Occupancy-Driven Energy Management for Smart Building Automation

Yuvraj Agarwal, Bharathan Balaji, Rajesh Gupta, Jacob Lyles, Michael Wei, Thomas Weng
Department of Computer Science and Engineering
University of California, San Diego
{yuvraj, bbalaji, jlyles, gupta, mwei, tweng}@ cs.ucsd.edu

Abstract

Buildings are among the largest consumers of electricity in the US. A significant portion of this energy use in buildings can be attributed to HVAC systems used to maintain comfort for occupants. In most cases these building HVAC systems run on fixed schedules and do not employ any fine grained control based on detailed occupancy information. In this paper we present the design and implementation of a presence sensor platform that can be used for accurate occupancy detection at the level of individual offices. Our presence sensor is low-cost, wireless, and incrementally deployable within existing buildings. Using a pilot deployment of our system across ten offices over a two week period we identify significant opportunities for energy savings due to periods of vacancy. Our energy measurements show that our presence node has an estimated battery lifetime of over five years, while detecting occupancy accurately. Furthermore, using a building simulation framework and the occupancy information from our testbed, we show potential energy savings from 10% to 15% using our system.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and Embeded Systems; J.7 [**Computers in Other Systems**]: [Industrial control]

General Terms

Design, Management, Human Factors

Keywords

Occupancy Detection System, Wireless Sensor Network, HVAC Control System

BuildSys 2010 November 2, 2010, Zurich, Switzerland.

1 Introduction

Buildings are known to be one of the largest consumers of electricity; the US Department of Energy estimates that buildings consume 70% of the electricty in the US [9]. Recent efforts have focused on making buildings more energy efficient, including research that target specific areas such as HVAC [10][12], lighting [8] and managing IT energy consumption [2][1] within buildings. The energy usage in a building can typically be divided amongst several subsystems, including plug loads, lighting, and mechanical equipment used for climate control [14]. Mechanical equipment includes the combined heating, ventilation, and air-conditioning (HVAC) loads and constitutes a significant amount of energy consumption.

Therefore HVAC systems are a prime target for optimization using dynamic control algorithms that can be implemented using a deeply coupled network of sensors (to measure environmental parameters such as temperature) and actuators (to affect the environment such as fans and chillers). Traditionally, most HVAC systems use only temperature and humidity as the primary inputs in determining cooling requirements [4]. This limitation can often lead to inefficient energy usage. For example, a room might be cooled to 22.9C regardless of whether there are any occupants.

In this paper we show that incorporating additional inputs to the HVAC controller is critical for increasing its energy efficiency. We believe that one of the key inputs to drive HVAC systems is fine grained occupancy information. Unfortunately, most occupancy sensors currently installed within buildings are fairly coarse-grained and inaccurate. Furthermore, these occupancy sensors are usually local in scope and only control lighting. Passive infrared (PIR) based sensors are often used (especially with local lighting) for occupancy; however, by itself PIR is limited to movement and does not detect actual occupancy in a given area. More advanced systems have been deployed, such as using cameras and vision algorithms, but these systems suffer from deployability, cost and privacy issues. In order to maximize the energy savings and spur rapid adoption we believe it is imperative to have an occupancy detection system that is accurate, inexpensive and easily deployable within existing buildings.

This paper focuses on an occupancy detection system that we have implemented with these goals in mind and its evaluation in terms of energy savings. We first describe the design of our low-cost wireless occupancy sensor with an empha-

