Electrical Energy Consumption Control in Buildings Using Wireless Sensor Networks

A Preprint

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ABSTRACT

Energy consumption in residential and commercial buildings has increased dramatically worldwide in the last decade, due to the constant population and economic growth, the proliferation of electronic and consumer appliances. This has dramatic footprint on the environment in terms of carbon emission, in addition to the economic impact. Green and smart building strategies will play a pivotal role to reduce this footprint and maximize economic and environmental performance. These strategies can be integrated into buildings at any stage, from design and construction, to maintenance and renovation. The use of modern Information and Communication Technologies (ICT), notably IoT solutions, for building control is one of the promising strategies for the future. The aim of this project was to explore this domain, and as a first step to develop a wireless sensor networks based solution for monitoring and energy management in offices. A prototype has been targeted as a proof of concept where sensors monitor physical parameters in CERIST offices (presence of people, ambient light, etc.), and accordingly actuate lighting, air conditioning, etc. This report is a short summery of the different parts developed in this project.

PROJECT IDENTIFICATION:

| Type          | Applied, development, Training |
|---------------|--------------------------------|
| Title         | Electrical Energy Consumption Control in Buildings Using Wireless Sensor |
| Project Head  | Djamel Djenouri                |
| Starting      | Juliet 2014                   |
| End Date      | December 2017                 |
| Partner       | NTNU, Trondheim, Norway        |

RESULTS:

A working prototype has been developed, featuring, optimal deployment for coverage, optimal duty cycling, realtime actuation for air conditional and lighting control. The prototype has been tested as proof-of-concept at the CEO office, and at another office (Building A) as well for harvesting long term data to evaluate the proposed solutions. Significant scientific results have been subject to publications in top tiered journals and conferences [1-6], which will be presented in the following.

Description of the prototype and related solutions
Participants

| Name                  | Title  | Quality (permanent, adjunct, collaborator, extern student, etc.) | Group | % of participation |
|-----------------------|--------|------------------------------------------------------------------|-------|-------------------|
| Djamel Djenouri       | DR     | Permanent                                                        | WSN   | 40%               |
| (Project PI)          |        |                                                                  |       |                   |
| Cherif Zizou          | Ing.   | Permanent (absent for 18 months)                                  | WSN   | 60% during 1 year  |
| Sahar Bouelkaboul     | AR     | Permanent                                                        | WSN   | 40% during 6 months|
| Roufallia Laidi       | Ing    | PhD Student (starting Jan 2016)                                   | WSN   | 100% during 20 months|
| Othmane Mokhtari      | Ing    | Engineer                                                         | WSN   | 100% during 5 months|
| Alumni Group members  |        |                                                                  |       |                   |
| Messaoud Doudou       | MR(B)  | Permanent (absent for 2 years)                                    | WSN   | 40% during 1 year  |
| Nouredine Lasla       | MR(B)  | Permanent (absent for 1 years)                                    | WSN   | 30% during 2 year  |
| Abdelraouf Aoudjaout  | AR     | Permanent (absent for 21 months)                                  | WSN   | 30% during 1 year  |
| Miloud Baga           | MR(B)  | Permanent (absent for 2 years)                                    | WSN   | 40% during 1 year  |

The prototype mimics a pervasive system that can be integrated in existing buildings without any complicated wiring or setting (Fig.1). Realistic constraints are considered for this purpose such as sensing-hole, battery limitation, user comfort, daylight harvesting, etc. To ensure maximum coverage in presence of holes, the optimal placement of PIRs is formulated as a mixed integer linear programming optimization problem (MILP). Experimentations have been carried out to quantify the effects of the holes on the detection accuracy and to demonstrate the impact of the optimal PIRs placement on energy consumption. To facilitated installation and integration without complicated settings, notably in existing buildings, the system is designed to be battery operated. Therefore, energy efficiency will not be limited to optimize energy consumption in buildings, but also to optimize consumption in the components of the system (sensors and actuators). Duty cycling is inevitable to extend the network lifetime of such components, but the setting of this cycle yields a trade-off in optimizing the energy consumption i) at the building level, vs., ii) that consumed by sensors and actuators. Reducing energy consumption (duty cycle) of sensors/actuators will delay non-occupancy detections and thus will increase the building energy wastage, and vice-versa. Duty cycling the radios is dealt with and modeled as a cooperative game, which allows to derive a Nash Bargaining as the optimal balancing cycle. The proposed approach is analytically investigated using realistic parameters of the existing hardware and users’ comfort. The results demonstrate that the system can survive for several years without battery replacement.

