An Experimental Investigation of Occupancy-Based Energy-Efficient Control of Commercial Building Indoor Climate

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Abstract— We present results from a week-long experimental evaluation of a scalable control algorithm for a commercial building heating, ventilation, and air-conditioning (HVAC) system. The experiments showed that the controller resulted in 37% energy savings without sacrificing indoor climate. In contrast to prior work that reports energy savings without a careful measure of the effect on indoor climate, we verify that the controller achieves the energy efficiency improvements without any adverse effect on the indoor climate compared to the building's baseline controller. This is established from measurements of a host of environmental variables and analysis of before-after occupant survey results. We present a complete system to retrofit existing buildings including the control algorithm and the supporting execution platform which includes the deployment of a wireless sensor network. Results show that there is a large variation in energy savings from zone to zone, which indicates that estimating energy savings potential of novel HVAC control systems is not trivial even from experiments—something that prior work with uniformly positive messages did not emphasize.

I. INTRODUCTION

Buildings consume nearly 40% of the energy in the United States, and a significant fraction of this energy is due to heating, ventilation, and air-conditioning (HVAC) systems [1]. Energy-efficient control of HVAC systems has become an active topic of research lately.

A number of recent papers have examined Model Predictive Control (MPC) for HVAC applications. Experimental evaluations of MPC have been reported in [2]–[4] with positive results: the controller has been able to reduce energy usage while satisfying constraints on space temperatures. One of the bottlenecks in applying MPC to building control is the variation from building to building in terms of equipment and dynamics, which requires building-specific tuning of models used in MPC computations. Consequently, such controllers may not be suitable for scaling up to a large number of buildings.

It has been shown in our prior work that it is possible to significantly reduce the energy used in maintaining indoor climate with rule-based control (RBC) algorithms that use real-time measurements of occupancy, which are simpler to apply than MPC [5]. It was concluded through

an extensive simulation study in [5] that the rule-based Measured Occupancy-Based Setback (MOBS) controller had performed similarly compared to a much more complex MPC-based controller in terms of both energy consumption and indoor climate conditioning. An independent study obtained similar conclusions [6]. Experiments in a single zone of a building corroborated these findings [7]. In contrast to prior work on MPC-based HVAC control, the MOBS controller does not require any building-specific or zone-specific tuning, which makes it highly scalable for deployment.

This paper reports the results of scaling up the implementation of the MOBS controller to several zones of a commercial building. Occupancy measurements were obtained with the help of low-cost, wireless sensor nodes equipped with motion detectors.

Our experiments were conducted in twelve zones of a commercial building on the University of Florida's campus. The results of the experiments confirm that the predicted performance of the MOBS controller from simulations and single-zone experiments does indeed persist when the control system is scaled up to multiple zones. Average energy savings of 37% were achieved without any adverse effects on the indoor climate as measured by temperature, humidity, and CO_2 levels as well as occupant feedback obtained from surveys before and during the tests. While the results were generally positive, both thermal comfort metrics and energy savings varied considerably among zones.

Among the prior work, [8]–[10] have also proposed and experimentally evaluated energy-efficient RBC algorithms that are scalable to a large number of buildings. However, these papers only report measurements of temperature as an indicator of indoor climate, while in practice both thermal comfort and indoor air quality (IAQ) must be maintained. Even thermal comfort is not completely determined by temperature alone; humidity is another important factor.

As an additional validation of the objective assessment of occupant comfort, we include the results of surveys of occupants' comfort and perceptions of IAQ before and during the experiments for *subjective* assessment. While many works in the literature have implemented new control algorithms and analyzed their performances via varying degrees of energy and comfort analysis, to our knowledge none have methodically examined if the tested controller has led to any change (positive or negative) in the occupants' perceptions of thermal comfort and IAQ. The ultimate metric for comfort is occupants' opinions, and we provide these in our analysis.

This paper is organized as follows. Section II describes

the building, HVAC system, control algorithms, and wireless sensor network (WSN) used in the experiments. We define our evaluation criteria in Section III. Experimental results are discussed in Section IV. Finally, Section V provides a summary of our results and avenues for future research.