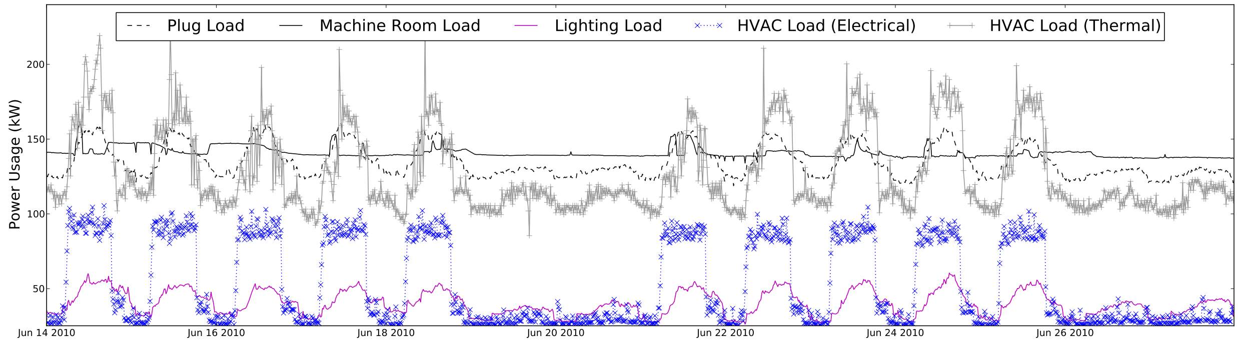

Figure 1. Detailed energy-use breakdown of the CSE department building for 2 weeks in June 2010. The HVAC loads have been broken down into two categories: 'electrical' such as pumps, chillers, fans and 'thermal' as denoted by the amount of heat taken out from the campus chilled water loop, expressed in KW.

sis on accurate occupancy detection. We then describe our wireless network infrastructure used to collect occupancy information. We evaluate our system in terms of accuracy and energy-efficiency and show that not only is our wireless occupancy system low-cost, it can accurately detect the presence/absence of occupants in individual offices. Finally, we evaluate our HVAC control system using Energy Plus, and quantify how occupancy information provided by our sensing platform can be used to reduce building energy use by 10% to 15%, and possibly more depending on the actual HVAC system.

2 Background

Using occupancy as a driver for intelligent control of HVAC and lighting systems has been explored previously. Prior research in HVAC control systems shows that occupancy information can be used to drive a more optimized HVAC schedule [15][20]. However, due to the difficulty in obtaining real time accurate occupancy data, many of these techniques focus on using pre-determined schedules. Many modern buildings use passive infrared sensors (PIR) to drive lighting; the PIR sensors are connected directly to local lighting fixtures and are rarely used for intelligent HVAC management. These PIR sensors are also simple movement sensors and often cannot actually determine if the room is occupied or not. Thus most use a timeout for shutting off the lights (30 minutes is common) which can be sub-optimal. Other methods for detecting occupancy include using sonar-based methods [17] or camera based systems [18] that bring up concerns relating to cost, deployment and privacy issues. CO2-based occupancy detection has also been examined - the main limitation of these systems is that they are very slow to detect events such as incoming people [19].

Many modern buildings already contain a limited number of wired sensors as part of a wired control system such as BACnet or LonWorks. A major barrier to more widespread deployment of sensors, however, is installation costs due to the need for additional wiring for each sensor. The advent of low-cost wireless sensor networks has enabled wider deployment opportunities of a large number of connected sensors [11] thus allowing for improved sensing (such as occupancy detection) in buildings. Padmanabh et al., for example, investigated using microphones and PIR sensors to drive more efficient scheduling of conference rooms [16]. Delaney et al. used PIR based wireless occupancy sensors to measure wasted energy in lighting even when there are no occupants [8]. These efforts however neither use occupancy information to drive actual systems nor evaluate accuracy of their detection sensor. Erickson et al. proposed a wireless network of cameras (which have the aforementioned privacy and cost issues) to determine real-time occupancy across a larger area in a building [10], focusing more towards coarse-grained floor-level occupancy detection.

Several efforts have looked at using occupancy data in the context of a home, as opposed to a mixed-use building. Gao et al. sought to use coarse occupancy data (leave home, return home) to drive a self-programming home thermostat [12]; however the focus is on the thermostat self-programming algorithms, and not on obtaining accurate occupancy. Barbato et al. used PIR sensing to determine occupancy in their smart building system; once again the focus was on algorithms supporting user profiles [5]. In either case, the scenario of a home (with a few occupants) as compared to a large building (with many occupants) is very different.

