users to get detailed and real-time information on the energy consumption and status (i.e., on/standby/off) of single appliances, even remotely. The system can also send periodic reports (e.g., by e-mail). Finally, GreenBuilding can send alert messages to the user’s portable device when some specific events occur (e.g., a device is active when it is supposed to be inactive), also suggesting possible actions to save energy.

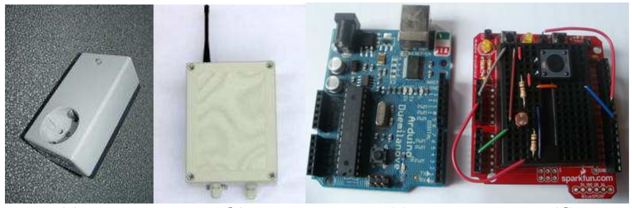
- **Elimination of stand-by consumptions.** Feedbacks on energy consumptions can make the user aware of possible energy wastes, e.g., standby consumptions. In order to automatically eliminate (or drastically reduce) standby wastes, GreenBuilding allows the user to specifiy an appropriate management strategy for each specific appliance. The system is able to recognize when an appliance is in standby mode and take appropriate actions to execute the strategy defined by the user. For example, the system can switch off a certain appliance after a predefined time interval has elapsed from when it entered the standby mode.

- **Scheduling of *flexible* tasks.** Some energy consuming tasks that do not require a directly user involvement can be scheduled for execution at some pre-programmed time, e.g., during night, when the energy cost is lower. Examples of such tasks include all those associated with white goods (e.g., washing machine and/or dishwasher). GreenBuilding allows the user to specify the exact time or time interval (e.g., the slot time when the energy costs are lower) when a certain task is to be executed by a specific appliance (e.g., the washing machine). Using a standby elimination rule, in addition to appropriate scheduling, can actually minimize the energy consumption of electrical appliances executing flexible tasks. For example, the washing machine can be switched on by the system only at the pre-programmed time. Once the task has been completed the appliance enters the standby mode. This is detected by the system and the washing machine is then switched off**.**

- **Adaptive control of electrical appliances.** A significant fraction of energy is wasted due to electrical appliances that are unnecessarily active, e.g., lamps switched on when the external light intensity is high, air conditioning system providing a too low ambient temperature, and so on. To eliminate such wastes, GreenBuilding relies on environmental sensors capable of monitoring ambient conditions (e.g., temperature, light intensity, humidity, presence of persons, etc.). Data acquired by environmental sensors are conveyed to the central server, through base stations located at each floor, and used by the system to adapt the behavior of each single appliance, based on rules specified by the user (e.g., desired light intensity).

III. Prototype Implementation

We implemented the previously described architecture in a prototype system. To reduce the number of electricity sensors, in our implementation we used two different infrastructures for monitoring and control. The monitoring subsystem is based on WiSensys [7] sensors (Figure 3-a) and base stations (Figure 3-b). WiSensys sensors plug into a standard electrical outlet and provide a standard outlet, at their turn. They measure the power absorbed by the appliance and send measurements to the base station, using a proprietary wireless communication protocol. Since there is only one base station in our testbed, it is connected to the central server through a direct RS232 link. In a real system the connection could be through an Ethernet link. The environmental sensor network consists of a number of light intensity sensors. We built light sensors by ourselves using the Arduino platform, which is a very popular open-source prototyping platform based on flexible, easy-to-use hardware and software [8]. Figure 3-c and Figure 3-d show the Arduino main card and the photo shield, respectively, used for implementing the light sensor. Finally, the control infrastructure is made up by a number of X10 receivers and one X10 controller manufactured by Marmitek [9].



(a) (b) (c) (d)

Figure 3. Monitoring devices used in our testbed: WiSensys sensor (a) and base station (b) for electrical power consumption monitoring. Arduino main card (c) and photo-shield (d) for light intensity monitoring.

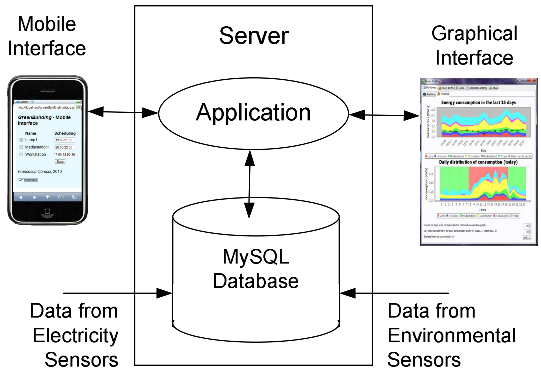
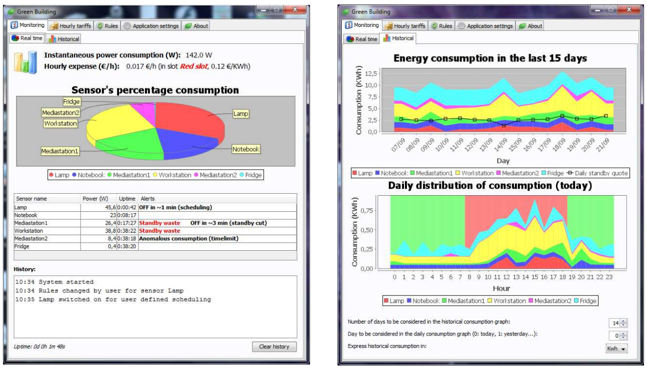


