Inverting HVAC for Energy Efficient Thermal Comfort in Populous Emerging Countries

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ABSTRACT

Emerging countries predominantly rely on room-level air conditioning units (window ACs, space heaters, ceiling fans) for thermal comfort. These distributed units have manual, decentralized control leading to suboptimal energy usage for two reasons: excessive setpoints by individuals, and inability to interleave different conditioning units for maximal energy savings. We propose a novel *inverted* HVAC approach: cheaply retrofitting these distributed units with "on-off" control and providing centralized control augmented with room and environmental sensors. Our binary control approach exploits an understanding of device consumption characteristics at on/off and factors this into the control algorithms to minimize consumption. We implement this approach as HAWADAAR in a prototype 180 ft^2 room to evaluate its efficacy over a 7-month period experiencing both hot and cold climates. We collect enough evidence to plausibly scale this evaluation, demonstrating countrywide benefits: with just 20% market penetration, HAWADAAR can save up to 6% of electricity per capita in residential and commercial sectors — resulting in a substantial countrywide impact.

CCS CONCEPTS

•**Computer systems organization → Sensors and actuators;**

KEYWORDS

thermal comfort, energy efficiency, inverted HVAC

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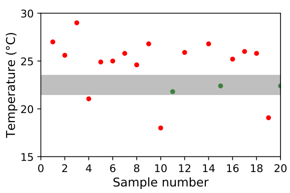
1 INTRODUCTION

We are in an era of global warming, with most studies indicating excessive use of energy being its leading cause. By most accounts, the greatest contribution to global energy expenditure and the ensuing green house gasses will come from emerging Asian countries [12, 25], such as China, India, Pakistan, and Bangladesh that in combination account for nearly half of the world population [13]. With their economic upsurge, the energy demands of these countries are rapidly rising; thermal comfort of built spaces making a significant proportion. It is projected that there will be a tenfold increase in the world consumption of energy for cooling by 2050 [20]. Thus, for example, China alone is expected to surpass the USA by 2020 as the world's biggest consumer of electricity for air conditioning estimated at a trillion kWh [11].

With the late uptake of efficient thermal comfort systems (like HVAC) in these regions, the majority of buildings still employ room-level units — such as window or split ACs, space heaters, ceiling, and sometimes ventilation fans (see Figure 3 for a typical room) — for thermal comfort. These buildings will be maintained for several decades with at least 80% to last beyond 2050 [19, 26], considering housing needs, economic constraints, as well as heritage protection. The challenge is compounded with the continental climate in most countries in the region, which is characterized by extreme temperature variations, both daily and seasonally. Consequently, this extreme climate also results in *excessive* energy usage.

Anecdotally, room occupants set these distributively controllable units to exceed appropriate temperature creating the kind of indoor environment in which occupants wear sweaters and use blankets in July [10]. We validate this observation by a survey of temperature readings shown in Figure 1; the data validating that a distributive approach to temperature setting results in inefficiency. These aggressive setpoints stem from i) a psychological reaction to outside



(a) Winters (b) Summers

Figure 1: Temperature measurements from randomly sampled rooms in the administrative and residential complexes of our university with room-level conditioning units: Temperatures often kept too high in winters or too low in summers with neither the incentive nor the capability to achieve thermal comfort at low energy budget. Our goal is to push these red dots into the shaded region (recommended range). Energy saving is a reward.

temperatures (which can be extreme), ii) possibly inappropriate AC sizing for the room resulting in insufficient comfort at a person's location in the room, or iii) a lack of per device thermal control (space heater without thermostat). Furthermore, these excessive settings also fail to meet conditioning standards [4], thus being detrimental for the health of the individual.

We propose a novel approach to solve this geographically unique problem; *distributed room-level conditioning* governed by a standards-compliant control abstraction, the *centralized building-level thermostat*. This is achieved by adding "smartness" to existing devices to maintain thermal comfort whilst saving energy. This approach is interesting as an inversion to the HVAC approach to managing thermal comfort: a *centralized conditioning* unit, the AHU, that distributes air to zones controlled by individual thermostats.

We present HAWADAAR[1], as an implementation of this inverted HVAC approach to evaluate its efficacy. HAWADAAR has three novel aspects that set it apart from the existing literature. First, its ability to interleave several modes of achieving thermal comfort — such as cooling using an AC, an evaporative cooler, or through air circulation using a fan — with an objective to minimize electricity consumption. Second, its *adaptive* two-position control strategy that intelligently orchestrates these units, accounting for thermal impacting factors such as internal and external thermal loads, room insulation, and device characteristics (transients and short cycling). Third, its ability to handle a wide variety of heating and cooling devices to deliver thermal comfort across a wide range of weather conditions 24/7 all year around.

Our work, thus, has the following significant contributions.

Inverted HVAC Approach: We present an approach that employs a centralized control abstraction to efficiently air-condition existing buildings, lacking HVAC, on a per-room basis. This approach to implementing thermal comfort is novel and especially pertinent to the socioeconomic and climatic constraints of emerging countries. We elaborate this approach and its IoT-inspired architecture in Section 2.

[1] local slang for *ventilated and (air) conditioned space*.

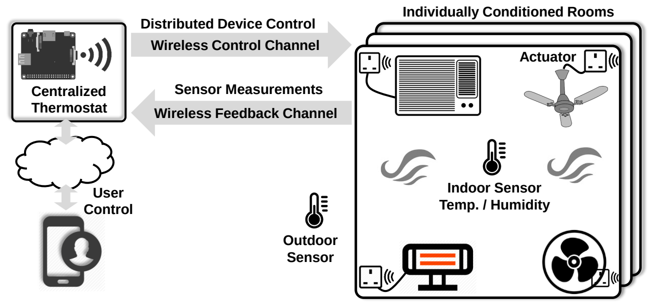


Figure 2: Inverted HVAC architecture: IoT retrofitting for distributed conditioning via a centralized control abstraction, to improve thermal comfort and energy efficiency of legacy buildings.

