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Feasibility of retrofitting centralized HVAC systems for room-level zoning

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ABSTRACT

Heating, ventilation, and cooling (HVAC) accounts for 38% of building energy usage, and over 15% of all US energy usage, making it one of the nation's largest energy consumers. A number of projects have attempted to optimize the control of HVAC systems by minimizing the energy wasted in conditioning occupied buildings or rooms. Researchers have proposed systems that turn off air conditioners or heaters when a house is unoccupied, or put the system into an energy saving deep-setback mode when the occupants are inactive, such as when they are asleep. These approaches enable the retrofitting of centralized HVAC systems, that are widely used within the United States, to be more energy efficient. An area that has not been as well explored is the retrofitting of centralized HVAC systems to save energy when the residents are at home and awake. In this paper, we demonstrate how to use cheap, off-the-shelf sensors and actuators to retrofit a centralized HVAC system and enable the heating, or cooling, of rooms individually, in order to reduce waste caused by conditioning unoccupied rooms. We call this approach *room-level zoning*. Sensors detect room state and learned activity patterns are used to predict occupancy. Based on this information, unoccupied rooms drift away from a user defined comfortable temperature if occupants are less likely to use them in the near future while occupied rooms remain at a comfortable temperature. Thus, conditioning only the rooms with a high probability of occupancy to the setpoint saves energy by decreasing the load on the HVAC system. We implement a room-level zoning system, called *Dual-Zone*, in a 1400 square foot house by retrofitting an existing centralized HVAC system with wireless temperature sensors to monitor room-level temperature, motion sensors to monitor occupancy, and wirelessly actuatable dampers to control the flow of conditioned air through the house. Dual-Zone statically zones the house into two zones: one conditioned at night and the other conditioned during the day. Initial analysis indicates that this method has a 20.5% energy savings over the existing single-zoned thermostat during a 20 day evaluation.

1. Introduction

The HVAC system is the single largest energy consumer in residential buildings, accounting for 43% of the residential energy consumption in the US [7], and over 60% in Canada [8] and the UK [17], which have colder climates. HVAC systems use most of this energy to heat or cool unoccupied spaces during long periods when people use only a small fraction of the house. Zoning systems have attempted to exploit this fact by dividing a building into two or more zones that they control by separate thermostats, so that the occupants can schedule the heating or cooling of each zone separately. However, zoning systems are expensive, and are, therefore, typically only used for course-grained zoning of the house: a typical configuration can condition the first floor living spaces separately from the second floor sleeping quarters for example. Such systems are both spatially and temporally course grained allowing the zoning of large areas, in this case floors of a building, separately and scheduling with a low frequency, for example switching between the living and sleeping areas only twice a day.

In this paper, we explore the effectiveness of using cheap and simple wireless embedded sensors and actuators to produce a fine-grained, room-level zoning system by retrofitting a centralized HVAC system and controlling the airflow into each room. Such a system could reduce wasted energy used to heat or cool unoccupied rooms. However, the energy savings of such a system is not a foregone conclusion due to three key challenges. First, the size of the HVAC system is typically chosen based on the size of the entire house, and so heating or cooling only a fraction of the house would result in an oversized system, which is typically inefficient. Second, restricting airflow into some rooms will create backpressure in the ducts, which can further reduce the efficiency of the HVAC system by causing leaks in the ducts and at the dampers. Third, most houses do not have insulated interior walls, and the lack of thermal insulation between rooms can lead to heat transfer between the conditioned and unconditioned zones. A number of previous

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studies have explored the possibility of room-level zoning, but these studies arrive at mixed and inconclusive results [26,28,29]. To our knowledge, Scott et al. [21] are the only researchers to carry out long term studies of room-level zoning in actual residences where they demonstrate energy savings when the HVAC system uses room occupancy predictions to control the heating of rooms. Yet, the researchers evaluate their room-level systems in British homes using radiators that are independently controllable for each room. Their implementation in the United States, where houses traditionally have centralized HVAC systems, resorted to centralized control where the system uses the occupancy of the whole house, rather than each room, to control the system.

In this paper, we demonstrate the feasibility of saving energy by retrofitting a centralized HVAC system and controlling it at the room-level. We implement a wireless sensor/actuator system that can be cheaply and easily deployed in existing homes. The system includes 21 temperature sensors and a wireless thermostat that controls the HVAC hardware and mechanically opens and closes dampers in order to control airflow through the home. The components used cost less than $500, and we expect a production version to cost considerably less. In contrast, traditional zoning systems often cost more that $5000. We deployed Dual-Zone in a 7-room, single-story, 1400 square foot house and measured the energy consumption of heating and cooling. Our results indicate that the system consumed 20.5% less energy than the existing thermostat over a 20-day experimental period. These results indicate that retrofitting an existing centralized HVAC system for room-level zoning has a potential for substantial energy savings, and warrants further investigation into this approach.

2. Background and related work

Traditional HVAC zoning systems for homes typically separate a house into floors and control each floor individually. These systems are often installed more for comfort than for energy savings, because a single un-zoned system that operates on multiple floors will often result in a warm top floor and/or a cold bottom floor. Floor-level zoning also makes sense in homes that have bedrooms on the top floor and living areas on the bottom floor. Floor-level systems have resulted in homeowners saving as much as 20–30% as compared to single zoned systems [29]. However, these systems are expensive and the energy savings can take years or even decades to produce a positive return on investment. Furthermore, it can be difficult to retrofit an existing home with a zoning system.

Commercial buildings often use zoning systems that divide a single floor into multiple rooms. This is especially common in hotels, banquet halls, and office buildings. For example, the discharge-air-regulation technique (DART) uses temperature sensors to control the HVAC fan speed [9]. Other systems include the Millennial Net [16] and Siemens APOGEE [11]. Just like the residential zoning systems, these solutions are expensive and are much easier to add to a new installation. Similarly, micro-environment systems (also called task-ambient conditioning) allow a worker in an office building to have fine-grained control over the ambient conditions around his or her working space, typically a desk. A number of systems, including Personal Environments from Johnson Controls [4] and Habistat from Interface Architectural Resources, are currently commercially available. The individually controlled spaces are not insulated from each other and operate within a single thermal zone. These systems trade off energy efficiency to increase occupant comfort. The systems can produce some energy savings by not conditioning desks that are not occupied, and a number of studies have shown substantial savings of micro-environment systems [2,19,20]. However, the cost of these systems is between $20,000 and $100,000 per desk, which is too large to produce a positive return on investment. Furthermore, this approach targets offices and would be difficult to transfer to homes, where usable space can be more difficult to instrument than a desk or cubicle.

