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Towards an Occupancy-Enhanced Building HVAC Control Strategy Using Wi-Fi Probe Request Information

Xuan Li[1]; Xuesong Liu[2]; and Zhen Qian[3]

[1]Ph.D. Candidate, Dept. of Civil and Environmental Engineering, Carnegie Mellon Univ., 5000 Forbes Ave., Pittsburgh 15213. E-mail: xuanli1@andrew.cmu.edu
[2]Assistant Research Professor, Dept. of Civil and Environmental Engineering, Carnegie Mellon Univ., 5000 Forbes Ave., Pittsburgh 15213. E-mail: pine@cmu.edu
[3]Assistant Professor, Dept. of Civil and Environmental Engineering, Carnegie Mellon Univ., 5000 Forbes Ave., Pittsburgh 15213. E-mail: seanqian@cmu.edu

Abstract

In the U.S, 2011, heating, ventilation, and air conditioning (HVAC) systems in buildings took nearly 20% of total energy consumption. To improve the efficiency of HVAC system and save energy, researchers have exerted great effort in developing models to optimize control schedule and strategies of HVAC systems. Such models not only can greatly reduce gross energy usage, but also maintain a comfort indoor environment. As one of the most important intrinsic factors for control models, however, real-time occupancy statistics has been rarely applied in previous studies, due to the difficulties in occupancy detection techniques including scalability, cost effectiveness and real-time consistency. Thus, the study discussed in this paper proposes an approach that utilizes processed probe request log dataset collected through Wi-Fi network for occupancy estimation and HVAC system control. The authors first discuss the requirements for the occupation information used in different optimization strategies for HVAC systems. In addition, occupancy detection approaches are explored and compared to illustrate that the WiFi-based approach fit the requirements of HVAC controls. Finally, WiFi-based occupancy detection and prediction approaches are investigated using a real-world case study, and an integrated framework for occupancy-based predictive HVAC optimization is proposed for future application.

Keywords: occupancy sensing; HVAC control; energy efficiency; information technology

INTRODUCTION

As one of the major energy consumption sector, building heating, ventilation, and air conditioning (HVAC) system accounted for about 20% of the total energy used in USA (Afram and Janabi-Sharifi, 2014). Thus, it is very crucial to reduce energy use and utility costs while guaranteeing sufficient indoor comfort for the buildings occupants. Currently, most HVAC operation logics assume that the space (zone) is occupied according to room or personal schedules, not accounting for the fact that most spaces are partially occupied and do not require full cooling/heating ventilation loads (Brandemuehl and Braun, 1999). Thus, using occupancy-based HVAC control system and strategies is very worthy of consideration, along with enhancing building insulation and updating energy efficient equipment (Oldewurtel et al. 2013). The efficiency of occupancy-based control has been widely verified by statistical analysis,

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simulations and real-world tests. For example, a survey conducted by Nguyen and Aiello (2013) showed that up to 40% energy saving could be achieved by using occupancy-based control, while energy unaware policies can add one-third to a building's designed energy consumption. In Oldewurtel et al. (2013), Kwok and Lee (2011), the simulation results indicated that the energy consumption is very sensitive to occupant's presence, and a 34% saving potential could be attained with a proper control policy. In Balaji et al. (2013) and Lu et al. (2010), the occupancy-based control was carried out in residential and educational sectors, and both of the application gained at least 20% energy saving. In all, the potential of energy saving using occupancy-based control is huge. However, in order to find precise control strategies, two major challenges remains: a proper technique for the acquisition, processing of occupancy data, and a well understanding of its spatial–temporal pattern.

Previous research studies have investigated a variety of occupancy detection approaches that use different types of computational methods and sensors, such as CO2 sensor, infrared sensor, camera, etc. Due to the different characteristics of these approaches, they have various strengths and weaknesses in terms of the real-time consistency, scalability, cost, accuracy, etc. To choose the most propriety approach for occupancy-based HVAC control, we first investigate the requirements for the occupation information to be used in different optimization strategies for HVAC systems. Second, we explored and compared occupancy detection approaches, and identified that the WiFi-based approach fit the requirements of HVAC controls. Finally, we implemented the WiFi-based occupancy detection and prediction approach using a real-world case study, and proposed an integrated framework for occupancy-based predictive HVAC optimization.