In order to quantify the potential savings that an occupancy driven HVAC system can have over a traditional system, we needed to measure the total energy used by the HVAC system as a fraction of the entire building energy use. At UC San Diego, we have instrumented the Computer Science and Engineering (CSE) building with several electricity and thermal submeters as part of our campus-wide Energy Dashboard effort [3]. The CSE building is a typical mixed-use building with people and supporting IT infrastructure. Completed in 2005, it is one of the newer buildings on the UCSD campus. As a result CSE was designed with energy efficiency in mind and hence uses techniques such as dynamic window shading, centralized ventilation and cooling/heating thermal requirements driven from a campus-wide chilled/hot water loop.

Figure 1 illustrates the energy use breakdown for the CSE building over two weeks in June 2010. We provide the breakdown of CSE in terms of several subsystems: 'Machine Room Load' which includes the energy consumed by the servers and the server room cooling fans, 'Plug Load' which mostly includes PCs and IT equipment plugged into the wall sockets, 'Lighting Load' and finally the 'HVAC load'. The HVAC related loads are divided into two categories: 'HVAC

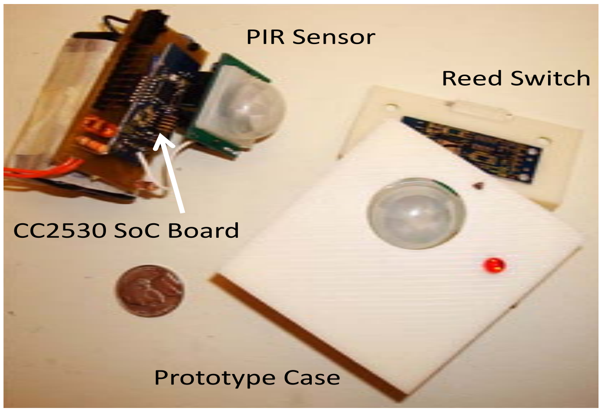

Figure 2. Picture of the Synergy occupancy sensor node.

(Electrical)' which denotes the electricity used to drive the mechanical and air handling equipment such as fans, pumps and dampers while the 'HVAC (Thermal)' load denotes the amount of heat transferred to the campus chilled water loop to cool the air. Since the thermal energy to cool (and heat) the building is derived from the campus chilled (hot) water loop, we convert the thermal load, measured in MMBTUs, into KW required to produce equivalent refrigeration using the campus central heat-exchanging plant (which has an overall efficiency of 0.9KW/tonne of refrigeration).

As can be observed from Figure 1, more than 50% of the CSE electrical load is IT related – 'Plug Load' and the 'Machine Room Load'. Lighting consumes another 10% to 14% of the baseline electrical usage. Interestingly, the HVAC related electrical loads (HVAC-Electrical) exhibits large variations and consume between 9% to 22% of the baseline electricity usage. The figure shows that this load is managed fairly well since during the nights and weekends (low occupancy) it goes down to less than 25kW as compared to during the weekdays (high occupancy) when the load is often close to 100kW. However, the 'HVAC thermal' load remains between 110kW to 175kW even during nights and weekends. A large portion of this is due to the cooling load required by the machine room servers (close to a constant 60kW) and the rise during the weekdays to around 175kW is primarily due to the cooling requirement in offices. This data clearly shows that the HVAC system consumes significant energy and using occupancy information to drive HVAC reduction can lead to substantial energy and cost savings.

3 Building Occupancy System

Our design of an occupancy detection system for buildings was based around several key objectives. First, we wanted to make the system as low cost as possible to spur deployment across a building wide scale, and as a result we aimed to keep the bill of materials for each node low. Second, we wanted the system to be incrementally deployable within existing buildings, without requiring large scale modifications such as new wiring. Finally, the occupancy detection algorithms should be very accurate since it is key in minimizing false-positives (which increases energy use), and more importantly false-negatives (which may lead to discomfort) when controlling the HVAC system.

