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Linking Building Energy-Load Variations with Occupants' Energy-Use Behaviors in Commercial Buildings: Non-Intrusive Occupant Load Monitoring (NIOLM)

Hamed Nabizadeh Rafsanjani,[a] Changbum Ahn[a*]

[a] *The Durham School of Architectural Engineering and Construction, University of Nebraska–Lincoln, Lincoln, NE 68588-0500, United States*

Abstract

Studies indicate that occupancy-related energy-use behaviors have a significant influence on overall energy consumption in commercial buildings. In this context, understanding and improving occupants' energy-consuming behaviors shows promise as a cost-effective approach to decreasing commercial buildings' energy demands. Current behavior-modification pursuits rely on the data availability of occupant-specific energy consumption, but it is still quite challenging to track occupant-specific energy-consuming behaviors in commercial buildings. On the other hand, individual occupants have unique energy-consumption patterns at their entry and departure events and will typically follow such patterns consistently over time. Thus, analyzing occupants' energy-use patterns at the time of their entry and departure events plays a critical role in understanding individual occupants' energy-use behaviors. To this end, this paper aims to develop a non-intrusive occupant load monitoring (NIOLM) approach that profiles individual occupants' energy-use behaviors at their entry and departure events. The NIOLM approach correlates occupancy-sensing data captured from existing Wi-Fi networks with aggregated building energy-monitoring data in order to disaggregate building energy loads to the level of individual occupants. Results from a 3-month long period of tracking individual occupants validate the feasibility of the NIOLM approach by comparing the framework's outcomes with the individual metering data captured from plug-load sensors. By utilizing existing devices and Wi-Fi network infrastructure, NIOLM provides a new opportunity for current industry and research efforts to track individual occupants' energy-use behaviors at a minimal cost.

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Keywords: Commercial buildings; Energy consumption; Non-intrusive approach; Occupant energy-use behavior; Profiling energy-use behavior

[*] Corresponding author. Tel.: +1-402-472-7431; fax: +1-402-472-3742
E-mail address: cahn2@unl.edu

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1. Introduction

In the U.S., buildings account for 40% of the country's total annual energy consumption; approximately half of this energy goes to the commercial sector, whose demand also continues to grow faster than other energy-use sectors [1, 2]. Such energy-use intensity and increasing consumption rates raise critical concerns about improving the energy performance of the commercial sector during the operational phase.

A general overview of current literature shows that conventional approaches to enhancing buildings' energy savings focus on retrofitting the building envelope and updating appliances. However, such approaches require large capital investments and sometimes are infeasible for existing buildings [3]. A growing number of recent studies emphasize the importance of understanding and improving occupant energy-use behaviors as a cost-effective approach for saving energy in commercial buildings [4–7]. However, the success of such studies critically relies on the availability of information regarding occupant-specific energy consumption. For example, if occupant-specific energy use is not determined correctly, the feedback outcome can have negative effects on occupants' energy-use behaviors [8,9]. However, an overview of the current literature shows that due to the difficulties in tracking the energy consumption of various occupants in commercial buildings, few researchers have addressed this issue [5,10]. Estimating individual occupants' energy loads in commercial building is still an extremely challenging task [5].

Conventional approaches to monitoring individual occupants' energy consumption typically have estimated an occupant's energy consumption in commercial built environments by using individual plug-load monitoring devices; unfortunately, such approaches are not applicable in practice as they need a large capital investment. Being able to economically and accurately estimate energy-use of individual occupants in a commercial building requires linking energy-consuming data with occupancy-sensing data [5]. Such links can lead to disaggregating building energy loads to the level of individual occupants. In our previous studies [10,11], we demonstrated that Wi-Fi connection and disconnection events within a commercial building are viable indicators for the starting and ending of individual occupants' energy-consuming behaviors, respectively; this finding can be targeted as a link between occupancy sensing and energy-consuming data. In addition, we found that individual occupants have unique energy-consumption patterns at their entry and departure events and will typically follow such patterns on a daily basis.

Based on these findings, our previous study [10] presented a non-intrusive occupant load monitoring (NIOLM) concept that estimates individual occupants' energy-load variation at their entry and departure events in commercial buildings. NIOLM extends the concept of non-intrusive load monitoring (NILM) to observe occupant-specific energy consumption—NILM techniques apply to the total energy data collected from a single meter to identify large appliances [5]. The current prevalence of NILM indicates its success and feasibility, especially in residential buildings; however, NILM's effectiveness in commercial buildings is quite limited due to the large number of similar appliances in use simultaneously [10].

The foundational pursuit behind NIOLM is to link energy-use data with occupancy-sensing data. The current status of occupancy-sensing technologies provides a good opportunity for economically monitoring individual occupants and their specific energy consumption [12]. NIOLM leverages existing Wi-Fi networks to track each occupant and links these data with aggregated energy-use data provided by buildings' energy management systems (BEMS). Since there is no need to install new infrastructure for NIOLM's execution, this tool would be especially economical for commercial buildings. This research extends the NIOLM concept into a real tool.

2. NIOLM algorithmic framework

In order to profile individual occupants' energy-load variations at their entry and departure events, the NIOLM algorithm consists of four major stages, as follow:

2.1. Detecting occupancy events

In the first stage, the entry and departure events of individual occupants in possession a Wi-Fi enabled device (i.e., smartphone) are detected based on the signal of their smartphones' transmitted packets received by building's Wi-Fi network's access points (APs). It is worth mentioning that there are usually multiple overlapping APs in a commercial building, and therefore Wi-Fi-based occupancy sensing can work at a minimal cost. The event detection is then