LITERATURE REVIEW

Occupancy Sensing and Estimation. Generally, we evaluated the current available occupancy sensing techniques mainly based on three factors: scalability, cost effectiveness and real-time consistency, which are the most important considerations for indoor occupancy detection system. To our knowledge, the most commonly techniques used for indoor occupancy detection and estimation includes CO2 sensors, Passive Infrared Sensors (PIR), vision-based system, Radio Frequency Identification (RFID) system, integrated sensing system, and Wi-Fi network system (Labeodan et al. 2015). A primary evaluation based on these three criterions is listed in Table 1.

CO2 sensors measure the concentration of carbon dioxide at ventilation return duct to calculated the corresponding counts of occupant in a certain space. It is very convenient and economical but it did have time delay between data collection and estimation, which makes it impossible to get real-time occupancy statistics. On the other hand, the accuracy of the estimation suffers from various factors such as airflow rate, outdoor air quality, etc.

Passive infrared (PIR) sensors have been largely used for non-individualized occupancy detection (Goyal et al. 2015). In Agarwal et al. (2010), PIR sensors were applied for occupancy detection across ten office rooms and achieved 15% reduction of energy consumption. However, the limitations of PIR sensors lie in that they could not measure the count of occupants but only binary signals, and they are unable to detect near-static objects without continuous motion.

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Vision-based systems use advanced cameras and image/video processing algorithm to distinguish occupants from background. In Shih (2014), Benezeth et al. (2011), and Erickson et al. (2009), such systems are proved to be very effective for occupant detection in room scale. However, privacy issues, prime cost and scalability for large number of occupants may hinder the wide application of this technique.

RFID system assign tracking and reference tags to occupants and buildings separately, and use signals received from both tags for occupancy estimation and localization. In Li and Becerik-Gerber (2012), the RFID system achieved an accuracy of 62% for mobile occupant detection in floor level. However, privacy, prime cost, and accuracy would be the major concerns for this technique.

To overcome the limitations of individual sensors, integrated sensing system has been developed such as Lam et al. (2009), Goyal (2015), Lu et al. (2010), and applied for occupancy detection widely. However, the primal cost might be a common issue for these systems.

Recently, researchers have explored the potential of using existing building Wi-Fi networks and Wi-Fi enabled devices owned by occupants to estimate the occupancy in room, floor and building levels. Wi-Fi is a widely used communication technology for data exchange between internet and other devices within a certain area. Mobile devices are connected through the network by sending probe requests containing user ID, MAC address, device type, brand to the Wi-Fi routers. The daily probe requests logs are recorded and maintained by system administers, and this rich information could be very helpful to capture the pattern of occupancy. Verified by Martani et al. (2012), Balaji et al. (2013), and Vattapparamban et al. (2016), this approach has been proved to be very effective for zone-level occupancy estimation with low cost and no time delay. Also, in Chen and Ahn (2014), a positive relationship between Wi-Fi connections and energy load increment has been revealed.

Table 1. Evaluation of Current Indoor Occupancy Detection Techniques

	real-time consistency	scalability	cost effectiveness
CO2 Sensors		√	√
PIR Sensors	√		
Vision-based System	√		
RFID System	√	√	
Wi-Fi Networks	√	√	√
Integrated System	√	√	

HVAC control methodology. Basically, HVAC control approaches can be categorized into two major branches: reactive control and predictive control. Reactive (rule-based) control directly couples input parameters and output actions, while predictive control generates policies based on historical actions and an estimation of future state. On/off, PI and PID, and fuzzy control are the commonly used reactive control strategies for HVAC system. Generally, PI and PID controllers are closed loop/feedback controls, not having any direct knowledge of the system to be controlled (Montgomery and McDowall, 2008), while fuzzy control is based on establishing a set of verbal rules, which takes continuous values inputs and produce logical command. On the other hand, Model Predictive Controller (MPC) are frequently chosen for HVAC predictive control.