Control Algorithms: We introduce intelligent control algorithms for the centralized thermostat. These algorithms are based on empirical and theoretical understanding of the (conditioning) device constraints (Sections 3), as well as factors impacting thermal conditioning, such as modes of heat transfer, room insulation, and perceived thermal comfort (Section 4).

System Evaluation, micro and macro scale: We perform extensive micro and macro-scale experiments on HAWADAAR prototype to demonstrate a) in Section 5, the efficiency of our algorithms in achieving setpoints ($<\pm 0.5°$C tolerance) with energy savings (at $<50\%$ duty cycle), and b) in Section 6, extending these results to countrywide scale in terms of the projected savings (6% per capita) for a given penetration (20%) of a HAWADAAR-like system .

We discuss related work along with future outlook in Section 7 before concluding the paper in Section 8.

2 HAWADAAR: THE INVERTED HVAC

We now describe HAWADAAR in detail to elaborate the inverted HVAC approach and its IoT-inspired architecture. We will then present setup details of a prototype system for a single room.

2.1 What's an Inverted HVAC?

The *inversion* of HVAC approach in our proposed system stems from the inversion of the location of control and conditioning units. We propose to use a set of disparate and distributed conditioning units to enforce control from a central location for an alternate to modern HVAC systems. This approach makes sense only when viewed in the context of the socioeconomic background we advocated earlier: populous emerging economies with widespread installation of room-level units where fitting HVAC is cost prohibitive. The novelty of our approach lies in identifying this unique opportunity.

The implementation of this approach, as shown in Figure 2, extends an IoT-inspired architecture that involves augmenting every installed unit[2] with wireless on-off control and distributively sensing temperature and humidity through a wireless back-channel (direct or multi-hop). A centralized hub-like device hosts a software based control abstraction, the *centralized thermostat* (CT), to trigger room-local control for the entire building. The CT can be configured

[2] ACs, heaters, ceiling and ventilation fans, personal comfort devices.

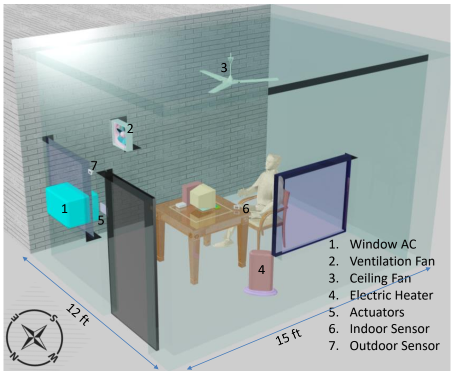


Figure 3: Hawadaar Deployment setup: A typical office room (180 ft^2) with legacy devices (1-4) and IoT retrofitting (5-7). The roof and three walls are exposed to elements.

on a per room basis by a user (e.g., the building owner), through a smartphone app, to either deliver a *setpoint* or *personalized comfort* — based on ASHRAE's personal comfort metric (PMV) [4] — within respective, standards-compliant comfort bounds. Further indoor sensors can be added to improve the per room sensing reliability and coverage; however, we emphasize on minimizing retrofitting costs assuming that the indoor sensor is deployed at a pertinent location where the required thermal objective has to be achieved. Additionally, an outdoor sensor is required for estimating a room's heat transfer coefficient (see Section 4.3) for intelligent actuation. For global access and refactoring into other applications (e.g. smart grids), the CT can be hosted in the cloud where an appropriate API layer can expose its control and measurements to user applications.

2.2 A prototype implementation of Hawadaar

We now present a practical realization of the inverted HVAC — Hawadaar — to demonstrate and then evaluate the efficacy of this approach. Figure 3 shows our deployment in a 180 ft^2 room equipped with multiple air conditioning units (fan, AC, space heater). This room is representative of closed spaces in the developing world, where all or a subset of these appliances are present. Our room-level evaluation can thus be extrapolated to homes, apartments, hotels, office buildings, etc. Furthermore, this room has three external facing walls and roof exposed to the elements, representing a challenging scenario for conditioning the room.

We reduce the retrofitting complexity by choosing to control each device with a COTS[3] smart-plug [32], that cost as low as \$2 when ordered in bulk. The existing device sockets are inserted into these plugs[4]. For convenience, we choose Z-wave based plugs [32] and temperature and humidity sensors [33]. We emulate our centralized thermostat using a Z-wave dongle attached to a RPi with all our control algorithms implemented on it. Thus, depending upon the magnitude of supply order, the current retrofitting cost per room with three conditioning units could be as low as \$10 including smart-plugs, sensor, and the amortized cost of CT.

[3]commercial off-the-shelf
[4]AC might additionally require a relay in between to cater for high surge currents.

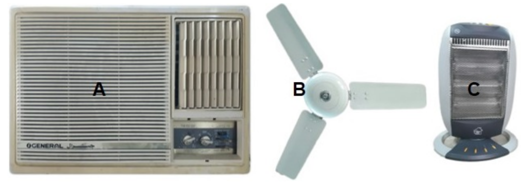


Figure 4: Air conditioning units under consideration: A) single unit window AC with 1-ton cooling capacity; B) ceiling fan with sweep size of 36 inches; C) electric space heater with three halogen elements.

We choose an arbitrary location for the sensor, i.e, the wall opposite to the AC when doing setpoint based control, similarly on the desk next to the fictional occupant in Figure 3 for PMV based control. This sensor, being wireless, can be placed at any appropriate location and, thus, the above evaluation is sufficient. These (one-per-room) sensors report their values once per minute to the CT.