Synergy Presence Node Design: Based on the above requirements we chose to build our occupancy platform using a combination of sensors: a magnetic reed switch door sensor and a PIR sensor module. As we show later in our evaluation, using these two sensors enabled highly accurate occupancy detection. For deployability reasons, the natural choice was to use a wireless solution. We chose the TI CC2530 System-on-Chip since it integrates an 8051 micro controller core with an 802.15.4 standard compatible radio in a small footprint and low-cost package. We have based our presence platform on the TI reference design, with some changes to accommodate our sensors. For cost reasons we used a printed antenna on the PCB itself and brought out several GPIOs that connect to the reed switch, which gets triggered by a small magnet attached to the door to each individual office. The board is powered off using three off-the-shelf AA 2850 mAH alkaline batteries. The board, batteries and the sensors are all placed in a case that we have fabricated. Figure 2 shows a photo of our prototype and the enclosure mounted flush with the door frame. Keeping in mind the design goal of making our platform low cost, the total bill of material per node (in quantities of 1000) is under 15$ including the cost of the CC2531 chip, sensors and the cost of fabricating the PCB.

Occupancy Detection Algorithm: We use the reed switch and the PIR sensors together to improve the accuracy of occupancy detection. The reed switch and the PIR sensor are both connected to interrupt-enabled GPIO pins on the CC2530 micro controller. The reed switch is able to sense when the door is open or closed. When the door is open, we mark the room as occupied. This is based on the fact that for a typical office building an open door denotes the occupant being in the office or being somewhere nearby. Similarly when people leave an extended period of time (such as the end of the day) they typically close the door to their offices for security reasons.

When a door close event happens, there are two possibilities. Either the person closed the door and headed out (room unoccupied) or the person just closed the door and is still inside the room (room occupied). To disambiguate between these two cases we use the PIR sensor to determine if someone walked near the door. If the PIR sensor goes high this means that there is still a person in the room and we mark the room as occupied. If the PIR sensor does not detect motion, then we decide that there is no occupant in the room. PIR sensors do exhibit some noise, and the air currents of a passing person may cause it to trigger. To compensate we have developed a simple algorithm that will ignore the first six seconds of pulses from the PIR sensor and sample constantly for two seconds after that. We map the pulses to the pulse pattern of a passing occupant compared to no occupant to determine if there is a person in the room or not.

There is one scenario where we will incorrectly declare a closed room to be unoccupied. If a visitor closes the door while the main occupant of a room is sitting still at his desk (such as typing on the computer), the PIR sensor will likely not detect movement and thus determine to room to be empty. To compensate, we turn on the PIR interrupt whenever we mark a room as closed and unoccupied. If we detect movement the CC2530 will wake up, poll the PIR and check

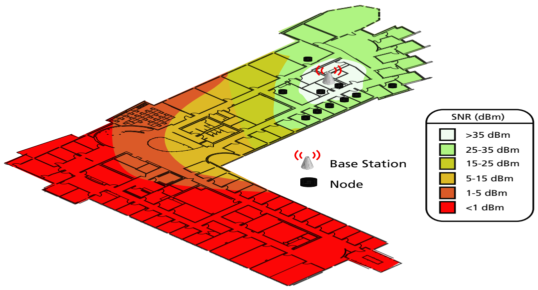

Figure 3. Layout of our test deployment.

the resultant pulse pattern for occupancy. If it passes, we determine the room to be actually occupied. While we assume that an open door means the room is occupied, we have also developed an algorithm that does not make that assumption. In buildings where open doors do not necessarily mean occupied, we revert to determining occupancy by using a 30 minute timeout, similar to how PIR-only sensors are run.

Our sensor module shares some similarities with a commercial sensor manufactured by Honeywell [13], which also uses a door sensor coupled with a PIR sensor. However this sensor is limited to only interacting with a remote setback device over a proprietary wireless protocol and is specifically meant for local control of a home-based HVAC system. It also requires significantly higher installation costs and is not meant for larger commercial buildings.