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MPC aims to predict the future state of the system by generating a control vector (output) that minimizing a cost objective function under constraints predefined by HVAC systems.

APPROACHES

Systematic predictive control of HVAC systems using occupancy information. Energy usage of HVAC systems are directly impacted by the cooling/heating load requirements. Hence, by predicting the loads, it is possible to optimize the HVAC control strategy, which typically is programmed using fixed schedule or occupancy detector. To achieve optimized energy management, previous studies have investigated rule-based set-point scheduling strategy and Model Predictive Control (MPC). Rule-based control allows switching and adjustment of occupied and unoccupied modes for set-point in different heat/cool zone (Erickson et al. 2009; Lu et al. 2010; Balaji et al. 2013). MPC minimizes the total energy consumption given pre-defined occupancy-related actions, and maintains the indoor comfort index within certain range (Mady et al. 2011; Dobbs and Hencey 2014; Goyal et al. 2015). Both approaches have been proven to have the potential for improving energy efficiency. Thus, the predicted occupancy information discussed in this paper would be integrated with these two approaches to adjust cooling/heating loads to improve the accuracy and effectiveness of the control strategies.

As we have discussed in the previous sections, occupancy detectors have been applied in commercial HVAC systems to augment the schedule-based control, which does not actively account for the actual cooling/heating needs of the space. However, the industry practice of occupancy detectors for HVAC systems only control over the binary status, occupied and unoccupied, of each space/zone. This approach works for local control on the terminal box. However, for systematical control of chillers that serve multiple buildings, and air handling units (AHU) that server multiple spaces, the actual number of occupants is needed to determine the total cooling/heating loads and adjust the control strategy. Hence, the research study discussed in this paper investigated the needs for occupancy information to support the systematical optimization of HVAC systems.

In commercial buildings, especially in campus where multiple buildings located close to each other, large scale chillers typically connected by bridges and serve one or multiple buildings at the same time. The total capacity of the chillers is determined by the temperature and flowrate of outlet chilled water. In order to ensure the correct functioning of cooling systems, chillers are typically operated at a higher capacity than the estimated cooling loads. But due to lack of modeling approach to predict the cooling loads for chillers, most of the cases chillers are set to produce unnecessary overcooled water. Hence, if the occupancy of buildings can be predicted hours earlier, setpoints of chillers can be adjusted using rule-based and MPC strategy to only provide enough capacity that is needed.

Similarly, control of AHU can be optimized if cooling/heating loads of the served spaces (typically located on the same floor or wing of the building) is known hours earlier. In order to achieve this objective, there is a need for a cost-effective solution to predict the amount of occupancy of multiple buildings. In the next section, we investigated the Wi-Fi network based approach to predict the occupancy information at floor and building level.

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Occupancy Detection and Estimation Using Wi-Fi Network. Given the investigations on the current occupancy detection techniques, Wi-Fi based approach meets the pursuits and could be integrated with HVAC control system with light preprocessing. For scalability, its coverage could be extended to building level with thousands of occupants, and could be gauged in floor level, or even room level. For real-time consistency, the processing of connections logs is very fast, and could be passed into the control system instantly for 24 hours a week. For cost effectiveness, it does not require setup or additional fees, and the daily operation could be done along with the maintenance of Wi-Fi networks. On the other hand, since our control strategies reply on an admissible rather than precise estimation of the occupancy, the accuracy would not be a major concern in our case. Even this, a study conducted in Balaji et al. (2013) proved an 86% accuracy of occupant detection could be achieved for office spaces on campus.