II. SYSTEM ARCHITECTURE

Tests were carried out in Pugh Hall (see Figure 1) on the University of Florida campus, which is a LEED Silver-certified building with a floor space of 40,000 sq. ft. and a variable air volume (VAV) HVAC system that has 3 air handling units (AHUs) and 65 VAV boxes. Each AHU conditions a mixture of outside and return air and then distributes the conditioned air to a number of VAV boxes through a single supply duct. Each VAV box has an airflow damper and a re-heat coil to modulate the flow rate of conditioned air delivered to its zone and re-heat the air. In the tests, twelve zones—each consisting of a single room—were controlled using the MOBS control algorithm described in Section II-A. The control commands at each VAV box were airflow damper position and re-heat valve position. Set points at the AHU were *not* manipulated by the MOBS controller.

The control system consists of the following components: (i) a control algorithm for computing commands for the HVAC equipment, (ii) a wireless sensor network (WSN), and (iii) a software infrastructure for data management and control execution. Control computation was performed on-line in a computer using MATLAB©. Commands are executed by overriding the commands computed by the building automation system with those computed by the MOBS controller using a higher priority in BACnet [11]. The control algorithm reads measurements from sensors through a relational database where the measurements are stored. Commands to the controlled VAV boxes are updated every five minutes.

A. Control algorithm

The controller currently used in Pugh Hall (the *baseline controller*) is very close to a dual-maximum control scheme [12], but the exact nature of the controller is unknown due to its proprietary nature. Detailed descriptions of the dual-maximum and the MOBS control logics are available in [5]; we provide a brief sketch here for the sake of completeness.

The dual-maximum control logic has four modes of operation of a zone based on the measured zone temperature: (i) re-heating, (ii) heating, (iii) dead-band, and (iv) cooling. Each mode is activated if the room temperature remains within a certain temperature band for more than ten minutes: (i) re-heating: below the re-heating set point (T_{RTG}); (ii) heating: between the re-heating and the heating set point (T_{HTG}); (iii) dead-band: between the heating set point and the cooling set point (T_{CLG}); (iv) cooling: above the cooling set point. In re-heating mode, the temperature of the air supplied to the zone is set to its maximum value (T_{high}), and supply air flow rate is varied by a PID controller. In heating mode, supply air flow rate is set to its minimum

value ($\dot{V}_{min}$) while supply air temperature is varied via a PID controller. In dead-band mode, supply air flow rate is set to its minimum value, and no re-heating is performed (i.e., the re-heat valve remains closed). In cooling mode, supply air flow rate is varied using a PID controller, and no re-heating is performed.

The baseline controller in Pugh Hall also employs a nighttime setback in which temperature set points are relaxed during the night when the building is presumed to be unoccupied (10:30 PM-6:30 AM).

The MOBS controller, which was proposed in [5], is similar to that of the dual-maximum controller. Instead of pre-specified, building-wide times for unoccupied mode (nighttime setback), real-time occupancy measurements are used to determine unoccupied times for each zone individually (occupancy-based setback). When a zone has been unoccupied for more than five minutes, it switches to the unoccupied mode; otherwise, it remains in the occupied mode. The heating/cooling/re-heating set points used in the MOBS controller were chosen to be the same as those used by the baseline controller; see Table I.

Apart from the zone temperature bounds, the MOBS controller determines the minimum air flow rate and minimum outside-air flow rate based on whether the zone is in occupied or unoccupied mode in accordance with ASHRAE ventilation standards [13]. The air flow rates are computed based on the measured occupancy count—i.e., the number of occupants.

TABLE I
CONTROLLER SET POINTS (° F)

T_{set}	T_{RTG}^{unocc}	T_{RTG}^{occ}	T_{HTG}^{unocc}	T_{HTG}^{occ}	T_{CLG}^{unocc}	T_{CLG}^{occ}
72.0	69.7	71.2	70.0	71.5	74.5	76.0