We note that our plug-based retrofitting limits our control to simple on-off for each device, and can introduce issues with regards to device safety if the control algorithm does not have appropriate hysteresis. Entirely for this purpose, we evaluate device constraints in the next section and use them to tune our algorithms in Section 4 to prevent energy waste as well as wear-and-tear.

3 DEVICES AND CONSTRAINTS

We first highlight thermal characteristics of air conditioning devices under consideration, then briefly review what device constraints are relevant and how they impact control, and subsequently derive these constraints empirically.

3.1 Air conditioning units under consideration

Figure 4 depicts the three devices currently employed by Hawadaar for distributed conditioning. With a 1-ton cooling capacity, the single-unit window AC provides *convective* cooling through a single-stage heatpump. In our setup, we position the setpoint of the AC's onboard thermostat to its minimum value, thus allowing Hawadaar to independently control the AC (without altering the control circuitory) for setpoints above this minimum value. The electric heater implements *radiant* heating through its three halogen elements, each consuming 400W. When tested under cooling and heating loads greater than 10°C, the minimum and maximum room temperatures achieved through the AC and heater are 18°C and 26°C, respectively. Both these values fall well outside the comfort zones for the respective seasons (see Section 5.2.2), thereby, already highlighting the potential of energy conservation through duty cycling; more so in the case of an electric heater without thermostat. The ceiling fan has a sweep size of 36 *inches* and can be regulated at five different speeds, with a maximum air velocity of 3.77 ms^{-1}. We set the fan speed to its maximum for on-off control by Hawadaar. While the fan only provides air movement, the AC and heater impact both temperature and humidity.

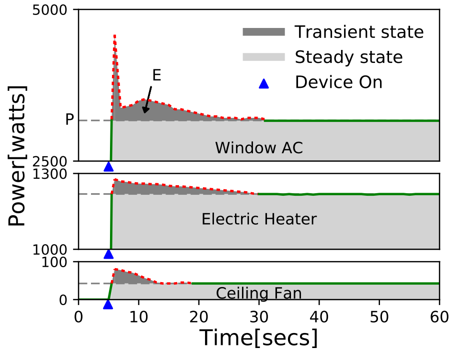


Figure 5: Transient vs steady state power consumption.

3.2 Relevant constraints and their impact

How accurately can HAWADAAR *maintain a setpoint?* This depends on how aggressively can it actuate the respective air conditioning devices. For example, in cooling, two-position control is achieved by switching a device *on* at temperatures exceeding T_{on} and *off* at temperatures below T_{off}, and ideally T_{on} should be identical to T_{off}. However, such a strict thermal objective is not achievable due to *deadband* requirement to prevent repeated on-off cycles, as well as two device specific constraints: *transient power* (the increased power consumption at startup) and *short cycling* (actuating it faster than the specified rate). HAWADAAR must be cognizant of these *hard* constraints; otherwise, the former could increase the overall energy consumption of the system and the latter could potentially damage or reduce the life span of a device. Thus, to calibrate HAWADAAR's control algorithm, we study both these characteristics in our setup and calculate the smallest safe interval t_{safe}, the minimum duration between switching the device off and then on. Alternatively, one could pick a large enough t_{safe} to make the algorithm agnostic to such device constraints but this could compromise thermal comfort [5]. The idea is to set t_{safe} to the larger of two intervals, i.e., $max(t_{tp}, t_{sc})$, where t_{tp} and t_{sc} refer to the respective transient power and short cycling constraints.

3.3 Deriving hard device constraints

Figure 5 shows the power consumption of devices in transient and steady state. To avoid the penalty of transient power due to frequent switching, the minimum duration (i.e., t_{tp}) for which a device must remain off is defined by the interval over which the excess transient power equals the power consumed if the device had not been switched off. Thus, we need to switch off for at least long enough that this saved steady state power compensates for the high transient power at the next startup. A longer off duration will indeed translate into power gains. In Figure 5, based on the area under the curve, we compute t_{tp} simply as $t_{tp} = \frac{E}{P}$, where E is the excess transient energy and P is the steady state power consumption. With regard to short cycling, there are no theoretical restrictions on the switching frequency of electric heaters and fans. Whereas, for window ACs, manufacturers specify a minimum off-duration of three minutes [23, 24]. Table 3 enumerates t_{safe} for each device that serves as a *hard* input constraint on the maximum switching frequency of the control algorithm. However, as we notice in Section 5.2.1, this switching frequency is not actuated even for very narrow comfort bounds.

Table 1: Device Constraints: t_{tp} is transient power and t_{sc} is short cycling constraint. t_{safe} is the larger of these two.

Device	t_{tp} (sec)	t_{sc} (sec)	t_{safe} = max(t_{tp},t_{sc})
AC	1.62	180	180
Heater	0.63	-	0.63
Ceiling Fan	4.3	-	4.3

4 THE CENTRALIZED THERMOSTAT

With device constraints clearly defined, we are now ready to build a control abstraction, i.e. the centralized thermostat. The CT allows to configure per room thermal settings through a mobile-app, to either maintain a setpoint or deliver personalized comfort (PMV), within standards-compliant tolerance. Firstly we explain why a reactive control strategy is employed in HAWADAAR instead of model predictive control (MPC) [5]. We then describe our control algorithm and its heat-transfer prediction mechanism, which is needed for the dynamic adaption of comfort bounds (i.e., the tolerance range) based on thermal load.