Numerous studies have explored the effect of providing individual temperature control in rooms resulting in mixed and inconclusive findings. One experiment tested the energy used to heat a single-room with 10 registers and leaky ducts while closing an increasing number of vent registers [26]. The results indicate that closing registers increases the pressure within ducts causing greater duct leakage and reduced system efficiency. However, since all registers were within the same room, this study did not determine whether the reduced efficiency outweights the savings produced by conditioning a smaller area; all register configurations were conditioning the same sized area.

A subsequent study developed an automated vent louver design for room-level zoning [28], similar to the one developed for our system and other similar systems [18]. The authors evaluate the system by dividing a house in Danville, CA into four zones and increase the temperature in each zone by 2–5 °F. They also increased the temperature in the entire house by the same amount. The results indicate that it takes less energy to increase the zone temperature per degree than it takes to increase the whole house temperature per degree, since the smaller zones heat up faster than the whole house, allowing the system to turn off sooner. However, this study only measured the transitional time and energy of a room-level zoning system, and it did not measure the steady state energy. In other words, it does not show the difference in energy required to *maintain* a particular temperature in a zone versus the whole house. This distinction is profound, because thermal leakage between adjacent rooms could cause system to also turn back on more quickly, nullifying the energy savings of turning off more quickly. This is often called *short cycling*, and it decreases system efficiency as well as reduce the overall lifetime of the equipment.

The latest attempt at occupancy-based room-level heating control is a system called PreHeat [21]. The authors implement occupancy-based heating control in houses in the United States and United Kingdom. In the United Kingdom, the authors exploited the radiators used to heat rooms in order to implement a room-level controlled heating system. In the United States, since the houses used a centralized HVAC system for heating, the authors used occupancy-based whole-house control similar to that proposed by Lu et al. [15]. The main weakness of PreHeat that we attempt to address is the lack of interaction between rooms in any of the models used for prediction. For instance, the authors predict the occupancy of each room based on the history of occupancy of that particular room without considering the occupancy of any other rooms. We demonstrate that taking into consideration occupancy patterns across a house would lead to higher accuracies in predicting the occupancy of a particular room. The authors also use a simple thermal model to predict when to preheat a room. The model is simply the average amount of time it took to increase the room temperature by a degree based on historical data. We present a model, which we are currently working on, that takes into consideration the thermal interactions between rooms.

Finally, there have been patents filed for occupancy-based zoning of HVAC systems using security systems [3] or motion sensors [22] to detect occupancy. While these systems attempt to solve the problem we are addressing, the effectiveness of their approach is not evaluated. Also, these systems fail to address hardware safety concerns that arise with implementing room-level zoning using a centralized HVAC system. Our approach is cognizant of the short-cycling and back-pressure that could reduce the lifespan of HVAC hardware and attempts to minimize the potential damage to hardware.

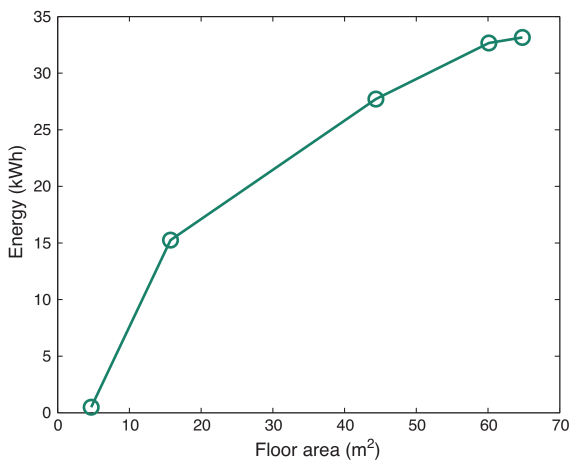


Fig. 1. With an ideal system, the amount of energy used for conditioning a building is almost proportional to the conditioned floorspace.

3. Intuition and preliminary Studies

Before implementing Dual-Zone, we performed two simulation studies to better understand whether such a system would reduce energy consumption, and why. We also carried out an analysis of a publicly available smart home data set [25] to verify that room usage frequencies change throughout the day. The following subsections explain these three studies.

3.1. Effect of an oversized HVAC system

In houses with a typical non-zoned central heating and air conditioning system, HVAC technicians choose the size of the system based on the expected load of the entire house. Therefore, there is a mismatch between the capacity of the HVAC system and the area being heated or cooled when the whole house is not conditioned. It is well known that oversizing an HVAC system results in reduced efficiency of the system. Our first study determines how much this oversizing would reduce the potential for energy savings of a room-level zoning system.

We used the EnergyPlus building energy simulation framework [5] to heat multiple buildings in simulation, with increasing size from 5 m^2 to 65 m^2. The model buildings had idealized insulation and leakage properties. The simulator conditions all buildings with the same sized HVAC system, sized for a 65 m^2 building. Fig. 1 shows the results indicating that the amount of energy required to heat a smaller building does indeed decrease, even if the size of the HVAC system remains the same. The sub-linear curve indicates that smaller buildings lose some efficiency due to the oversizing of the system. However, this loss in efficiency does not outweigh the gains from heating a smaller space. From these results, we postulate that room-level zoning can be effective, even when applied by retrofitting a home with an existing HVAC system sized for the entire house.

3.2. Inter-room leakage

Homes often have thin non-insulated walls and even doors between adjacents rooms, which can reduce the effectiveness of room-level zoning because of thermal leakage between rooms. Our second study was designed to explore how much this leakage would reduce the energy savings of a room-level zoning system. We used the EnergyPlus simulation framework to heat a single room in a two-room building. We used five variations of the floor plan of the house, and the conditioned room had a different number of exterior walls in each variation. Fig. 2 shows the five variations along the x-axis. The figures shows the energy required to heat the shaded room for each floor plan as a bar graph above each variation. These results indicate that the energy required to condition a room is dramatically reduced as the number of exterior walls of the room decreases. In other words, a neighboring room is a better thermal insulator than an exterior wall, even if the wall between the conditioned room and the neighboring room is not insulated. This result indicates that leakage between conditioned and unconditioned zones will not eliminate the energy-saving potential of room-level zoning.