B. Wireless sensor network

The MOBS controller requires real-time measurements of occupancy count in each zone. Even though not used in control computation, measurements of humidity and CO_2 concentration are desired for post facto analysis to determine a controller's effect on thermal comfort and IAQ. These sensors were not available in the building. A wireless sensor network was therefore deployed to obtain these measurements. Each wireless sensor node (shown in Figure 2) measures occupant presence (through a PIR sensor), CO_2 concentration, temperature, and relative humidity. Each node is equipped with a TI MSP430 microprocessor and a CC2500 radio operating in the 2.4 GHz band. Nodes use their radio transceivers to transmit their measurements to base stations throughout the building using TI's SimpliciTI communication protocol. The base stations are Dreamplug computers running Linux with their own radio transceivers. The base stations write the sensor data to a database through the Internet. For more information about the WSN and its design, the reader is referred to [14].
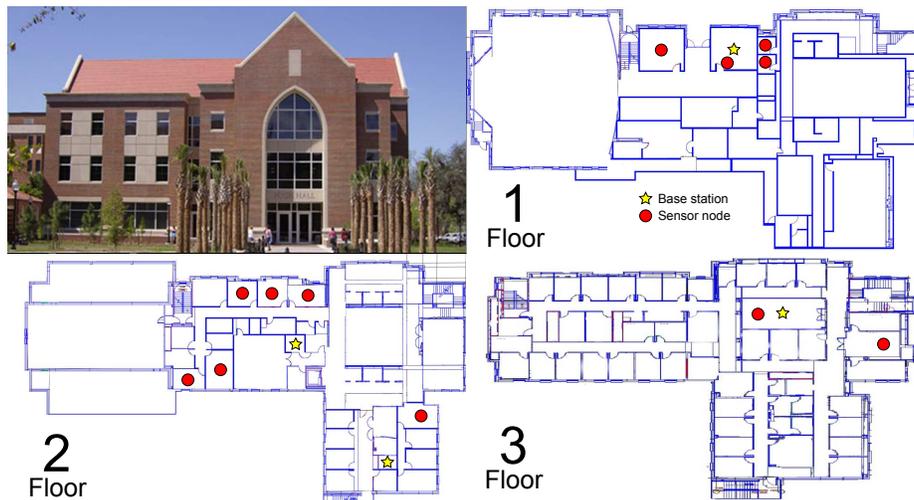
Fig. 1. Pugh Hall and the locations of the wireless nodes (circles) on each floor. Base stations are represented by stars.
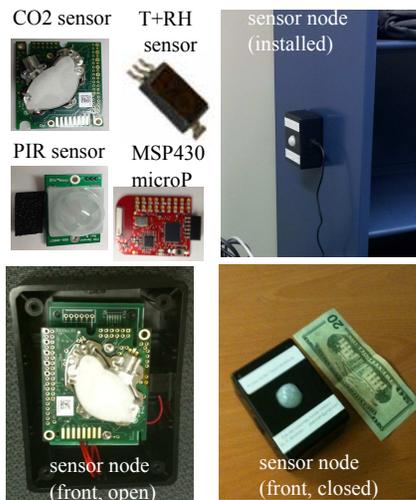
Fig. 2. Wireless sensor node deployed in Pugh Hall [14].

A PIR sensor only provides presence/absence measurements, but the MOBS controller requires occupancy count measurements. Occupancy count was estimated by assuming that whenever a room is occupied, it is occupied by its design occupancy. All of the rooms except the conference rooms had a design occupancy in the range of 2 to 4.

III. EVALUATION CRITERIA

We measure the performance of a controller in terms of how well it maintained indoor climate for occupants and how much energy it consumed per day.

A. Indoor climate

We evaluate indoor climate through thermal comfort and IAQ. Thermal comfort is determined by many factors; here we consider temperature and humidity. ASHRAE standard 55.1 [15] specifies a range of temperature-humidity values in which a majority of building occupants are believed to

be comfortable, which is shown in Figure 3. To perform an objective comparison of temperature-constraint maintenance, we define the following measure, called *daily temperature deviation*, with a unit of °F·minutes:

$$\Delta T = \int_0^1 d(T(t), [T_{\text{low}}(t), \ T_{\text{high}}(t)]) dt \qquad (1)$$

where t is in the unit of days, T_{low} and T_{high} are the lower and upper bounds on the space temperature, respectively, and $d(x, I)$ indicates distance between x and the interval I. A similar metric for humidity, ΔH, is also defined. The interval for the humidity metric is chosen as 0 to 0.012 in accordance to ASHRAE thermal comfort standards; see Figure 3. Since there is no universally accepted measure of IAQ, we take CO_2 concentration as a rough measure of IAQ.

Physical variables do not capture all factors that affect thermal comfort. The ultimate measure of comfort is occupants' perceptions of comfort. To determine the controllers' effects—if any—on occupants' perceptions of comfort, web-based surveys were conducted during both baseline and test weeks that asked occupants to rate if their workspaces felt un/comfortable overall and stuffy/fresh.