As an ideal testbed with largely covered Wi-Fi networks, several studies have been conducted on educational sectors (Martani et al. 2012; Balaji et al. 2013; Chen and Ahn 2014; Vattapparamban et al. 2016). In these studies, the information of connected/disconnected time, MAC address, type, user ID (hashed) in the probe requests logs are adopted to identify unique occupant during given time intervals. In a similar manner, we collected and analyzed a probe requests logs of one academic building in Carnegie Mellon University, from 11/10/2016 to 11/22/2016. For privacy concerns, we only use the information of connected/disconnected time, hashed user ID, router ID, total traffic (MB) and duration for occupancy estimation. We assume a valid connection has nonzero duration or total traffic, and the duration does not exceed 30 hours. Also, since it is possible that one unique user may have several devices connecting through the network at the same time with one user ID, Hashed user ID are used to avoid duplicated counts for a specific user in any given interval. On the other hand, the information of location (floor, room) of the connection could be revealed from the router ID. We define the interval as 15 minutes, which could be adjusted for different purpose. The temporal and spatial pattern of Wi-Fi are shown from Figure 1 through Figure 4.

In Figure 1, the daily Wi-Fi connection count for 13 days is plotted in day scale. It is shown that the processed data could successfully reflect the occupant trends for the academic building, in the magnitude of 10^3. Also, the daily peak is usually reached around 1:30 pm, and the peak values across different workdays are similar.

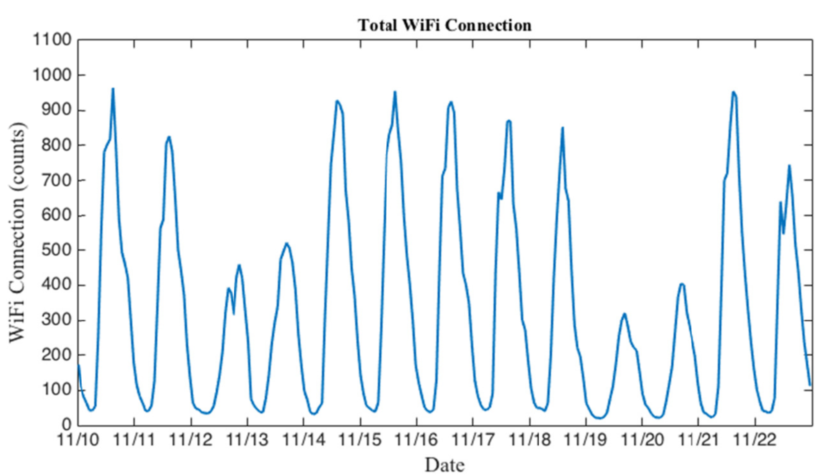

Figure 1. Total Wi-Fi Connection

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To uncover the occupancy pattern in floor and room level, we further analyzed the total daily count in Floor 3 (café), Floor 4 (classrooms and offices), Floor 6 (offices), and for a typical classroom, open area, offices in Figure 2 and Figure 3 separately. The trends captured by Wi-Fi connection match the assumed capacity of each floor and room, and the pattern varies a lot based on the functionality of the subspace.

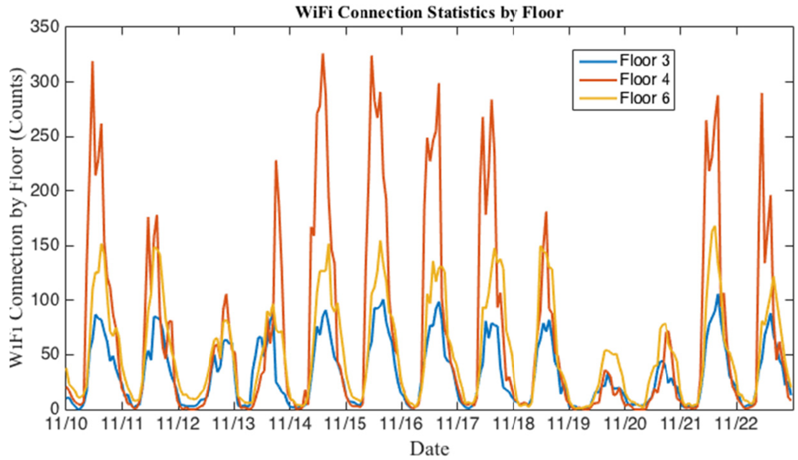

Figure 2. Total Wi-Fi Connection (By Floor)