Wireless Network and Occupancy Server: We have designed our wireless network infrastructure as a tiered topology. Each of our wireless Synergy presence nodes communicate with their local base station over the 802.15.4 radio using the ZigBee protocol. While there are other options such as 6LoWPAN, we chose ZigBee because the stack is provided by TI free of cost and is certified by the ZigBee Alliance. The wall-powered base stations are implemented as low-power small form factor PCs with a similar CC2530 based radio plugged in over USB. The network is self-organizing. When a Synergy presence node powers on, it automatically connects to the nearest base station with the preset parameters (a specific extended PID and cluster ID). Once connected it will send occupancy data to its parent base station.

There can be multiple base stations on a floor of a large building, and each base stations is connected to the building backbone network using either Wi-Fi or Ethernet. Although the base stations are capable of doing some pre-processing with the occupancy data (such as algorithms to control a series of actuators in a specific location), they currently act as relays to send the data received from the Synergy presence nodes to a central server (a DELL PowerEdge R700). A process on the server then stores the data into a central database.

We can then analyze the occupancy data in real time to determine the appropriate actuator actions. For example, in our HVAC control system the two options are to run the HVAC system to achieve a set point temperature when the particular office is occupied, or reduce cooling to drift to the setback temperature during unoccupied periods.

We have written an application that does just this, but do not currently interface directly with the building HVAC system to perform actuations based on occupancy since that could potentially lead to user annoyances during our experimentation phase. We are however investigating mechanisms that would allow interfacing, on a limited scale of a single floor, with the MetaSys building management system. Meanwhile, we use this occupancy information as inputs to a detailed simulation framework that we have built to quantify the expected energy savings as described in the next section. We have also implemented a website that allows this occupancy information to be observed in real time using the floor plan of our building. Due to the expected privacy issues that may arise, we have currently restricted access to this website to the building administrators in case it is needed for emergency response conditions.

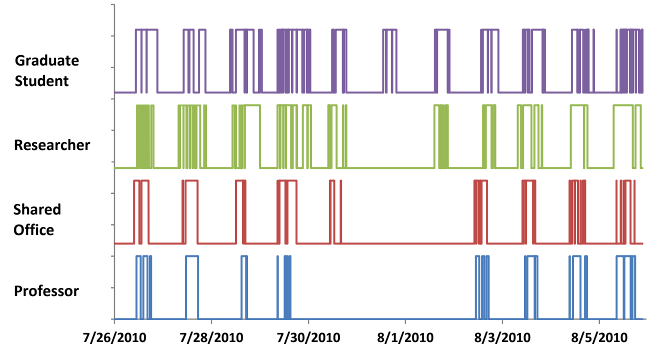

Figure 4. Occupancy over ten days for an example set of four rooms.

4 Results and Evaluation

In this section we describe the results of our pilot deployment of the Synergy presence nodes. We then evaluate our system for accuracy and energy consumption. We finally simulate the deployment using EnergyPlus in order to quantify the potential energy savings of using our Synergy presence detection system.

4.1 Test Deployment and Results

We deployed our system across one of the wings of the CSE building and collected data for several offices over two weeks. Figure 3 shows the floor layout with the Synergy presence nodes marked. The rooms that were monitored include several faculty offices, two shared student offices, a small workshop laboratory, a computer room, and a small conference room. Figure 4 shows the occupancy data collected for several of those rooms over ten days at the end of July. As this data was recorded in the summer, the occupancy patterns will be different from the school year, but some interesting observations can still be seen. Professors tended to be absent for long stretches of time, which supports the theory that it is always hard to find one's advisor. Shared offices tended to be occupied for long periods of time, as someone was likely to be in it. Almost all the occupants would leave their offices for an hour or more for lunch or meetings several days of the week. Throughout each day, there were still many periods of vacancy for all of the deployed rooms. These large periods of unoccupancy suggest that occupancy can be an effective driver of HVAC systems.