B. Energy consumption estimation and comparison

There are three sources of power consumption: cooling power, heating power, and mechanical (fan) power. We estimate the cooling power consumed by each zone from measurements of the air entering and leaving the zone. The total cooling power consumed by the zones in which the MOBS controller was tested is then estimated by summing the power of each zone. A similar method is used to estimate the heating power. Fan power consumption is estimated based on a linear model relating the measured power and mass flow rate.

Ideally, comparisons between two distinct controllers should be made by testing them under identical conditions, which is impossible to perform in practice since weather and occupant-related loads are never exactly the same for any
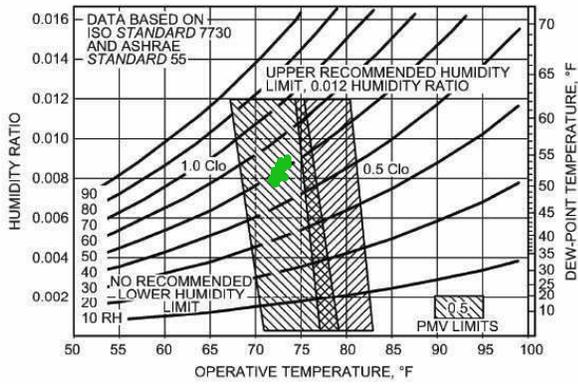
Fig. 3. Green dots: measurements of temperature and humidity in one of the test rooms during April 24, 2013. The dashed region is where "80% of sedentary or slightly active persons find the environment thermally acceptable" [15].

two days. As an alternative, we compared each day of the week of experiments with the same day of another, baseline-controlled week with similar weather conditions.

We perform a search over all days of 2013 and all available days of 2014, and the day with the most similar weather conditions is used as the baseline day. In evaluating weather similarity, we consider both enthalpy and temperature as evaluation criteria because the power consumption of the AHU is a function of the outside-air enthalpy but the decisions of the baseline controller are based on the temperature. Additionally, we only consider the same days of the week (e.g., only Mondays are compared to the Monday of the test week). This decreases the chance of vastly different occupancy schedules between the test and baseline days. Additionally, holidays were not considered.

IV. RESULTS AND DISCUSSION

The MOBS controller was implemented for six days from 00:00 hours April 21, 2013 through 24:00 hours April 26, 2013. The rooms/days in/during which the test was conducted are called the test rooms/days. The locations of the test rooms are shown in Figure 1.

A. Thermal comfort and IAQ

Figure 3 shows measurements of temperature and humidity in one of the test rooms for a test day. For this room and day, the daily temperature deviation, ΔT, defined in (1) was 0. This was not the case for all rooms and days; Figure 4 shows box plots of ΔT for each of the test rooms during the test period and the corresponding baseline days. As with the baseline controller, ΔT was small for most zones on the test days, but a few zones had occasional large violations. ΔH was uniformly 0 in all test zones on all test days.

The large daily temperature violations that occurred in rooms 3 and 4 were due to actuator saturation: the maximum air flow rates allowed in those rooms were not enough to service the large thermal loads experienced by them. Rooms 3 and 4 were small study rooms and were subjected to
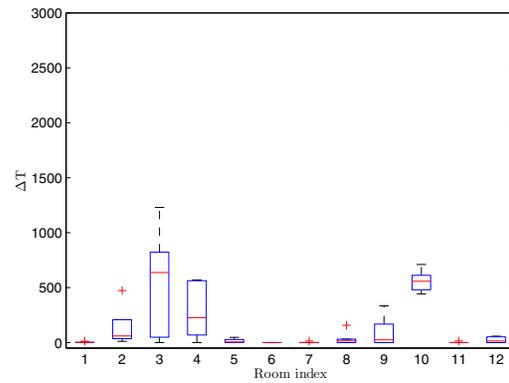
(a) Baseline
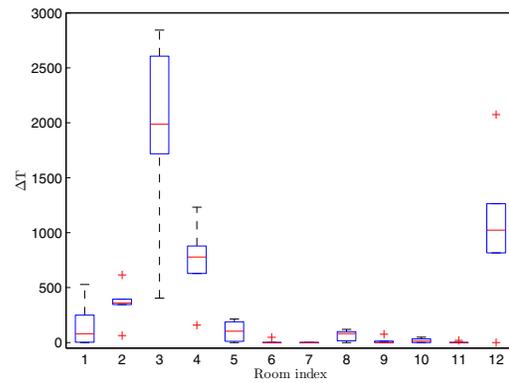
(b) MOBS

Fig. 4. Box plot of daily temperature violation of each room during the test (six samples per column).

large thermal loads due to the presence of students and their electronics during the test week, which coincided with the period of final exams for the semester.

