Data Driven Feedback for Optimized and Efficient Usage of Decentralized Air Conditioners

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***Abstract*— In the context of developing countries, buildings account for around one-third of aggregate energy consumption with decentralized air conditioners (AC) being the major contributor. The possibility of room-level control, together with buildings substandard thermal insulation make decentralized ACs, an attractive target for energy conservation. Our overall objective is to provide targeted feedback for optimized and efficient use of ACs by the occupant without affecting their thermal comfort. In our first work, we developed a system PACMAN for non-intrusive (using ambient temperature information) prediction (prior-usage) and estimation (post-usage) of AC energy consumption. We adapted a thermal model from existing literature and validated our approach using the data collected in an in-situ study conducted across seven homes in Delhi (India). The dataset contained around 2200 hours of usage data from the different ACs, room types, and thermostat temperatures. We achieved an average accuracy of 85% and 83% with the best accuracy of 97% and 93% for the estimation and prediction of AC energy consumption respectively, across all homes.**

During the study, we realized that easy-to-collect ambient information such as temperature (using various pervasive and ubiquitous devices such as smartphones) can generate actionable feedback for the occupants. We also observed that human activity, room structure, and several such factors impact the performance of PACMAN. Thus, we next performed controlled experiments to understand the effect of these factors on PACMAN and thus enhance our thermal model. One of the main conclusions was that sensor position plays a crucial role in the optimal control of AC. Also, windows exposed to the environment outside the room makes the most significant impact on AC energy consumption. In our ongoing work, we focus on finding the optimal position for the thermostat to reduce AC energy consumption without affecting occupant's thermal comfort. In future, we plan to propose a framework to detect anomalies in AC within time, as delay in that might lead to appliance failure or inefficient outcome.

I. Introduction

Decentralized Air Conditioner (AC) is commonly used in both residential and small-scale commercial buildings across developing countries. These buildings contribute a significant proportion of total electricity consumption with AC being a major power consuming appliance. The widespread presence of AC further motivates the need for its optimized and efficient usage. Previous studies have extensively looked into the optimization of central HVAC (Heating, Ventilation and, Air Conditioning) units, mostly found in developed countries and large commercial buildings. Different occupancy, fixed running schedules, together with higher possibilities for leakage within the ducting system, across the zones differentiate central HVAC from decentralized ACs and grounds motivation for the need of a separate investigation in this domain with the focus being energy conservation.

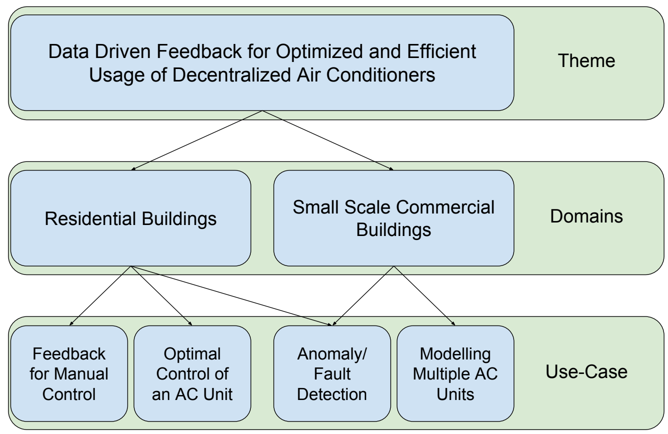

Fig. 1: We plan to explore various use-cases under the domain of residential and small scale commercial buildings. By working on these sub-problems, overall goal is to generate feedback for optimized and efficient use of ACs across these buildings, by leveraging on data from pervasive and ubiquitous devices.

Our overall goal is to generate data-driven feedback for an optimized and efficient use of ACs. The advent of ubiquitous and pervasive devices (e.g. smartphones, wearables) together with crowd sensing applications, made sensing of ambient information quite easy. Given our research interests and the current scenario (of data collection), we plan to explore various use-cases (Figure 1) in this domain. We next discuss each use-case in further details, explaining current state-of-art along with our broad vision.

A. *Feedback for Manual Control*

Existing literature has well studied the feedback to occupants regarding appliance level energy consumption. Such feedback can be generated by monitoring the appliances in real-time [1]. However, it requires extensive installation and also incurs heavy maintenance cost. Bidgely, PlotWatt and various studies [2], [3] looked into the non-intrusive way of providing the similar feedback by disaggregating meter-level data from smart meters. However, using such direct or indirect monitoring systems limit the feedback to energy consumption details without getting into actionable insights for the occupants [4]. Therefore, recently we proposed a near-real time system, PACMAN to map similar ambient information with the prediction (prior-usage) and estimation (post-usage) of AC energy consumption. Energy estimation, post-usage targets informative feedback to the occupant about the impact of the chosen settings, eventually supporting better decision making over time. Predictive feedback, at the beginning of the usage, aims at influencing occupants' behavior, when it matters the most, leading to real savings.

B. Optimal Control of an AC Unit

The impact of actionable feedbacks to the occupants depends upon the nature of residents towards the energy savings. However, optimized use of ACs requires smart sensing and efficient control algorithms capable of reducing the energy consumption without affecting occupants' comfort. Current state-of-art majorly focuses on either completely simulation based models [5] or purely data-driven models [6]. Programmable thermostat and Nest are some notable efforts in data driven modelling using location and occupany information. But the poor interface (programmable thermostat) and inaccurate learning (Nest) increased the AC energy consumption in some scenarios [7], [8]. However, model should incorporate spatiotemporal changes in the room temperature depending upon the occupants' activities. Also, the aim of AC is to maintain the temperature within certain bounds in an enclosed space. Unfortunately, these bounds are decided based on its testing in the lab environment under constrained environment. But AC's performance depends on various factors, ranging from the structure of the enclosed space to real-time dynamic activities (occupant, activities, the number of doors and windows) in the room. Therefore in this use-case, we focus on the optimized control of AC by looking into optimal sensor positioning and develop context-based thermal models.