4.1 Why two-position control?

The CT runs an intelligent control algorithm that performs *adaptive* two-position control: dynamically adjusts the *soft* constraint (comfort bounds) around a fixed setpoint to satisfy the *hard* device constraints. We use this simple reactive control strategy instead of a complex model predictive approach for three key reasons: First, unlike centralized HVAC taking tens of minutes to take effect, these room-level conditioning units affect human comfort immediately [18]. Second, room insulation levels in older buildings are suboptimal, thereby requiring an immediate response to deliver adequate thermal comfort. Finally, a reactive control strategy is inherently sensitive to changing thermal loads; for example, air conditioning will run for longer if there are more occupants than usual in the room. This eliminates the need for complex thermal load estimations, further simplifying our pilot system design.

4.2 Algorithm: adaptive two-position control

We first describe the algorithm in the context of maintaining a setpoint and later extend our description to delivering personalized comfort. We do not make any assumptions regarding the relative humidity and use *heat index* (a.k.a. "apparent temperature" or "feels like") as our temperature metric. Thus, a setpoint is defined in terms of heat index; not the ambient temperature. Hence, before making a control decision, the temperature value is first converted into its corresponding heat index (HI), which is calculated as follows:

$$HI(T,R) = c_1 + c_2T + c_3R + c_4TR + c_5T^2 + c_6R^2 + c_7T^2R + c_8TR^2 + c_9T^2R^2 \quad (1)$$

Where T is the air temperature, R is relative humidity, and c_n are Rothfusz regression constants [28]. For brevity, we use the general term "temperature" (instead of heat index) to simplify the description of our algorithm.

Algorithm 1: Setpoint based adaptive two-position control.

```
Input: desrired setpoint (T_s), tolerance
while True do
    T_in ← read_sensor()
    T_on ← T_s + tolerance/2
    T_off ← T_s − tolerance/2
    if T_in > T_on then
        switch_on(AC)
    else if T_in ≤ T_off then
        predicted_temperature ← T_{t_off + t_safe}
        if predicted_temperature ≤ T_on then
            switch_off(AC)
            update(prediction_parameters)
            reset(tolerance)
        else
            extend_tolerance(tolerance)
```

4.2.1 *Setpoint algorithm.* To begin, the algorithm needs two inputs, the required setpoint T_s and comfort bounds (soft constraint); the latter defines two control positions T_{off} and T_{on} symmetrically around T_s. Thus, with a cooling device, in order to achieve T_s as the average temperature, we must satisfy $T_{t_{off}+t_{safe}} \leq T_{on}$, i.e. once the device is turned off, the temperature after the minimum safe off duration t_{safe} (hard constraint) will not exceed T_{on}. This may, depending upon the thermal load, require the algorithm to symmetrically extend the tolerance range on both sides of T_s, as described in Algorithm 1. For this, the algorithm needs to predict at time t_{off} (cf. Secton 4.3) the temperature at time $t_{off} + t_{safe}$ in order to decide whether to turn off the device or extend the tolerance range to meet the hard constraint. With a minor adjustment, i.e. by swapping T_{off} with T_{on}, this algorithm is also used to actuate a heating device.

4.2.2 *PMV algorithm.* The same baseline algorithm is used for delivering personalized comfort with the following two extensions: First, the thermal constraint is not the heat index but PMV described as follows:

$$PMV = f(M, T_a, T_r, v, P_a, I_{cl}) \tag{2}$$

Where, M is the metabolic rate of the occupant (assumed $70W/m^2$ for an office worker); T_a is the air temperature; T_r is the mean radiant temperature (set equal to T_a); v is the relative air velocity in m/s^{-1}; P_a is the relative humidity; and I_{cl} is the clothing insulation factor of the occupant (set to 0.6 *clo* assuming a usual office dress code of a long sleeved shirt with trousers). In our work, we assume some of these parameters to calculate PMV and realize that in practice these are difficult to accurately ascertain; however, this does not affect the fidelity of the results. Second, while the heat index based setpoint only utilizes the heater and AC, additional factors in equation 2, such as air movement, also allow us to use the ceiling fan for maintaining a desired PMV level. Thus, as described in Algorithm 2, we program the CT to prioritize the use of low-energy fan, and only turn on the AC when air circulation alone cannot keep the PMV within the required comfort bounds.

Algorithm 2: PMV based two-position control.

```
Input: comfort_range, set of on devices (ON)
while True do
    calculate(PMV)                              // see equation 2
    if PMV > upper_bound then
        if ON= ∅ then
            v ← AIR_VELOCITY_fan
            calculate(PMV)
            if PMV ∈ comfort_range then
                ON ← ON ⊎ fan                   // switch-on fan
            else
                v ← AIR_VELOCITY_AC
                ON ← ON ⊎ AC                    // switch-on AC
        else if fan ∈ ON then
            ON ← ON \ fan                       // switch-off fan
            v ← AIR_VELOCITY_AC
            ON ← ON ⊎ AC
    else if PMV ≤ lower_bound then
        ON ← ∅                                  // switch-off all devices
```

4.3 Predicting the room's heat transfer rate

The room's heat transfer depends upon both external and internal thermal loads. The external thermal loads result in heat transfer through the building envelope from external elements such as the sun, the earth, and the outside environment. While, internal thermal loads come from heat generated within the room by people, lighting, equipment etc. As discussed in the previous section, in order to satisfy the hard constraint, the CT needs to predict the temperature $T_{t_{off}+t_{safe}}$. The prediction model should thus account for both external and internal thermal loads whilst being simple and self calibrating. We note that the maximum duration of this prediction, in our setup, is just three minutes imposed by the AC. This, by the way, also provides a maximum theoretical duration of discomfort. Since we dynamically update our prediction parameters, as discussed below, our system can repeatedly fix prediction errors.