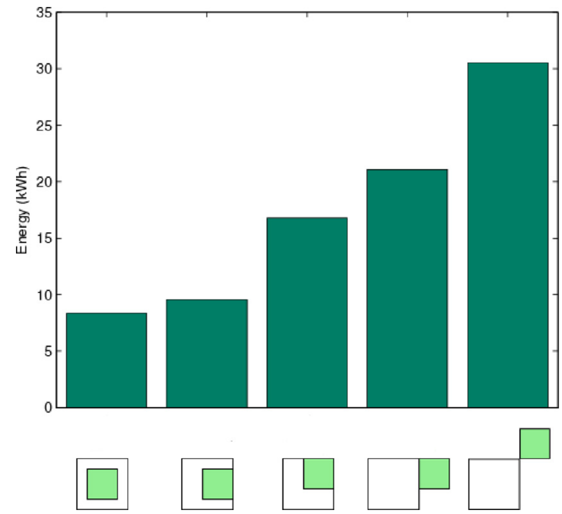


Fig. 2. The energy required to condition a room decreases with the number of exterior walls. The x-axis depicts the position of the conditioned room (shaded) with respect to the unconditioned room (unshaded).

3.3. Room occupancy

Finally, our preliminary analysis showed that residents do not use all rooms of an occupied house concurrently. For example, Fig. 3 depicts the empirical analysis of one home, showing that residents primarily use only one room at night, three rooms in the evening, and four rooms in the morning.

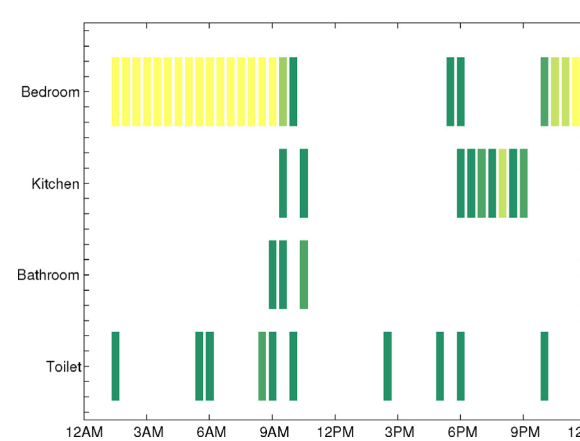


Fig. 3. The frequency of room usage throughout a day changes. Darker colors indicate lower frequency while brighter colors indicate higher frequency usage with yellow being the highest frequency. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

4. Challenges

Implementing a room-level zoned centralized HVAC system poses practical challenges. These include maintaining a minimum airflow and preventing short cycling for HVAC hardware safety, predicting room occupancy with no history, and coordinating the conditioning of zones. We describe these issues below.

4.1. Minimum airflow

HVAC systems produce different output airflows depending on the operating stage. For instance, the HVAC system in the house where we carry out experiments produces 830 ft^3/min (CFM) of conditioned air when cooling in stage 1, 1200 CFM of air when cooling in stage 2, etc. The ductwork for HVAC systems are carefully designed so as to allow most of this air to leave through registers. This prevents pressure buildup in ducts, *back-pressure*, which can increase leakage through cracks in ducts and improperly insulated connections. Back-pressure can also damage HVAC equipment by reducing the rate at which air flows over the coils that carry the refrigerant. The lower airflow would result in insufficient heat transferred to the refrigerant causing it to return to the compressor in liquid form, without fully evaporating, which can damage the compressor.

Zoning a centralized HVAC system involves closing ducts so that air only flows to a subset of a house. When a zoning system closes more ducts than a particular threshold number, or closes them in the wrong configuration, back-pressure could build up resulting in energy wastage due to leakage and equipment damage. In order to enable room-level zoning of a centralized HVAC system the controller has to consider the buildup of back-pressure when making actuation decisions.

4.2. Short cycling

Manufacturers recommend a minimum time for which an HVAC system should operate at a particular stage before transitioning to a lower stage, for instance transitioning from stage 2 to stage 1 or turning off from stage 1. Transitioning before this minimum threshold increases the wear and tear on the equipment due to it cycling more frequently and does not allow the pressure to equalize between cycles. Therefore, in implementing a system that controls the HVAC equipment at a fine granularity, it is essential that we ensure the compressor is not short cycled. This adds another factor for the controller to consider when making actuation decisions.

4.3. Occupancy prediction

Occupancy-based HVAC systems are either *reactive* or *predictive*. Reactive systems use room-level controllable HVAC equipment such as radiators or window air-conditioner units. These systems then monitor rooms for occupancy and turn on or off the occupied room's conditioning unit in response to detected occupancy. Coordination between zones is not an issue for such systems since the heating or cooling units are independent. Existing reactive centralized HVAC systems focus on whole house conditioning so that the system turns on when residents are in the house and off when they vacate the house, or rely on customized ducts with bypass ducts that prevent back-pressure. While bypass ducts can prevent the problems associated with back-pressure, a purely reactive centralized zoned system fails to exploit a lot of the energy savings possible due to zoning because it has to turn on whenever a resident enters a room that is not at the setpoint. In a house with a lot of activity, such a control scheme could result in a zoned system being no more efficient than a centralized HVAC system because it is always on. Another drawback to reactive systems, both whole-house and room-level, is the need to quickly heat or cool a space when occupied. This rapid conditioning can be less efficient than maintaining the space at a setpoint.

Predictive systems attempt to predict when a house, or rooms, will be occupied and start pre-heating or cooling the space so that it can be conditioned over a longer period of time using a more efficient HVAC stage than the rapid conditioning required during reaction. Yet, prediction is difficult due to the large amount of historical data needed to make an accurate prediction. This difficulty increases with the temporal granularity of a prediction. For instance, it is much easier to predict room occupancy within the next six hours based on history, but much harder to accurately predict room occupancy within the next five or ten minutes. The accuracy of prediction increases with historical data, but the amount of data necessary increases as the size of the prediction window decreases.

4.4. Zone coordination

The biggest challenge to implementing room-level zoning using a centralized HVAC system is coordinating the conditioning of zones so that energy is not wasted by the compressor constantly being in operation or air leaking between conditioned and unconditioned zones. We attempt to minimize the inefficiency by conditioning thermally homogeneous zones together so that the temperature gradient within such zones is small. This would reduce the amount of leakage out of conditioned rooms and minimize the amount of time the HVAC system is on when an unoccupied room becomes occupied because it would be close, in temperature, to the neighboring rooms and, thus can quickly return to the setpoint after which the compressor can be turned off.

5. Implementation

We implemented Dual-Zone in order to empirically test the ability to save energy with this approach. Our implementation involves: (1) sensing occupancy, (2) sensing temperature at the room-level, (3) controlling air-flow into rooms, (4) controlling the HVAC system, (5) software to control the system, and (6) an Android-based user interface.

5.1. Occupancy detection

The occupancy detector reads in motion sensor values every minute and uses the algorithm in Fig. 1 to identify occupied rooms. The algorithm analyzes the motion sensor firings within the last *1 min* interval and, for each room in the house, identifies if more than 50% of the sensors fired in order to detect occupancy.