The prototype includes:
- Sensor devices, including PIR, temperature, light, that are connected to actuators (smart switches).
- A solution on PIR sensor deployment for optimal coverage in offices.
- Optimal setting of parameters to enable effective usage of batteries, with lifetime estimated to up to 5 years for the sensor mote and 9 years for the actuator (smart switch).
- Sensor and relay node indoor deployment by considering realistic physical layer parameters in building environment.

**Sensor nodes deployment** PIRs are low-power sensors that use pyroelectric transducers, which convert infrared radiations into electrical signals. To increase the PIR sensitivity, a *Fresnel lens* is used. It concentrates infrared radiations onto the detector. This results in a field-of-view (FoV) that is more like a discrete set of beams or cones with many sensing-holes. To be detected, the movements of the person should take place within the FoV. Fig.2(a) illustrates the different types of motion made by a human and the corresponding maximum sensing-hole size for which the motion can be detected by a PIR. The sensing-holes should not exceed 0.6 m to ensure an efficient detection of a sitting person’s hand motions. The size and distribution of the holes impact the granularity of the PIR detections. Fig.2(b) illustrates the projection of the actual FoV of a Panasonic EKMB PIR sensor on a two-dimensional plane. The PIR is placed at the ceiling of an office and the projection is performed on the plane parallel to the ground and
elevated at a typical height of desks, where most of persons’ low movement activities take place (e.g. arm and hand movement when sitting). The figure shows the presence of several sensing-holes that represent more than 87% of the total monitored office area, and their sizes vary from one region to another within the PIR’s FoV. They may exceed 1m in some areas. These large sensing-holes may affect PIR-based occupancy detection systems and cause incorrect decisions, such as turning off a light or HVAC in the presence of a person, which limits the credibility of the system.

To deal with the sensing hole problem, we formulate a Maximum PIR Coverage (MPC) problem that finds the optimal positions of the PIRs for maximum coverage in the area of interest while considering the sensing-hole. To simplify the formulation, we consider the projection of the covered area on a two-dimensional plane as explained before. Despite such simplification, the computation of the detection zones for a given set of PIRs is difficult to formulate mathematically. The monitored area is discretized and considered as a set of points, where a point will be considered...
covered if it is within the coverage zone of at least one PIR. The obtained formulation is a mixed linear program to which we applied the Big-M method for transformation into standard form.

We have deployed an experimental PIR-based occupancy detection system to monitor an office and quantify the impact of the sensing-holes on the performances of the system. The PIR we used (EKMB PIR sensors from Panasonic) has been integrated to an nRF51-based mote (by Nordic Semi-conductors), which features a low-power SoC that embeds an ARM Cortex-M0 MCU, and a 2.4GHz wireless transceiver. We integrated the sensor to the mote via the available pins. The considered deployment area is a single-occupant office of $3.3 \times 2.4 \text{ m}^2$. Most activities are concentrated over the office desk that received greater weights in the corresponding entries in the weighting matrix (denoted $\phi$). The discretization step was fixed to 0.3 m resulting in a grid of $11 \times 8$ points. While the whole the office space falls within the sensing range, the real covered space is not the continuous space over this range but includes gaps (sensing-holes that has been explained above), and it might be represented as a set of discontinued squares (Fig.2.b). Three deployments scenarios have been evaluated. The first one corresponds to the optimal solution of the MPC problem when using one PIR (Fig.3). This deployment covers nearly 63% of the desk’s area. Optimal full coverage of this space is ensured with 3 PIRs, which corresponds to our second deployment scenario depicted in Fig.4. In the third scenario, a single PIR was placed using hole-unaware placement as shown in Fig.5. It shows the real impact of sensing-holes on the performances of the detection system. It is worth noting that existing solutions consider the deployment represented by the third scenario as optimal since they ignore the presence of the sensing-holes and consider the PIR covers the whole space within its sensing range (all the office). This is effective in space with high motion (halls, doors, etc.), but not offices.