Instead of developing a complex thermal model for the room, we use realtime sensor measurements to glean the heat transfer coefficient using Netwon's law of cooling as a first approximation. A similar strategy has also been employed in a personalized comfort system [18]. According to the law, "the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings". Thus, given an outside temperature T_{out} and room temperature T_{in}, the rate of thermal energy loss for the room is proportional to the temperature difference:

$$\frac{dT}{dt} = -k(T_{in} - T_{out}) \tag{3}$$

We set $T = T_{t_{off}+t_{safe}}$, $T_{in} = T_{off}$ and $t = t_{safe}$ and solve the above equation to estimate a room's heat transfer coefficient (k):

$$k = \frac{\ln \frac{(T_{t_{off}+t_{safe}} - T_{out})}{(T_{off} - T_{out})}}{t_{safe}} \tag{4}$$

However, we repeatedly update k just before T_{on} (i.e., when all the devices are off), aiming for an *aggregate account of both external and internal thermal loads* using a single heat transfer coefficient

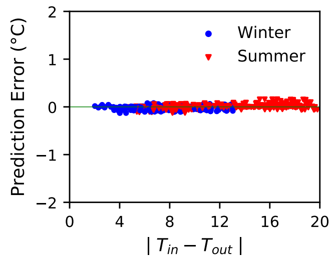


Figure 6: Prediction accuracy: our simple model achieves high accuracy with a root-mean-square error of 0.18°C.

(k). The sensed $T_{t_{off}+t_{safe}}$ in round n is used to calculate the k value to predict $T_{t_{off}+t_{safe}}$ in round $n+1$ as follows:

$$T_{t_{off}+t_{safe}} = T_{out} + (T_{off} - T_{out})e^{-kt_{safe}} \tag{5}$$

Figure 6 depicts the accuracy of our prediction mechanism for numerous samples over a wide range of indoor and outdoor temperature differences. We can easily conclude that this model is sufficiently accurate for a reactive control strategy with a maximum required prediction length of just three minutes.

5 EVALUATING THE DEPLOYMENT

Our pilot deployment seeks answers to two fundamental questions regarding a thermal comfort solution: i) *How comfortable is it?* and ii) *what are its energy benefits?* To answer the first question, we evaluate the minimum temperature tolerance (*best effort* service) required to operate HAWADAAR. This best effort service is also relevant to satisfy high comfort requirements of a demanding user and to stress test Algorithm 1. To answer the second question, we compare energy consumption in multiple settings. For example, when varying tolerance around a fixed setpoint; when exceeding appropriate temperature settings, based on our anecdotal observation substantiated in Figure 1; and by interleaving devices of variable energy consumption, as in Algorithm 2.

Although our deployment setup is in place since November 2016, here we only report results from experiments during two challenging weather spells occurring between Jan. 25 - Jan 28, 2017, and May 1 - May 15, 2017, respectively. Throughout these experiments, the room occupation varied between 0 (at night) to at most 3 (during the day) occupants.

5.1 Thermal comfort: the best effort service

This part of the evaluation corresponds to the adaptive control that minimizes the tolerance range ($|T_{off} - T_{on}|$) whilst satisfying hard device constraints. Thus, as described in Algorithm 1, the off-time of a device is fixed at t_{safe} while the on-time (duty cycle) is a function of thermal load at a certain instant of time. We expect the algorithm to minimize its tolerance range, given the device constraint (t_{safe}), such that $\frac{T_{off}+T_{on}}{2}$ is always approximately equal to the required setpoint (T_s). In other words, we want our system to achieve two goals: (i) dynamically adapt the tolerance range and thus the duty cycle based on the thermal load, and (ii) deliver an average temperature — in terms of heat index — that does not deviate from the required setpoint. An inaccurate temperature prediction at T_{off} could potentially lead to such deviations. Figure 7 verifies the fidelity of our algorithm and its temperature prediction under varying but high external thermal loads, when the setpoint is kept near the middle (24°C) of ASHRAE's specified comfort range for summers. We can clearly see that HAWADAAR achieves its goals by successfully adapting the tolerance range oscillating around the setpoint. Even at such high thermal loads, HAWADAAR is able to maintain a temperature tolerance of just ±0.4°C (see Figure 7 for 3PM onwards). Since the AC has the longest t_{safe}, these results represent the *worst case* of this best effort service.

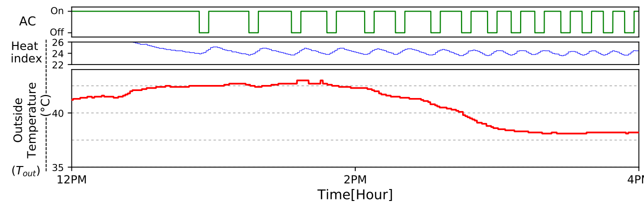


Figure 7: The best effort service: HAWADAAR successfully adapts the thresholds of its two-positions symmetrically oscillating around the setpoint. The heat index reflects the room temperature.

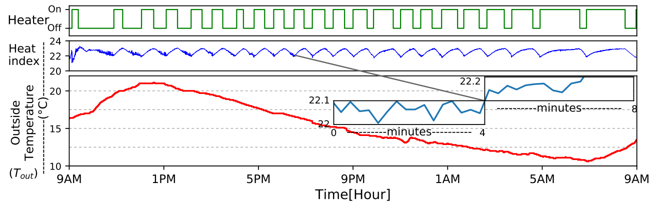
5.2 Quantifying energy benefits of HAWADAAR

The are two main aspects of HAWADAAR's implementation that bring about its energy benefits. First, its standards-compliant thermal comfort resulting in aggressive duty cycling of single units. Second, when available, its ability to prioritize low power devices. This section evaluates these two aspects of energy efficiency in multiple thermal settings.