Algorithm 1 *(Identify occupied rooms).*

for $r \in rooms$ **do**
  if $sum(PIR_{fired}(r))/sum(PIR_{total}(r)) > 0.5$ **then**
    $OCCUPIED \Leftarrow r$
  end if
end for

Fig. 1 is a highly simplified room occupancy algorithm since motions sensors would fail to detect occupancy if the occupants are motionless, for instance if they are asleep. Therefore, the algorithm could use knowledge of the movements of occupants into and out of rooms. One approach to achieve this is using height sensor on doorways as proposed by Hnat et al. [10]. But, this approach relies on a sophisticated tracking algorithm in order to distinguish between multiple occupants and differentiate between events such as two occupants entering a room from two doorways as opposed to a single occupant entering a room from one of the doorways and leaving

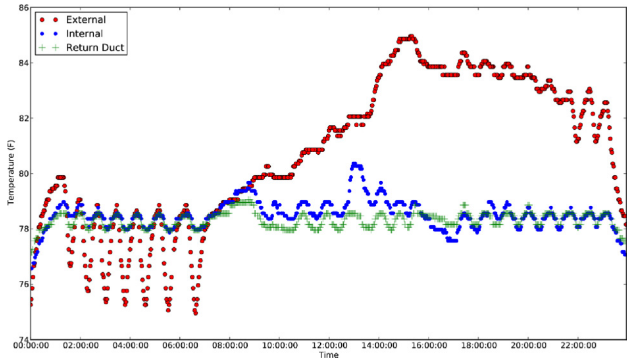


Fig. 4. The variation of temperature on a sensor placed on an internal wall, an external wall, and near the return duct.

from another. In order to control the complexity of Dual-Zone we decided to use the simplified occupancy detection algorithm.

5.2. Sensing house temperature

We monitor the home's temperature at a fine granularity by instrumenting the house with wireless temperature sensors placed on the walls. For the deployment discussed in this paper, we used 21 off-the-shelf temperature sensors manufactured by La Crosse Technology [14]. Because the temperature across the house is not uniform, one challenge in designing a room-level zoning system is to choose how to process the temperature readings to approximate the true average air temperature in each room. This problem also arises during whole-house conditioning when more than a single temperature sensor is available [13].

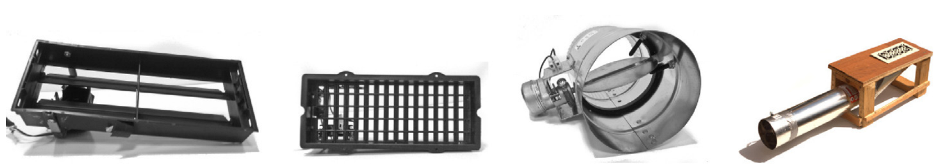
Fig. 4 shows the temporal variations of temperature sensors placed throughout the house. A sensor placed in the center of the house, directly in front of the only return register, senses the mix of air from all rooms. A second sensor is on an internal wall and a third sensor is on an external wall. The figure shows that the temperature sensor on the internal wall varies with the temperature of the individual room, which is slightly more than the variation of the centrally placed sensor. However, the sensor on the external wall is subject to wild temperature swings. On the left side of the graph, it is clear that the sensor has much greater downward swings than the internal sensors. This is because is it subject to direct airflow from the ducts, which are typically placed on external walls. It is also subject to heat that concentrates around the window mid-day. Because of these large temperature fluctuations, we decided to use only sensors on the internal walls of each room: the temperature in a zone is the average of the temperatures of each of the internal sensors in the rooms comprising the zone.

5.3. Controlling air-flow into rooms

In order to control the airflow into individual rooms, we designed and built *active registers and dampers* that can be wirelessly opened or closed. While controllable registers are commercially available, they actuate based on either preset temperatures or temporal schedules. Commercial active registers that are controllable through a remote control would be hard to integrate with our wireless control system and such registers are expensive, costing over $50 each. By designing our own registers by retrofitting passive registers with servo motors, we were able to build active registers for under $20 each, excluding the cost of the radio and microcontroller, that integrated wirelessly with the rest of the Dual-Zone infrastructure. Our design improved through three generations as shown in Fig. 5. We implement the registers using commercial, off-the-shelf (COTS) components including an operable register, a servo motor, and a small amount of custom circuitry (Fig. 6). These components resulted in a cost of less than $20 per register excluding the cost of the TelosB mote used for wireless communication. We built upon prototypes and even commercial versions of similar hardware that are currently available [26–28,24], but go beyond these devices by integrating them into a cooperative, wireless system.

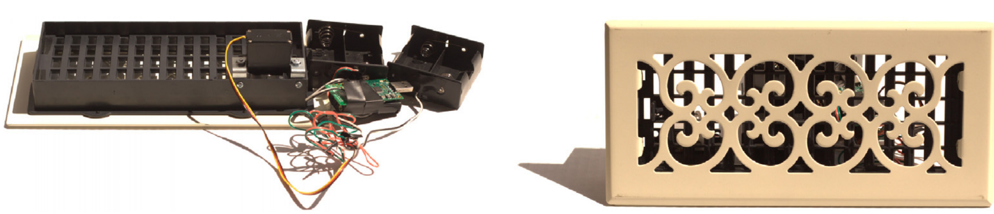
We measured the effectiveness of the registers using the bench-top testing framework shown in Fig. 5(d). The first generation registers were inefficient at blocking air when closed. The second generation registers improved this aspect by blocking nearly 100% of airflow but was noisy when opening and closing. Due to these reasons we resorted to dampers used in commercially implemented zoned systems as our third generation of airflow controllers.

We measured how effective these registers are at directing airflow into different rooms using a Kestrel 4100 Pocket Air Flow Tracker manufactured by Nielsen-Kellerman [12]. This sensor, placed above the register, provides a measure of airflow in terms of cubic feet per minute (CFM) that is coming out of the register. This



(a) 1st Generation (b) 2nd Generation (c) 3rd Generation (d) Bench-Top Test Rig

Fig. 5. Three generations of active registers. (a) The first generation uses servo motors and a rotating louver design, but exhibited too much leakage. (b) The second generation uses a sliding gate design to solve the leakage problems, but causes too much noise. (c) The third generation is a commercial in-line damper with a servo motor used for traditional zoning applications. (d) The bench-top test rig used to verify that the second generation wirelessly controlled active registers have almost no air leakage.