Figure 5 shows the temperature, humidity, and CO_2 concentration measurements in room 11 during a test day (Wednesday, April 24, 2013) and the corresponding baseline day (Wednesday, May 15, 2013). Included in the figure are the zone temperature bounds for each controller. For the MOBS controller, these bounds are computed in real-time based on occupancy measurements provided by the wireless sensors. Note that the bounds are stricter during the occupied periods than during the unoccupied ones. The baseline controller changes its bounds only twice during the day due to the nighttime setback. Note also the spike in CO_2 concentration around 7 PM. Room 11 is a heavily used conference room, and the spike may have been caused by the presence of a group of people much larger than the design occupancy. This was the only instance for any room in which the CO_2 concentration exceeded 1000 ppm.

B. Energy savings

Figure 6 shows the total daily energy consumption (over all twelve test zones) of both the baseline and MOBS
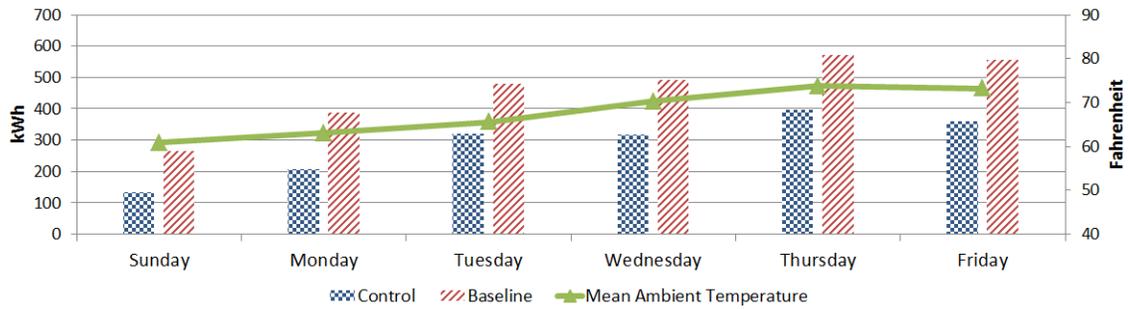
Fig. 6. Daily energy consumption of MOBS and baseline controllers and daily mean ambient temperature.
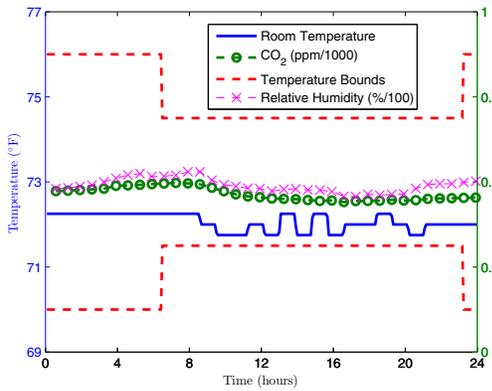
(a) Baseline, room 11
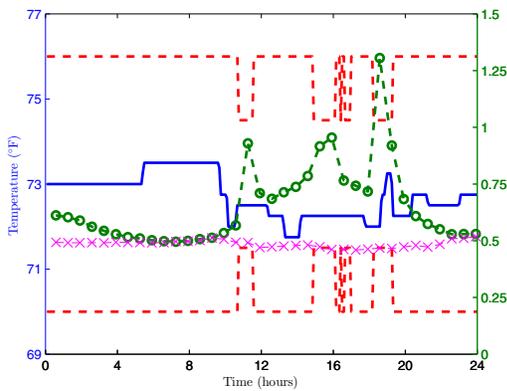
(b) MOBS, room 11

Fig. 5. Results of the MOBS controller on April 24, 2013, and of the baseline controller on May 15, 2013 (best matching baseline day for April 24), for a specific room. The dashed lines represent the upper and lower temperature bounds (left axis).

Fig. 7. Box plot of daily energy savings as percent of average baseline.

controllers. For the entire week, the MOBS controller resulted in the consumption of 1.73 MWh while the baseline controller consumed 2.75 MWh—indicating the MOBS controller reduced energy usage by 37%. The energy savings were comparable to the reduction in airflow (32%). By using occupancy measurements rather than a fixed schedule, the total flow during the daytime was reduced.