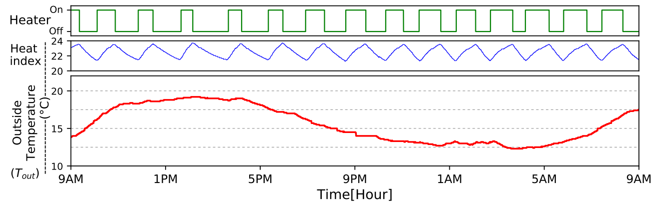
Comparing energy savings in an experimental setting is not straight forward, as each day has its own parameter variations that affect how much energy should be spent to cool or warm a room. To draw logical conclusions, we still try to make approximate comparisons between days with similar average air temperature while minimizing the variance among internal thermal loads.

5.2.1 When varying tolerance around setpoint. We want to see if changing the tolerance level around a fixed setpoint affects the energy efficiency of the system. We use two tolerance ranges: ±0.5°C and ±1°C, thus satisfying category A (2°C) of ASHRAE's comfort requirement in terms of temperature deviation [4]. We keep the setpoint approximately at the middle of the comfort range: 22.5°C in winters and 24°C in summers, as depicted in Figure 8. For this part of the evaluation, the indoor sensor is placed on the wall opposite to the window sill, where the AC is installed (cf. Figure 3). We make the following key observations:

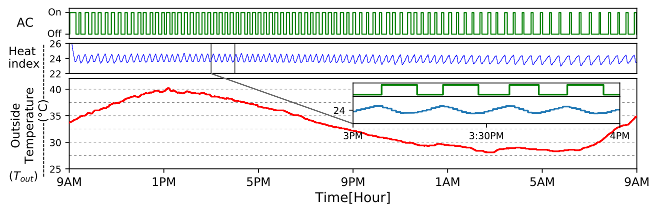
The nature of the heat transfer mechanism results in different thermal behaviors. The rise and fall of room temperature is gradual in winters (cf. Figures 8(a) and 8(b)) but rapid in summers (cf. Figures 8(c) and Figures 8(d)). In other words, the *period* — one complete on-off cycle — is larger for the heater in comparison with the AC as a consequence of the heat transfer mechanism. For the AC, cooling occurs through air convection. This can be short-lived after the AC is switched off as the air absorbs heat from the surrounding objects including external walls rapidly. For the heater, radiation is the physical mechanism of heat transfer, both in the



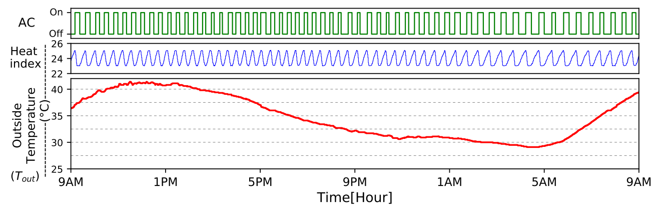
(a) Winter, January 25th (±0.5°C tolerance)



(b) Winter, January 27th (±1°C tolerance)



(c) Summer, May 8th (±0.5°C tolerance)



(d) Summer, May 10th (±1°C tolerance)

Figure 8: Setpoint evaluation: Results are shown for two tolerance levels. The heat index reflects the room temperature. The thermal behavior in winters and summers is different due to the nature of heat transfer mechanisms: *convection* for AC and *radiation* for heater. The latter yields higher energy savings with wider temperature tolerance around the setpoint.

Table 2: Daily energy savings of HAWADAAR through aggressive duty cycling of single units. Savings from AC are not applicable in this particular case as we expect the AC's onboard thermostat to achieve similar results for the same temperature settings.

Tolerance	On-time (hours/day)		Energy Consumption (kWh/day)		Energy Savings (kWh/day)	
	Heater	AC	Heater	AC	Heater	AC
±0.5	14.42(60%)	9.3(38%)	17.5	31.35	11.6	–
±1	11.26(47%)	9.27(38%)	13.6	31.15	15.5	–

form of visible and non-visible light, and effects all the surrounding objects not just the air. This process of heating is slower but longer lasting after the heater is switched off as the room air continues to absorb heat from heated objects maintaining a residual warm air temperature.

The nature of heat transfer has a contrasting impact on energy efficiency of HAWADAAR over different tolerance levels. Table 2 summarizes the energy consumption and total on-time of devices per day. In winters, we can see that the on-time of the heater is reduced by approximately 3 hours when the tolerance increases from ±0.5°C to ±1°C. In contrast, in summers the AC on-time per day is similar for both tolerances. There are two reasons: First, the "slow start" of radiative heating makes it less efficient for frequent switching, as this increases the number of times the cold halogen element will have to be reheated (see magnifier in Figure 8(a)). Second, as described above, the ability of radiative heating to sustain the air temperature for longer durations given a larger tolerance range.

As an aside, duty cycling of the heater at ±0.5°C daily saves a further 11.6 kWh (40%) compared with continuous operation. Since ACs have onboard thermostats that already duty cycle, assuming similar setpoints and tolerance, such savings are not applicable.