(a) Wireless Controller (b) Face Plate of Active Register

Fig. 6. A wirelessly controlled active register built by augmenting a standard vent register with a TelosB mote and a servo motor.

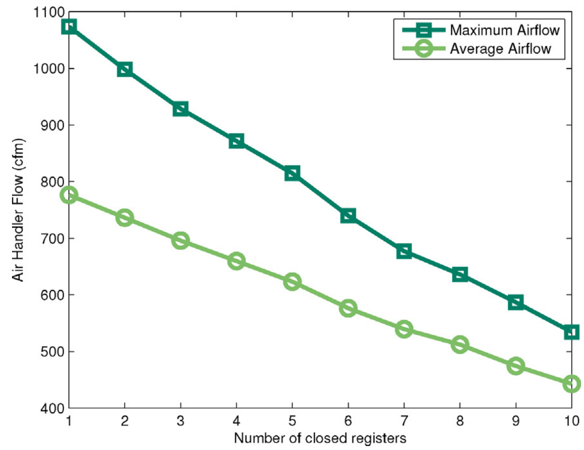


Fig. 7. Efficiency decreases as registers close due to the total air volume output by the system decreasing.

measurement uses the known size of the register and the speed of the air. Fig. 7 shows that the total airflow coming from all registers decreases as more registers close. When all registers are open, the average airflow is approximately 800 CFM, which matches the specification of the air handler in this house. However, as more registers close, the average airflow approaches 450 CFM, which is almost half. Total airflow does not approach zero because some air escapes even from the closed registers. This result verifies that closing registers does decrease the overall efficiency of the system because it reduces the total airflow output, as suggested by [26]. Therefore, actively cooling only half the house would not cause double the amount of air to be available to the cooled zone, because some air escapes due to backpressure, increased duct friction, duct leakage, and leakage from the closed registers.

5.4. Controlling the HVAC system

Dual-zone uses a simple state machine (Fig. 8) to control the HVAC system through four possible stages: *Float*, *Hold*, *Cool 1*, and *Cool 2*. Cool 1 and Cool 2 represent different stages of the HVAC system in which the compressor and hair handler operate at different cooling capacities. Hold causes the HVAC system to maintain the current temperature at the thermostat, and float causes the HVAC system to turn off.

Table 1
Adjusting the thermostatic setpoint, *ThermSP*, with respect to the temperature that sensed by the thermostat, *ThermTemp*, controls the operating stage of the HVAC equipment.

State	Action
Float	ThermSP = ThermTemp + 1
Hold	ThermSP = ThermTemp
Cool 1	ThermSP = ThermTemp − 1
Cool 2	ThermSP = ThermTemp − 2

In order to control the HVAC equipment, the Dual-Zone controller must interface through an Internet-controllable thermostat manufactured by BAYweb [1]. However, the BAYweb thermostat can only change its setpoint; it does not allow direct control over the equipment. In order to control the equipment, therefore, we modify the setpoint of the thermostat *ThermSP* to be higher, lower, or equal to the temperature measured at the thermostat *ThermTemp*. When we want to put the equipment into the *float* state, we use a setpoint that is higher than the current temperature. This causes the thermostat to turn off the equipment. Similarly, when we want to hold or lower the temperature, we use a setpoint that is the same as or lower than the current temperature, respectively. To lower the temperature quickly, i.e. to use stage *Cool 2*, we use a setpoint that is two degrees lower than the setpoint. This exploits the PI controller built into the thermostat, which causes the equipment to go into high stage cooling when the temperature is two degrees from the setpoint for more than 5 min. Table 1 summarizes the operation of the system. This coarse-grained control over the equipment is not ideal and could have caused some loss of efficiency and energy waste. In future work, we expect an improved control system to produce better results.

5.5. Software implementation

We wrote the control software in Python. The programs written in Python read from the temperature and motion sensors and send actuation commands to active registers and the HVAC hardware. Fig. 8 presents the state machine of the controller. The controller transitions the HVAC system between the four states listed in Table 1 depending on the current state, the average temperature (*aTemp*) in the active zone, and the setpoint (*SP*) using hysteresis to prevent rapid fluctuations between the states. This program collects the data used to analyze Dual-Zone.

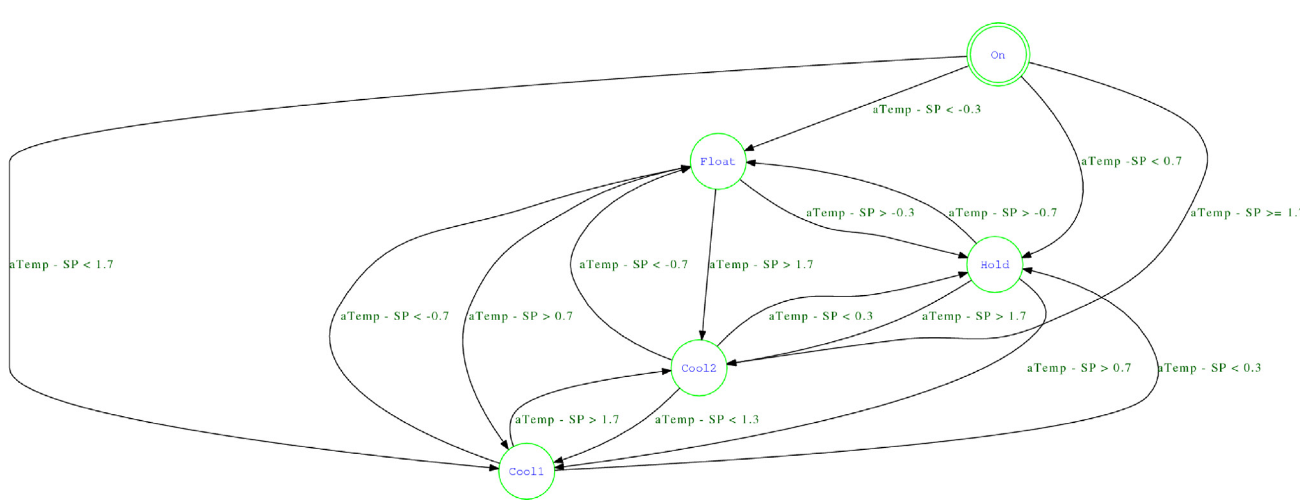


Fig. 8. The zoning controller attempts to maintain the average temperature of the active zone (aTemp) at the desired setpoint (SP) by transitioning the system between five states.