C. Anomaly/Fault Detection

The efficient use of AC demands identification of faults in its various components well before it impacts appliances performance. Previous research [9] shows that anomalous appliances can increase energy usage and decrease occupant comfort. In future, we plan to develop data-driven thermal models for anomaly detection in AC using ambient information, for both residential and small-scale commercial buildings.

D. Modelling multiple AC Units

In contrast to developed countries, small-scale commercial buildings (e.g. Banks) prefer multiple AC units in place of central HVAC system due to cost and maintenance involved. However, modeling a space with multiple AC is difficult when compared with the spatio-thermal model of space with single AC unit. As they work as independent units, their coordinated scheduling can result in optimized usage in terms of overall AC energy consumption and user comfort. Previous studies [10] have looked into such optimizations for central HVAC. However in this sub-problem, we plan to focus on the coordinated scheduling of decentralized AC units, to reduce energy consumption while maintaining user comfort.

II. Problem Statement

In this work, we plan to bridge the research from theoretical simulations of decentralized air conditioners with the data driven models. Aim of this work is to make optimized and efficient use of widespread ACs (in the context of developing countries) leveraging easy-to-collect ambient information such as temperature, humidity etc. To understand real-world challenges, we plan to validate our approach using controlled experiments and in-situ deployments across various residential and small-scale commercial buildings.

III. Research Summary

We now discuss our progress over the problem defined in the previous section and insights gained during our investigation.

A. PACMAN (Completed)

In our recent work, we proposed a near real-time system PACMAN, for non-intrusive (using room temperature) prediction (prior-usage) and estimation (post-usage) of AC energy consumption [11]. Building on the existing thermal model [12], we proposed an end-to-end architecture to map ambient information with AC energy consumption that otherwise would require plug-level monitoring. To empirically validate the performance of PACMAN, we conducted an in-situ study across seven homes in Delhi (India). We collected around 2200 hours of usage data from the different ACs, room types, and thermostat temperatures. We achieved an average accuracy of 85% and 83% with the best accuracy of 97% and 93% for the estimation and prediction of AC energy consumption respectively, across all homes. Besides, our investigation also opened up some concrete problems for future work in the domain and presented various use cases of the learned thermal model:

1) Fault detection in AC.
2) Optimal control of AC to reduce energy consumption.
3) If fused with smart meter data, it can improve disaggregation accuracy for NILM algorithms [13].
4) Identifying changes in the thermal behavior of the room (e.g. detecting that the door/window has been left on while AC is running) and prompting the occupant for an impact of such actions.

During this study, we realized the impact of various factors on the room temperature that affect our prediction and estimation accuracy. Thus, we planned a controlled experiment to dig further in this domain.

B. Controlled Experiments (Completed)

In our second work, we performed controlled experiments in an apartment to understand the impact of different activities on the AC's energy consumption. To normalize the effect of external temperature, we divided the day into 1-hour windows while performing various activities; (1) Door/Windows being open/close, (2) Other appliances (fans/lights) running in the room, (3) Presence of occupants and their activities, (4) Changing AC settings and sensor position. Based on the insights from these experiments, we learned that sensor position plays a crucial role in deciding user comfort and AC energy consumption.

C. Optimized Control of AC (Ongoing Work)

Motivated by the results of controlled experiments, we are currently working on optimized control of AC. In decentralized ACs, thermostat (while sitting inside the AC) majorly drives its control logic. However, internal thermostat is an incorrect representative of occupants' comfort (as occupant in some other part of the room). Therefore, we aim to find optimal sensor location in the room to reduce AC energy consumption without compromising on occupants' comfort. As the control algorithm of AC is proprietory to the manufacturer, any change in that would require hardware changes in the AC. However, our ongoing work also plans to smartly switch between thermostat temperature to generate custom compressor cycles of AC, to maintain user comfort from any location in the room (outside the AC).

D. Future Work

Till now, we have been exploring the residential space by generating feedback for both manual control and automated control to optimize on AC energy consumption. Next, we plan to explore small-scale commercial buildings and develop thermal models for multiple AC units. We wish to understand the impact of coordinated scheduling of these units on overall energy consumption and occupants' comfort. Anomaly and fault detection have been well studied for HVAC systems; however there still exist open problems to be worked upon. Anomaly/fault detection is a challenge in both residential and small-scale commercial buildings. Therefore, we plan to investigate this sub-problem in both the domains, leveraging thermal models and knowledge from residential space, developed by that time. To conclude our study and understand its impact in terms of energy consumption, we also plan to validate our results by doing behavioral studies in real-world.

IV. Conclusion

In conclusion, we presented our initial efforts as PACMAN to map ambient information with the energy consumption of ACs. In our first work, we also identified various open problems and use cases for the domain. We then performed controlled experiments in an apartment with AC to understand impact of various settings and activities on the performance of AC. Based on the insights, our ongoing work plans to optimize control of AC using smart devices such as Tado[1]/ Sensibo[2] to reduce AC energy consumption while maintaining user comfort. In initial phase, we implemented our approach in form of simulations. Next, we plan to validate the same using the real-world experiments. For effective usage of AC, we also plan to work on anomaly detection in decentralized ACs. We first plan to investigate various kind of possible anomalies together with existing literature done in this context. We also plan to deploy sensors across small-scale commercial outlet for the better understanding of the problem. Towards the end, we plan to do an in-situ deployment to understand impact of our proposed approach in terms of energy savings.

[1]https://www.tado.com/en/

[2]https://www.sensibo.com/

V. Acknowledgement

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