5.2.2 When exceeding appropriate temperature settings. We now want to highlight the energy benefits of HAWADAAR due to its ability to implement centralized policies, thus prohibiting excessive use of

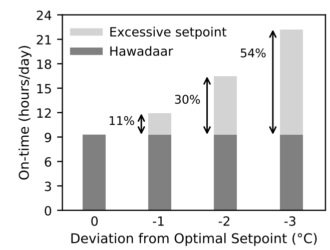
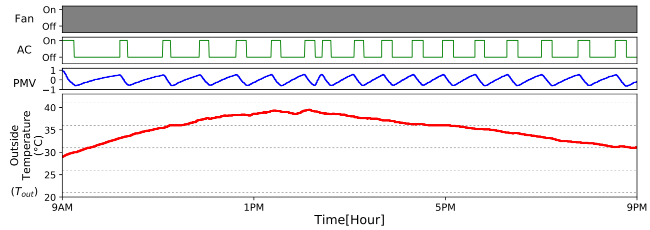


Figure 9: Optimal vs excessive: The standards-compliant HAWADAAR saves energy by prohibiting excessive setpoints.

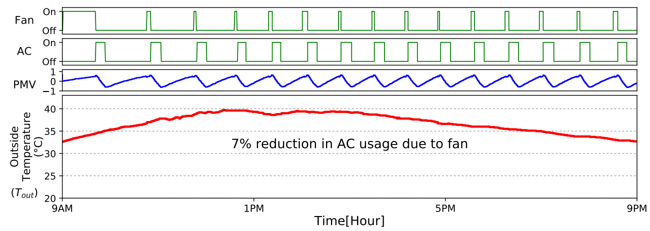
conditioning units. This refers back to our anecdotal observation in Section 1. Figure 9 shows how the AC on-time increases when the setpoint veers from optimal (24°C) to excessive (23, 22, and 21°C). We can see that even a single degree deviation from the optimal setpoint increases the on-time by 11%, which translates to ≈5 kWh per day. Similar observations, in the context of centralized HVAC, have been reported in [22]. These results clearly reiterate the need for an HAWADAAR-like solution to implement centralized policies in regions, where the excessive and unhealthy use of conditioning units puts tremendous load on their stressed power grids.

5.2.3 By interleaving devices of variable energy consumption. We now turn our focus on HAWADAAR's energy efficiency when thermal comfort is defined in terms of PMV. The idea is to evaluate the energy benefit of interleaving low-power ceiling fans. We measure this impact for ASHRAE's recommended range of PMV (-0.5 < PMV < 0.5) during two noticeably different weather conditions occurring at different times of the day in hot summers.

Day time results. Figure 10 shows results for maintaining PMV with (Figures 10(b)) and without (Figures 10(a)) a fan during hot daytime. We can observe that, under challenging weather conditions, the use of a fan has limited impact on the operational time of the

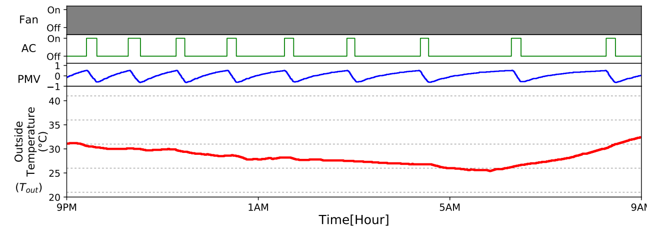


(a) PMV without fan (May 2nd)

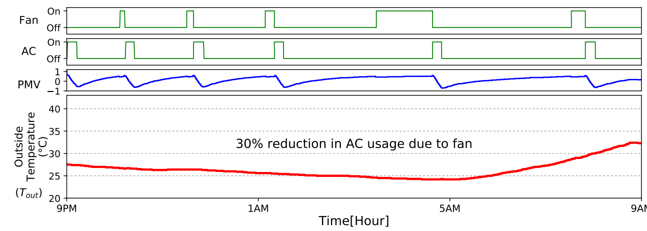


(b) PMV with fan (May 3rd)

Figure 10: PMV evaluation (day): In hot conditions, interleaving a fan has limited impact on AC usage. The fan extends the duration for which PMV remains within specified range without using AC but results in a further rise in temperature, adding to the cooling load of AC.



(a) PMV without fan (May 2nd/3rd)



(b) PMV with fan (May 4th/5th)

Figure 11: PMV evaluation (night): In moderate condition, the AC on-time is significantly reduced (≈30%) due to HAWADAAR's ability to intelligently interleave the fan.

AC, for two reasons. Firstly, the ceiling fan pushes down the hot air that rises up after absorbing heat from surrounding objects, thus increasing air temperature. Secondly, the use of fan extends the duration for which PMV remains within specified range due to air circulation resulting in a further rise in air temperature. This increases the cooling load of AC during hot weather conditions.

Night time results. The impact of the fan is significantly pronounced under relatively moderate weather conditions at night, as can be seen in Figure 11. The prolonged use of ceiling fan helps maintain a desired PMV without the need for a high-power AC, resulting in ≈30% reduction in AC usage. These types of energy optimizations through aggregate usage of devices are highly unlikely through manual operation or device specific thermostat; and definitely not possible at night with occupants asleep.

Overall, with PMV as comfort metric, we record a 15% reduction in AC usage per day, that translates into approximately 2.5 kWh of energy savings after subtracting the power consumed by the fan.

6 ESTIMATING COUNTRYWIDE BENEFITS

To illustrate the energy benefits of HAWADAAR on a countrywide scale, we use the results from Section 5, together with estimates of annual electricity consumption on air conditioners and electric heaters in residential and commercial buildings. We are interested in extrapolating energy savings for an emerging economy that is populous, with a sizeable middle and upper middle class in urban areas living in buildings which can be retrofitted with HAWADAAR, and faces extreme climate with significant temperatures variations in summer and winter months.

The main challenge we encounter in this exercise is the lack of electricity consumption estimates in buildings (residential or commercial), at an aggregate level or by end use, in such a context. To address this, we employ an international benchmarking approach that uses plausible inputs from US electricity consumption surveys, to arrive at conservative estimates of annual electricity consumption in residential and commercial buildings on air conditioners and electric heaters in our typical economy. The inputs and assumptions underlying our projected savings are discussed below.