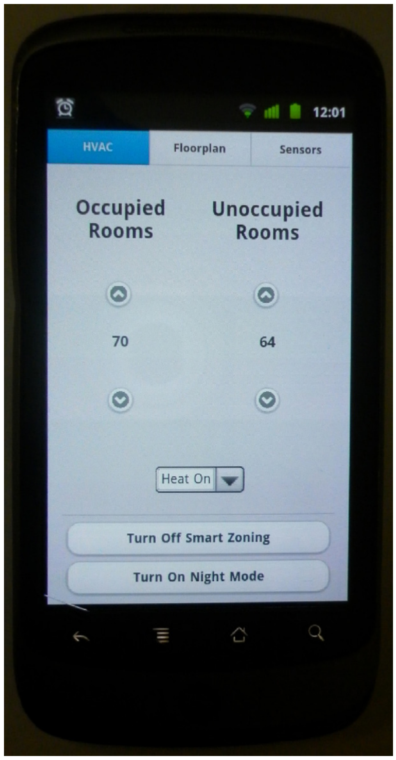


Fig. 9. Android smartphone-based user interface to HVAC controller.

5.6. *Android user interface*

The Android smartphone-based user interface indicates the currently active zone and the setpoint and setback temperatures. In addition, it allows the user to switch between the heat and cool mode and between Dual-Zone and whole house conditioning. The user is also able to turn off the HVAC system through this interface. Fig. 9 depicts the main interface through which a user interacts with Dual-Zone. It indicates the temperature of occupied rooms, the *setpoint*, and the temperature of unoccupied rooms, the *setback*.

6. Evaluation

We deployed Dual-Zone in an 7-room, single story, 1400 square foot residential building shown in Fig. 10. For simplicity, we divided the house into two zones. Dual-Zone actively conditions the red zone; composed of the living room, dining room, and kitchen; between 8:00 AM and 9:30 PM while it conditions the blue zone; composed of the bedroom, nursery, toilet, and mudroom; between midnight and 8:00 AM. Between 9:30 PM and midnight the whole house is conditioned. We compare this approach to conditioning of the whole house using an off-the shelf programmable thermostat manufactured by *BAYweb* [1]. In both cases, occupants control the setpoint temperature of the house. This means that the experiments measure the energy required to keep the occupants comfortable with both systems, as opposed to keeping the space at a particular setpoint.

In order to minimize the effect of changing whether patterns on energy consumption, we alternated control of the HVAC system between the single-zoned whole house control and the sub-zoned controller over a twenty day period, such that each system ran every second daty. Both systems executed for a total of 10 days. We monitor the energy consumed by all systems in the house using The Energy Detective (TED) [6] real-time in-home energy management system and deduce the amount of energy used by the HVAC system using the operation logs generated by the BAYweb thermostat.

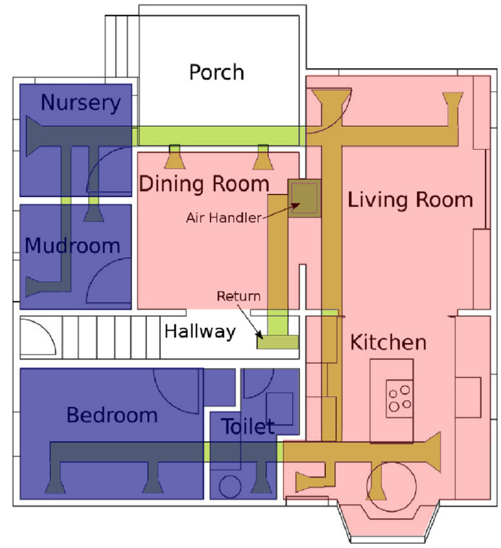


Fig. 10. We evaluate Dual-Zone in this residence. Light red shows the rooms composing Zone 1 and dark blue indicates the rooms composing Zone 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

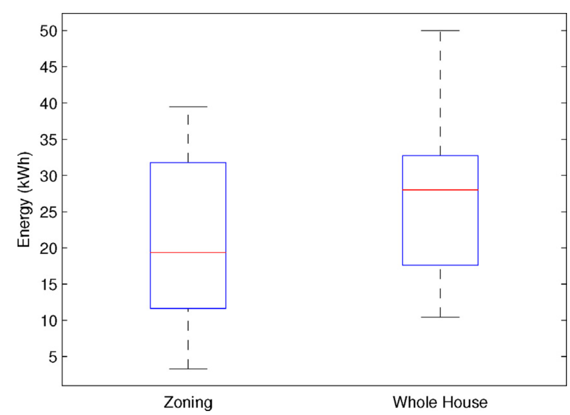


Fig. 11. The implementation of Dual-Zone uses 20.5% less energy than whole house cooling on average.

Fig. 11 shows the energy consumed in conditioning the house using Dual-Zone and whole house conditioning. This graph indicates that whole-house conditioning consumes 20.5% more energy, on average, than the prototype implementation of Dual-Zone.

Fig. 12 presents a scatter plot of the actual energy consumed in conditioning a house using Dual-Zone and whole house conditioning. The *y*-axis indicates the energy consumed for a

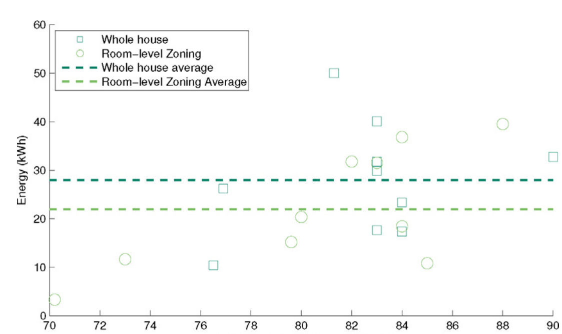


Fig. 12. The effect of outdoor temperature on energy usage. The dotted lines indicate the average energy used over the experimental period.

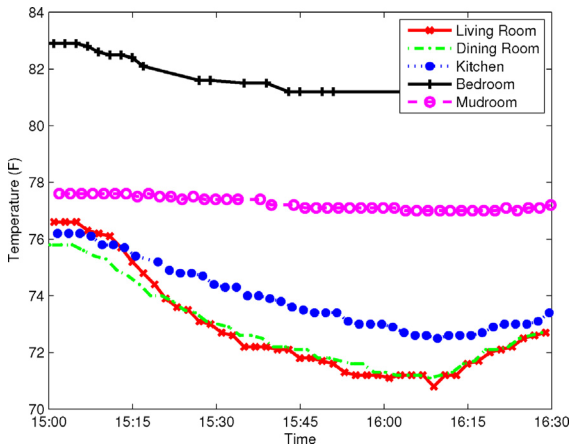


Fig. 13. Temperature response of both conditioned and unconditioned rooms as the active zone temperature drops from 76 °F to 72 °F.

particular day with the average temperature of that day shown on the *x*-axis. The color of the scatter points show the control algorithm. The result is statistically significant at the $\alpha = 0.15$ significance level.