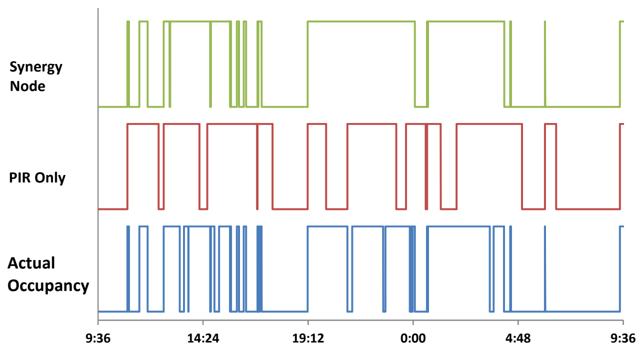

Figure 5. Graph showing accuracy of our system vs. ground truth and the PIR-only node.

4.2 Accuracy

Detailed accurate occupancy information is critical in order to achieve any occupancy-driven control system. Over two days we constantly monitored the hallway to record the actual occupancy for each of the rooms. This gives us ground truth with which to compare our sensor readings. In order to compare our system with commonly deployed PIR sensors, we also monitor the room with a PIR-only sensor using a 30 minute timeout (the sensor will consider the room occupied up to 30 minutes after the last detected movement).

Figure 5 compares the actual occupancy with our Synergy presence and the PIR-only sensor node. We notice that our sensor node matches the actual occupancy well, with the exception of periods where the occupant leaves the room for a few minutes but leaves his door open. We also see a few instances where the sensor detected an unoccupied room that was actually occupied. This happened because a visiting student closed the door of the office while the occupant was on his computer. It was not until a few minutes later that the PIR interrupted the CC2530 and the Synergy sensor node detected the occupant.

The PIR-only sensor is considerably less accurate, marking the room as occupied for long periods when the room is actually unoccupied. Also for small periods of time, the PIR-only sensor actually marks the room as unoccupied when there is still an occupant. This can happen when the occupant remains relatively still (such as typing at a computer) for a long period of time. The PIR-only sensor will not detect the movement and thus assume that the room is unoccupied after 30 minutes of inactivity. Note, the timeout period can of course be adjusted, but a trade off occurs between greater energy savings and inconveniencing the occupant.

4.3 Energy Consumption and RF Range

To ease deployability our presence nodes are wireless and battery powered, which requires careful consideration of their energy consumption to ensure long lifetimes. Our choice of components, including the CC2531 SoC, the PIR and the reed sensor, reflect that goal as all of these parts have low power consumption. We utilized the deep sleep modes supported by the CC2531 micro controller extensively, and made sure that the presence nodes operate at low duty cycles (we use an interrupt driven architecture as opposed to polling the sensors constantly). We measured the current consumption of our sensor using a FLUKE digital multimeter. In deep sleep mode the entire presence node consumes 30uA at 4.5V. On detecting any activity, the PIR sensor consumes 350uA. Furthermore, if an event is detected, the sensors wakeup the CC2531 to process the event and transmit a packet to the base station, and the power consumption rises to 29mA for the duration of the transmission. Conservatively, if a presence sensor has to detect 50 events during each day, we calculate a battery lifetime of 7.27 years using our current 2850mAh batteries based on these measurements, which exceeds the lifetime of the battery itself.

Since we opt for a low-cost PCB antenna, the radio range will be limited compared to a more costly antenna. To determine the range, we measured the signal-to-noise ratio (SNR) from the node to the base station using the reported values from the CC2530 to determine base station coverage. Below 5 dBm, the connection between the base station and the node became unreliable and intermittent. Above 15 dBm, the connection was stable and maintained a consistent throughput of about 7 KB/s. Our analysis shows that a single base station suffices to cover 1/3 of a floor in the building (Figure 3), and therefore we believe three to four base stations will be enough to provide coverage to an entire floor.