To evaluate the performance of the system in the three deployment scenarios and under different time-out values (continuous time of absence reports by sensors before considering the space is vacant), we have measured two metrics, i) the comfort level, and, ii) the waste in energy usage. The first metric quantifies the ability of the system to preserve the convenience of users. That is, the ability not to disturb the occupants by keeping office energy supply on when they are present in the target area (i.e., ability to overcome false absence (FA)). The second metric reflects the proportion of
time the system fails to effectively detect (or react to) the absence of occupants, which implies a missed opportunity to reduce the energy consumption. Fig. 6 plots the Cumulative Distribution Function (CDF) of correct absence decisions as a function of the required time to take that decision (timeout). The results show fast convergence of the proposed solution vs. hole-unaware deployment. These results help in selecting the corresponding timeout to achieve a particular true absence (TA) probability (percentage). For instance, to realize 90% of TA, the timeout should be set to 20 sec, 35 sec and 80 sec for optimal3, optimal1, and hole-unaware deployment scenarios, respectively.

We can also notice from Fig. 7 that the performance of the optimal solution using only one PIR is very close to the optimal full coverage solution using three PIRs. Compared to hole-unaware solution, Optimal3 allows to reduce energy wastage up to 9% for high comfort level, and Optimal1 to up to 7.5%

We also considered placement of relay nodes (RNs) in the building environment and we proposed an original solution that consists of: i) the usage of a realistic physical layer model based on a Rayleigh block-fading channel, ii) the calculation of the signal-to-interference-plus-noise ratio (SINR) considering the path loss, fast fading, and interference (which reflects the indoor environments), and iii) the usage of a weighted communication graph drawn based on outage probabilities determined from the calculated SINR for every communication link. Overall, the proposed solution aims for minimizing the outage probabilities when constructing the routing tree, by adding a minimum number of RNs that guarantee connectivity. In comparison to the state-of-the-art solutions, the conducted simulations reveal that the proposed solution exhibits highly encouraging results at a reasonable cost in terms of the number of added RNs. The gain is proved high in terms of extending the network lifetime, reducing the end-to-end delay, and increasing the goodput. While the prototype has only been deployed in single offices so far, the solution of optimal RNs placement will be useful when extending the prototype to the building scale, notably in multiple-floors buildings.

**Extending system lifetime**
As the proposed control system relies on battery-operated sensor motes, it is important to optimize the battery power usage. Each mote should switch to power-save mode during inactivity periods. Since the radio is the most energy hungry component, the medium access control (MAC) protocol plays a key role in extending the system lifetime, by controlling the radio states and by employing low duty-cycles. In our occupancy detection scenario, the sensor-mote requires to report its new PIR or ambient light readings to (for example) the switch-mote to instantly turn on the light when the space becomes occupied or when the ambient light level becomes undesired. Instantaneous reporting is required to meet the expected users’ comfort. Because the moment when the occupancy state changes is unknown, the radio transceiver of the switch-mote should be always in standby (receive mode). This causes waste of an important amount of energy given that consumption in the reception mode is significant. The trivial solution to this problem is the implementation of a low duty-cycle MAC protocol, where energy saving is achieved by repeatedly switching the radio between active and sleep modes. This is known in literature by duty-cycling. In active mode, a node can receive and transmit packets, while in the sleep mode, it completely turns off its radio to save energy. We targeted the use of existing duty-cycled MAC solutions (LPL used for illustration), while optimizing operation parameters. To ensure the users’ comfort required by the automatic light control system and extend its lifetime, we proposed to embed the switch-mote with a low cost PIR sensor. The later will be responsible of triggering the switch-mote once a movement is detected. By placing the switch-mote within the light-switch, next to the space entry, the new PIR sensor will be able to capture any entry and thus, enable the system to instantly turn on the light when the space becomes occupied. In this case, the switch-mote’s transceiver can be turned off without affecting the users’ comfort requirement. However, because the FoV of the new PIR sensor used by the switch-mote is mainly directed towards the space entrance, the latter cannot autonomously determine if the space is actually unoccupied (i.e., cannot rely on its PIR for that). This information can be only provided by the sensor-motes that have an appropriate coverage of the monitored space, i.e. deployed using the solution described previously.