Fig. 13 shows how the temperature of rooms in different zones vary as the temperature in the active zone drops from 76 °F to 72 °F. In this graph, the bottom three lines shown the temperature of conditioned rooms over time while the top two lines show the temperature of unconditioned rooms. Although some leakage is evident, particularly in the top line, the temperatures of the unconditioned rooms remains higher than the conditioned rooms. These temperature traces explain how room-level zoning is able to save energy by reducing the size of the conditioned space.

In order to better understand these results, Fig. 14 illustrates how effective the active registers were at activating and deactivating the red and blue zones. It is clear from this figure that the greatest airflow in a zone occurs when the registers in the other zone close. However, airflow to the inactive zone does not stop, nor does it all get directed to the active zone. In future work, we expect an improved active register system to produce better energy saving and thermal insulation results.

7. Work in progress

In this paper we zone a residential centralized HVAC system at the room-level and use this prototype system to carry out the first long term experiments to demonstrate the feasibility of saving energy through such a retrofit. This project is a work in progress and there are two directions in which we have, and in the process of, improving it. The first is a transition from statically defined zones to dynamically changing zones, and the second is a more sophisticated controller than the simple state machine presented in this paper.

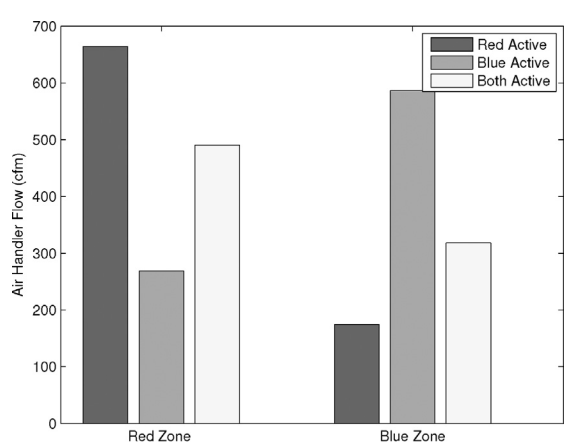


Fig. 14. Activating different zones affects air flow but does not redirect all air flow from one zone to another.

The system presented in this paper involved switching between pre-defined static zones temporally. That is, the active zone is decided based on time of day with knowledge of occupant activity used to manually define the zones. The ultimate goal of this project is to dynamically activate sub-zones based on occupancy. This would involve the controller using historical information on occupancy to pre-condition sets of rooms with the highest probability of being occupied while reacting to the actual locations of occupants. We are moving towards achieving dynamic predictive occupancy-based HVAC control through a two phased approach. The first phase involves implementing a reactive system that does not predict occupancy, but instead reacted to the real-time readings from occupancy sensors to define zones dynamically. We briefly describe this approach and some of the pitfalls we encountered in Section 7.1. The second phase involves implementing a predictive room-level zoning system. This requires the prediction of both occupancy and the effect of actuation on room temperatures. Section 7.2 describes some of our efforts in predicting room occupancy. Section 7.3 describes an approach proposed by Smith et al. [23] that we are pursuing in order to predict the effect of HVAC actuations on room temperatures.

While our preliminary implementation did not consider energy efficiency due to the experimental period being less than a month a commercial system would have to be highly energy efficient. The greatest energy consumer in wireless embedded networks is the wireless communication. Thus, in Section 7.4 we describe some optimizations that can minimize the number of messages passed and thus reduce the energy consumption.

7.1. Reactive control

In a room-level zoned system that reacts to occupancy, rather than predicts occupancy, the system adds an occupied room to the active zone. If a room is vacant for more than a certain period of time, the system adds it to the inactive zone. Adopting such an approach naively results in two problems. The first is fluctuations between active and inactive zones as residents move through the house and the second is rooms being uncomfortable when entered after a long period of being vacant due to the time it takes to heat up or cool down. We attempted to overcome the first issue by classifying rooms into two types of occupancy: *transitional* and *stable*. Transitionally occupied rooms, such as passageways, bathrooms, or wardrobes, change their occupancy state frequently. Residents occupy such rooms for short durations of time and therefore, we ignore their occupied states when making HVAC control decisions, yet leave their dampers open so that they receive conditioned air ensuring their temperature is not far from the setpoint. Dual-Zoner considers rooms that go from being transitionally occupied to being stably occupied when making HVAC control decisions.

We defined a room to be transitionally or stably occupied based on the frequency of sensor firings. We obtain these frequencies by processing historical occupancy data for each room and attempting to minimize the total duration Dual-Zoner considers a room occupied while minimizing either the number of false negatives (for transitional occupancy) or the number of transitions between occupied and unoccupied states (for stable occupancy). Fig. 15 shows the occupancy patterns obtained by processing ten

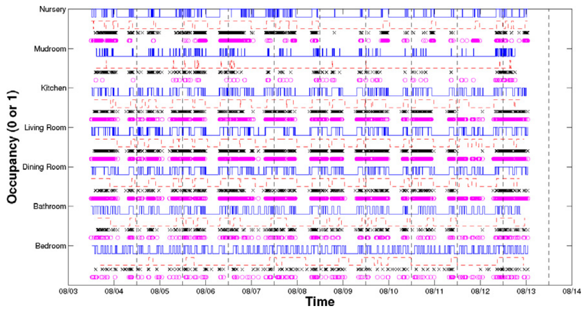


Fig. 15. Transitional and stable occupancy detected using the occupancy model. The solid line represents transitional occupancy, the dashed line represents stable occupancy, the *X*'s depict the firings of the *X*10 motion sensors in rooms, and the *O*'s depict the firings of the PIR sensors on doorways.

days worth of data. It is clear that transitional occupancy captures frequent occupancy changes as detected by aggregated sensor firings, while stable occupancy captures long-term room usage. The zone controller constantly monitors the occupancy sensor firings and classifies a room as being either vacant, transitionally occupied, or stably occupied by comparing the observed frequencies to the threshold frequencies obtained by processing the historical data.

7.2. Predictive control

As mentioned above, reactive control results in warm up and cool down periods when a resident enters a room after a long period of vacancy. During this time, the occupant might be uncomfortable as the room's temperature has drifted away from the setpoint. In order to overcome this, our current version of the system attempts to predict occupancy and condition a room when the expected cost of leaving the room unconditioned outweighs the cost of conditioning the room in terms of energy used and duration of time an occupant would be uncomfortable.