4.4 Simulation

In order to demonstrate the benefits of our Synergy presence system, we simulate an example building along with its HVAC energy consumption. We use EnergyPlus, which is the US Dept of Energy's next-generation building energy simulation program [7] that improves on previous simulators such as BLAST and DOE-2.2 [6]. EnergyPlus allows the user to model a building, define thermal/HVAC zones, and incorporate various HVAC systems. The user also specifies schedules that detail occupancy, control set points, and other internal loads that affect heat gain. With the input data defined, EnergyPlus can simulate thermal conditions for the building and its zones and the HVAC operations required to maintain the temperatures in the building.

4.4.1 Simulation Parameters

We model a simple single floor building that mirrors the floor plan of our deployed wing of the CSE building (the simulated building contains several offices, a conference room, some shared labs/offices, and an outside hallway area). The occupancy rates for the offices and lab rooms in the simulation come from the occupancy data we collected in our deployment. We simulate this building for HVAC energy costs using both a baseline mode where HVAC is turned on during working hours the entire time at 22.9C and our HVAC control system that turns on the system when there is occupancy and throttles it back when there is no detected occupancy. We set a temperature for 22.9C for occupied operation and 26.1C for the setback. The actual HVAC system we model is an idealized air-flow that assumes perfect efficiency. We simulate this building over four months in the summer using a weather file from a typical warm city.

4.4.2 Simulation Results

Our results are shown in Figure 6. The graph shows that the daily HVAC savings using our occupancy system is between 10% to 15%. The variations depend on the specific temperature for that day. The significant energy savings

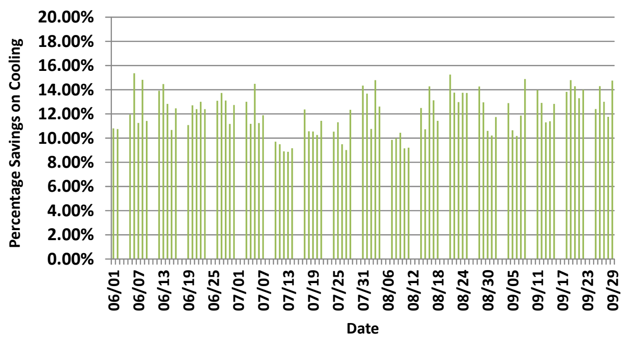

Figure 6. Graph showing energy savings using our occupancy system over the summer.

come from the fact that the building can save energy when a room is not occupied by lowering cooling. Our control procedure was merely to throttle back cooling to 26.1, however more aggressive and optimized HVAC operation schemes can be implemented that will save even more energy. The actual amount of energy savings depends on the building construction, specific HVAC system being used, the occupancy schedule, and many other factors, but regardless of the specific parameters, our simulations show that the opportunity for savings is clearly there. Given that HVAC related loads consumes over 400 kW in our CSE building, a 15% reduction will lead to an estimated savings of 480 kWh over an 8 hour day.

5 Conclusions and Future Work

In this paper we have presented the design and implementation of a low-cost and incrementally deployable occupancy detection system using battery operated wireless sensor nodes. Our evaluation across a ten room initial deployment shows that our choice of sensors and occupancy detection algorithm can detect occupancy accurately. Using this occupancy information as input to a simulation model of a building, we show that the HVAC energy consumption can in fact be reduced from 10% to 15% using our system. We also believe that the actual energy savings might even be greater with more aggressive control algorithms that can utilize the occupancy information provided by our sensors to duty-cycle HVAC systems further. Going forward we will expand our sensor package to account for people counting, not just binary occupancy data. We are also actively looking into robust privacy controls.

6 Acknowledgments

We wish to thank Robert Austin, Walter Richardson, and John Dilliott at UCSD Physical Plant Services who assisted with the energy calculations. We would also like to thank Jawon Lee for her assistance in setting up the servers. This work is supported by Multiscale Systems Center (MuSyc) under the Focus Center Research Program (FCRP) supported by DARPA/MARCO and also NSF CCF/SHF Grant 1018632.

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