Both the sensor-mote and switch-mote are in power save mode with the radio turned off when the office is unoccupied. When a person enters the office, the new PIR sensor will trigger the switch-mote to immediately turn on the light and start duty-cycling the radio to receive occupancy state or ambient light reading from the sensor-mote. Whenever the later detects the activity in the office or read a new light value, it will activate its radio and start sending the new information to the switch-mote using the packetized preamble model similarly to the LPL scheme. The switch-mote keeps duty-cycling its radio until receiving an absence state. The sensor-mote returns to sleep mode after sending the new state. When an absence is detected, the sensor-mote reactivates its radio and reports the switch-mote in order to turn off the light and enable it to go to sleep mode to save energy. The duty cycle period of the switch-mote has a conversely effect on the two motes’ lifetime. To calculate the optimal value of the wake-up period that enables making a balance between the sensor-mote lifetime and that of the switch-mote, we formulated the problem using game theory. We used the Bargaining model to define our two-player game. Instead of defining the individual nodes as players— which is common in the literature. The game players in our model are the systems objectives (sensor-mote and switch-mote lifetime). This limits the number of players and makes it independent from the problem size, which is scalable. The utility function of each player is used by the model to determine the optimal wake-up period parameter. Each player threat the other with using his best optimal point obtained from a non-cooperative game in which the player finds his best optimal operating value, i.e., player sensor-mote obtains its longest lifetime at the cost of decreasing the switch.
mote and vis versa. A bargaining game is then defined in order to find an agreement operational point that satisfies both players. We considered a weighted model, where the desired sensor-mote lifetime is given a weight, i.e., it is \( \alpha \) times more important than the switch-mote lifetime \((\alpha \geq 1)\). Fig.8 depicts the obtained results (lifetime and duty cycle parameter) for values of \( \alpha \) ranging from 1 to 5. The figure shows that sensor-mote lifetime can reach more than 9 years without battery replacement for 2 years lifetime for switch-mote, which is a tolerable frequency of replacing batteries of the switch that is usually more accessible than sensor-mote.

![Figure 8:](image)

**TRAINING:**

Undergraduate internships: One student for short internships (1 month).

Masters: Three students for short internships (1 month).

Doctorate: Two students working on the projet (ongoing).

**COLLABORATION:** NTNU (Norwegian University of Science and Technology), Trondheim, Norway. Mobility Grant has been obtained from The Norwegian Research Council to cover research visits to NTNU.

**DIFFICULTIES MET:** Completely Unstable Human Resources, with too many long leaves (for a year and more) of staff simultaneously. Several risk management measures have been taken to deal with this problem. Many researchers have been involved midterm during the project lifetime. Further, some objectives have been cut down (generalization of the prototype to several buildings).

**PERSPECTIVE:** The project has been limited to sensing and realtime actuation for energy control in offices. Considering jointly energy optimization and user comfort services is an interesting perspective. Here by comfort, we are not taking about optimal timeout values to avoid disturbing users with false actuations (which has already been dealt with in the project), but we refer to more advanced services such as including security services, customized AC, etc. Moreover, sensing has been limited to the use of sensor motes. Integrating sensing through other IoT devices (smart phones), smart meters, information from the cloud etc., will be required to achieve the above mentioned advanced services.

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