We analyze a number of occupancy prediction models using ten-fold cross-validation in order to identify the model that maximizes the accuracy prediction while minimizing the amount of data required to make a large percentage of predictions. Fig. 16 shows the accuracy of five different occupancy prediction models. The first model uses just the current state of a room (occupied or vacant) in order to predict the occupancy of that room at different times in the future; the second model uses only the current time in order to predict future states; the third model uses the state of a room and the time; the fourth model uses the states of a room and its neighbors to predict the future state of a particular room; and the fifth

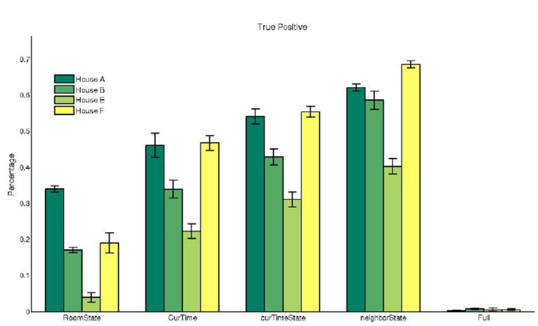


Fig. 16. True positive percentages for five models of occupancy analyzed using data collected from four houses over three months.

model uses all of these features. As the graph shows, using all of the features drastically decreases the prediction accuracy because the three months of data was insufficient to build such a detailed model. We are currently in the process of building a model that allows us to achieve the accuracy of the full model without the need of a long training period.

Based on this cross-validation, using only the current time results in a prediction accuracy of 81%. If the predictor uses the current room state instead, this accuracy increases to 84%. Including the neighboring room states increases the accuracy further to 86%. Combining the current time and the current room state as the features for the model increases the accuracy to 87% and using the states of all the rooms and the current time as features gives an accuracy of 95%. Yet, this high accuracy for states of all rooms at a given time requires a large amount of data to build a complete model that can predict future states for all current states of the house. With three months worth of data used for the cross validation, about 70% of the training set for the final model could not be validated due to their being no complete matches with the testing set.

These results indicate that an accurate room-level occupancy predictor has to make a trade-off between accuracy and the amount of data required to train the model. The most detailed model from among those evaluted had sufficient data to make a prediction only 30% of the time even though the predictions it made were 95% accurate. Simpler models, such as those that used only the current time or the current room's state as a feature, have sufficient training data to make predictions for almost all instances, yet their prediction accuracy is low. Thus, an ideal occupancy predictor for a dynamic room-level zoning system would be able to make the trade-off between all available models in order to produce the most accurate prediction possible with the available data. For instance, a system that is initially deployed would use the simpler models due to the small amount of training data being available. Over time, as the system collects more training data, it can train more detailed models and can make more accurate predictions. Such an approach would enable an off-the-shelf system to start working as soon as the user installs it and improve in its effectiveness the longer it is in operation. The challenge in implementing such an occupancy predictor is deciding between all available models for the model which will provide the most accurate prediction. We are investigating a number of approaches in implementing such a *hierarchical* predictor.

7.3. Temperature prediction

In addition to predicting occupancy, the dynamic room-level zoning system has to predict the effect of HVAC control changes and damper actuations. The main challenge in making such a prediction is isolating the effect of an actuation on a room's temperature from the effect of the weather. For instance, a South-facing room could be affected by sunlight to a much greater degree than a room facing another direction. Thus, the rate at which it cools would be less than for another room, or a room shaded from the sun. This increases the difficulty of building a accurate model to predict room temperature changes based on HVAC and damper control.

Smith et al. proposed a model that uses two stages to simplify this prediction [23]. The first stage attempts to predict the rate of heat gain or loss due to outdoor weather conditions by collecting data during periods when the HVAC system inactive. The second phase uses data collected when the HVAC system is active to predict the *change* in the rate of heat gain or lost in a room due to the conditioned air provided by the HVAC system. We are attempting to utilize this temperature predictor in order to implement the dynamic room-level zoning system.

7.4. Optimize message passing

The following sections describe some of the optimizations that could help minimize the number of messages passed and, thus, optimize energy consumption.

7.4.1. In-network data processing

In the prototype implementation of Dual-Zone, all sensors transmitted readings periodically. By programming the sensors with their location and incorporating a time-sync protocol, the sensors could transmit their temperature or motion readings only if they are in the currently active zone. This simple optimization could almost halve the number of messages sent by a sensor, potentially doubling their battery life. For temperature sensors which have an average lifetime of a year, an increase to two years is beneficial.

7.4.2. In-network aggregation

Another optimization that could increase the system lifetime is in-network aggreagation. Each of the two zones could form independent neighborhoods with an aggregation tree built from the furthest sensors towards the base station. Each sensor aggregates the average temperature of the zone by calculating the sum of its and its children's temperatures and passing it up the tree along with the count of the number of summed temperatures. The base station would receive a temperature sum from the zone along with the total number of sensors within the zone. The base station uses this information to calculate the average temperature of the zone. In the preliminary implementation of Dual-Zone, for N sensors where sensor i is at a depth of d_i from the base station, the number of messages transmitted each time is $\sum_{i \in N} d_i$. Using in-network aggregation reduces the number of messages sent to equal the number of sensors in the network N. In-network aggregation only proves beneficial if the system involves a multi-hop network since in a single-hop network the base station can receive all transmissions and carry out computations centrally.

7.4.3. Data fusion

Finally, data fusion can minimize the number of messages passed to the base station by aggregating the motion sensor and temperature sensor values at a leader node within each zone. By processing both the temperature and motion sensor data within the network, the number of messages passed by both sensors up to the base station is minimized. This approach provides savings only for large networks where all the nodes in a particular zone are multiple hops from the base station.

8. Conclusions

In this paper, we present an implementation of a room-level zoning system to minimize the energy consumed for heating and cooling homes by conditioning only occupied spaces. Our preliminary analysis shows that an existing single-zoned residential HVAC system can be easily retrofitted with such a system. Even with leakage from the registers and imperfect isolation between rooms, whole house zoning consumed 20.5% more energy than this system over the course of a 20-day study. While longer-term studies are necessary to eliminate potential effects of weather during the study, these results are promising and warrant further investigation into this approach, especially in light of the shortcomings of our prototype, as described in Section 5, and that we only evaluated multi-room zones instead of individual-room zones.

One important limitation of room-level zoning is the difficulty in controlling the zones individually: our current implementation requires the manual setting of the temperature in each zone, which can be a difficult task for the typical household. In ongoing work, we are extending our room-level zoning system to use occupancy information to enable simpler, more automated control of each room.

Acknowledgement

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