Figure 4. Software Architecture.

Figure 4 shows the software architecture of the system. The core component is the energy manager application running on the central server and implemented in Java. It is responsible for (**i**) processing data on power consumption of appliances measured by electricity sensors, (**ii**) providing appropriate reports to the user, (**iii**) processing data originated by environmental sensors, (**iv**) accepting configuration parameters and energy management rules from the user, (**v**) sending appropriate commands to appliances – through the control network – depending on current environmental conditions and according to user's rules.

Data acquired by electricity sensors are stored in a MySQL database at the server. The user can log on the system, even remotely, and access different kind of real-time and historical graphical information, through a set of tabs. Figure 5-a shows the tab presenting information on real-time power consumptions. The user can immediately recognize the contribution of each single appliance to the overall power consumption. The same tab also includes some (textual) information to make the user aware of possible energy wastes (e.g., appliances in standby mode). Figure 5-b shows another tab presenting historical information on the energy consumption of single appliances, i.e., the energy consumed in the last 15 days (top-side plot) and hour-by-hour in a specific day (bottom-side plot). The former plot also highlights the overall standby consumption. The latter plot allows the user to better understand how energy consumptions are distributed during the day. This is particularly important if energy costs follow a hourly-based tariff.



(a) (b)

Figure 5. GreenBuilding tabs presenting: (a) breakdown of real time power consumptions, (b) energy consumptions of different devices during a time interval and in a specific day.

GreenBuilding also provides a set of tabs for introducing configuration parameters and defining energy conservation rules on single appliances or classes of appliances. Figure 6 shows how to define a rule for a certain appliance. On the left side of the tab, there is the list of all controlled appliances. Once the specific appliance has been selected, the user can specify one or more rules for (**i**) eliminating the standby consumption, (**ii**) scheduling flexible tasks at pre-programmed times, or (**iii**) performing appliance-specific actions (e.g., for lamps, adaptive power control based on environmental light intensity)[1].

In addition to the graphical interface described above, GreenBuilding also provides a simplified interface for portable devices (e.g., cell phones). The simplified interface still allows the user to look at real time and/or historical information on electrical consumptions, change configuration parameters, and specify/change rules for each single appliance (or class of appliances). In particular, the user can check the status of each appliance and switch it on and off, even remotely. Therefore, the GreenBuilding-enabled mobile device can be used as a sort of remote control. In addition, the simplified interface allows the user to receive alert messages on his/her portable devices if some event occurs (e.g., an appliance that is supposed to be switched off is still in active/standby mode).

[1] Depending on the specific appliance, some of the mentioned strategies could not be available.

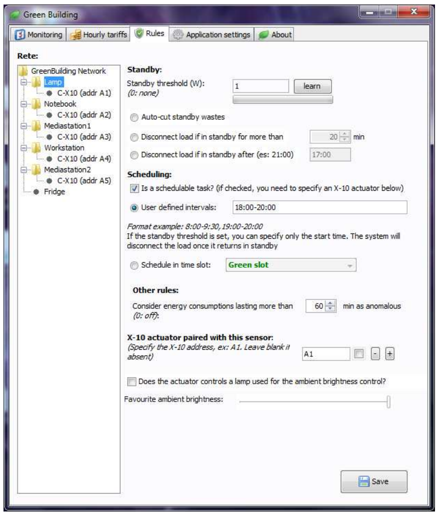


Figure 6. GreenBuilding tab for defining energy conservation rules.

IV. Experimental Evaluation

To test and evaluate GreenBuilding we deployed a number of electricity and environmental sensors and X10 actuators in a real environment (i.e., a household scenario) and measured the power consumption of a set of appliances for a relatively long time interval (15 days). The objective of this experimental study is to investigate possible energy wastes and user's bad habits in using electrical appliances. We also implemented some energy conservation strategies for some appliances, and measured the corresponding energy savings. The experimental results show that GreenBuilding is able to provide significant energy savings, by eliminating standby consumptions and/or adapting the behavior of appliances to the real environmental conditions.

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