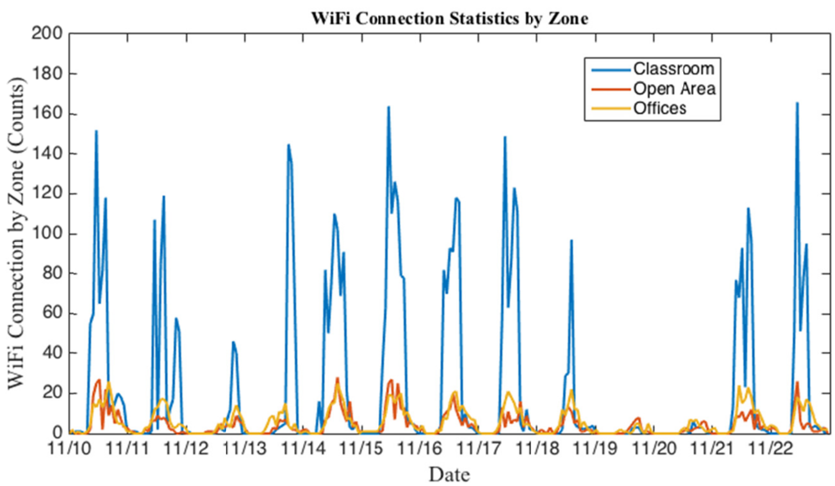

Figure 3. Total Wi-Fi Connection (By Zone)

Finally, In Figure 4, we rearranged and compared the total connection counts according to weekdays, which indicated a clear matched pattern. Thus, "weekday" could be a good feature to for occupancy prediction in future.

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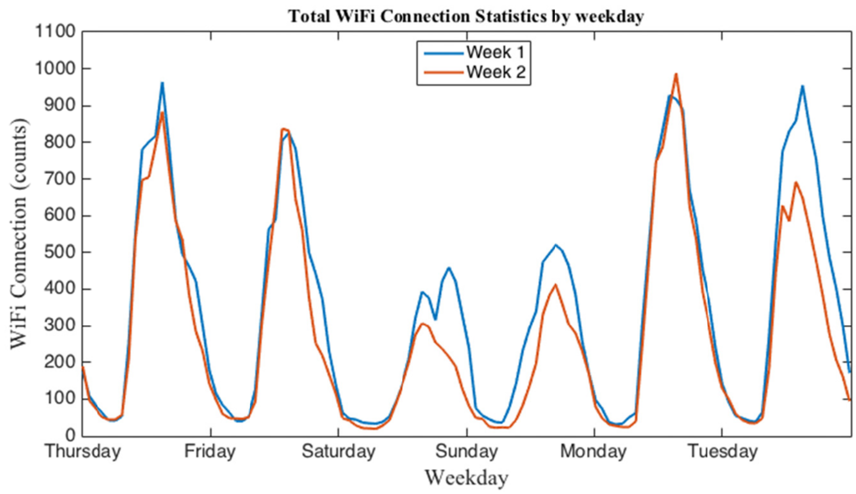

Figure 4. Total Wi-Fi Connection (by Weekday)

CONCLUSIONS

Occupancy information provide insights on the cooling/heating loads of HVAC systems and therefore, directly impact the strategy for optimized control. The study discussed in this paper investigated the control strategies that can be used to improve the energy efficiency of chiller and AHU using the occupancy detection approaches. We analyzed the requirements of occupancy information, explored and compared the previous studies on various techniques for detecting occupancy, and concluded that the WiFi-based approach is the most appropriate one for optimal HVAC controls considering scalability, cost effectiveness and real-time consistency. A case study was carried out to assess the feasibility of using WiFi-based data to predict occupancy information at floor and building level. The results confirmed our evaluation of the WiFi-based approach. For the next step, we will focus on investigating the correlations between the occupancy information and energy usage in HVAC systems to developing predictive models for automated optimal control.

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