These savings are close to those observed in the single-zone experimental study reported in [7], which were 40%.

The simulation study in [5] indicated energy savings of 42-60% from the MOBS controller depending on weather and zone type. We believe the difference between simulation and experiments is mostly due to the nighttime setback implemented at the AHU during the experiments that was not incorporated in the simulation study.

Just as with temperature regulation, there was a large variation in percent energy savings between rooms. Figure 7 is a box plot of each room's energy savings as percent of average baseline consumption for each room. The MOBS controller occasionally resulted in increased energy consumption over baseline, but positive percent savings were generally larger than negative percent savings. This is even more so when looking at nominal savings (in kWh, not percentage). The largest increase in daily energy consumption was less than 14 kWh, but the largest decrease in daily energy consumption was greater than 45 kWh. The increase in energy consumption of the MOBS controller occurred in the rooms in which the baseline controller was supplying an inadequate amount outside air so that the MOBS controller had to increase air flow rate to meet ventilation standards.

C. Occupants' perceptions of thermal comfort and IAQ

Apart from variables such as temperature and humidity, the perceived thermal comfort of an occupant depends on a host of other variables such as air velocity, clothing, radiant

heat, etc. [16]. Many—if not most—of these variables are nearly impossible to measure. Finally, there are subjective components to a person's perception of comfort as well.

To assess the impact of the MOBS control strategy on the occupants' perceptions of comfort and IAQ, web-based surveys were conducted. Occupants were e-mailed a link to a web-based questionnaire that asked them to rate their overall comfort and air quality in the last five minutes, both on a numerical scale of 1 to 5, from very uncomfortable to very comfortable and from very stuffy to very fresh.

Three waves of surveys were conducted: Wave 1 was during the installation of the wireless sensors in the building; Wave 2 occurred after the installation was complete but before the MOBS control tests were conducted; and Wave 3 occurred during the week when the control tests were in effect. Twenty-seven participants completed questionnaires from all three Waves. In general, the occupants responded positively to the MOBS controller, with more than 84% of participants rating the air as fresh (above the midpoint of the scale) and room conditions as comfortable (above the midpoint of the scale) in all three waves.

Paired samples t-tests indicated no significant differences in response to the item measuring overall air comfort (un/comfortable) in the workspace between the control test period, Wave 3 (Mean = 2.75, Standard Deviation = 2.00), and the baseline period of Wave 1 (M = 2.71, SD = 1.92), t(23) = -.07, p = .94. Similar results were found for paired sample t-tests comparing perceived comfort between Wave 3 and Wave 1 (M = 2.95, SD = 1.47), with $t(18)$ = .53, p = .60. In terms of the perceived air freshness measure (stuffy/fresh), it is interesting to note that participants perceived greater freshness during the MOBS test period (Wave 3), M = 2.82, SD = 1.59, than during the first baseline period (Wave 1), M = 1.64, SD = 1.65, $t(21)$ = -3.78, $p < .010$. However, there were no significant differences in perceived air freshness during the Wave 2 baseline period, M = 2.70, SD = 1.59, and the MOBS test (Wave 3), M = 2.65, SD = 1.87, $t(18)$ = -.53, p = .6. In short, the MOBS controller was not associated with decreases in reported occupant comfort and air freshness.

V. Conclusion and Future Work

The primary energy savings by the MOBS controller were achieved from reduction of air flow rate during unoccupied periods. The baseline controller uses a large flow rate throughout the day to ensure IAQ is maintained. Using occupancy measurements, the flow rate can be reduced during unoccupied times.

An important observation is that significant energy savings were achieved with PIR sensors that provide binary presence/absence measurements—not occupancy count. Accurately estimating the exact number of occupants in a room is still an open problem, but our results show that, for small office areas and even conference rooms, binary occupancy measurements can yield significant savings without the need for expensive hardware or complex estimation algorithms.

The overall cost of each sensor node was $215, and the total cost of deployment in the entire building is approx-

imately $14,000. The annual HVAC energy cost of Pugh Hall is approximately $60,000, so annual energy savings up to $23,000 may be expected. This means the WSN will have paid for itself in less than a year! It should be mentioned that since there were considerable variations in energy savings from zone to zone and from day to day, the *yearly* energy savings may not be the same as the average daily savings observed in the test.

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