6.1 Inputs and assumptions

The first input is the annual electricity consumption by end use in buildings in the US as recorded in the *Residential Energy Consumption Survey* (RECS) [14] and *Commercial Building Energy Consumption Survey* (CBECS) [6]. The RECS provides data on annual electricity usage in kWh for residences, while the CBECS provides data on electricity usage in kWh and floor space in square feet for commercial buildings in different climate regions of the US by end use, such as air conditioning and space heating, amongst other uses. The simplifying assumption we make is that US electricity consumption data is representative of electricity usage in emerging economies. There are undoubtedly variations in building materials, appliance efficiency, and engineering systems in the US relative to any developing country, and we should expect the US consumption to be lower when accounting for better technologies for cooling and heating. This would lead us to start out with more conservative estimates of consumption in emerging economies, and thus more conservative estimates of savings. To ensure that consumption patterns due to seasonal variations are similar to our context, we

Table 3: Inputs for estimating total annual electricity saving.

	Average	Hot Humid	Mixed-Dry/Hot-Dry	Mixed-Humid
Residential AC ($kWh/household$)	2442.00	4077.00	1899.00	1777.00
Commercial AC (kWh/ft^2)	3.10	5.34	2.10	2.52
Commercial Heating (kWh/ft^2)	0.34	0.12	0.15	0.52
Population				
Number of households	10 million			
Commercial Floor Space	1000 million square feet			
Penetration Rate	0–50%			

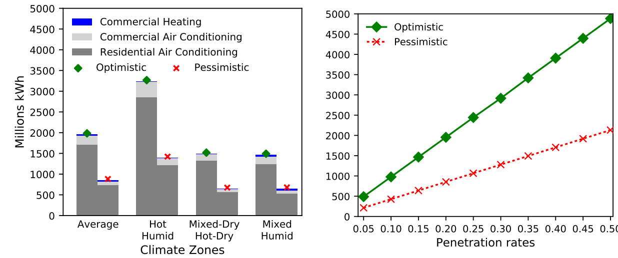
take care to focus only on buildings in hot-humid, mixed-humid, and mixed-dry/hot-dry building regions [5].

The second input is the stock of residential and commercial buildings that can benefit from Hawadaar. We calculate energy savings for a large emerging economy, with significant urbanization. We assume a total population of 250 million persons, urbanization rates of 40%, implying an urban population of 100 million persons. Assuming that half of the urban population lives in buildings where Hawadaar can be used, and average household consists of 5 persons, we have a beneficiary population of 10 million households or residential units. To arrive at estimates of commercial floor space, we use plausible numbers of the density of commercial floor space per capita of various developing countries available from recent research [16], assuming that the stock of commercial floor space is 1000 million square feet.

The third input is the penetration rate of Hawadaar in our beneficiary population. In the base case, we assume that the average penetration rates of Hawadaar for air conditioners is 20%. For electric heaters, we assume 20% penetration in commercial buildings and 0% in residential units, as we expect natural gas based space heating to be predominant in households due to its cheaper cost; currently not supported by Hawadaar.

Finally, based on our empirical results in Section 5, we normalize energy savings emanating from both the key features of Hawadaar: (i) aggressive duty cycling of single units and (ii) interleaving of low-power devices. In the first case, we set energy savings from AC to 35% (cf. Section 5.2.2): This is the *optimistic* case where we assume an average deviation of ≈-2°C from the optimal setpoint based on our anecdotal observation. Hawadaar can preempt such excessive settings to claim its energy savings because it is standards-compliant. In the second case, we assume the energy savings from AC to 15% (cf. Section 5.2.3). This is the *pessimistic* case where we disregard our anecdotal observation and only consider savings from Hawadaar's ability to minimize energy consumption through interleaving low-power devices when using PMV as a comfort metric. We strongly believe that this is the bare minimum benefit of deploying Hawadaar. Finally, in both cases the energy savings from electric heater are set to 40% (cf. Section 5.2.1), assuming no onboard temperature control units and that only commercial buildings use this type of heating.

Our inputs to calculate projected savings are summarized in Table 3. Total savings are found by multiplying the per unit air conditioner and electric heating consumption for different climate zones with savings above, assuming a penetration rate of 20%. We also calculate savings for different penetration rates. With these



(a) By climate zones at fixed Hawadaar penetration rate of 20%.

(b) By varying market penetration.

Figure 12: Countrywide estimates of annual energy savings.

inputs, we calculate very conservative estimates of total savings (cf. Figure 12), which can be considered a lower bound on actual savings that may be realized from implementing Hawadaar.

6.2 Savings and environmental impact

Figure 12(a) shows the countrywide estimate of energy savings by different climate zones at a market penetration of 20%. In the optimistic scenario, savings range from 1462 million kWh to 3237 million kWh, and in the pessimistic scenario, savings range from 645 million kWh to 1393 million kWh. Savings are higher for cooling in humid zones, given the higher consumption per household and per unit area. Similarly, heating consumption and thus savings are higher in climate zones with greater need for heating during the year. Given our assumptions about the population size, residential air conditioning accounts for ≈85%, while commercial air conditioning and heating together account for 15% of total estimated savings. In Figure 12(b) we display the effect of changing the penetration rates on savings for the buildings located in average climate zone. Total savings rise proportionally with penetration rates, as we assume a uniform consumption rate in our population.

To understand the magnitude of total energy savings, we can also express them as a fraction of per capita consumption in the residential and commercial sectors. Assuming an average per capita electricity consumption of 255 kWh in residential and commercial sectors[6], the estimates in Figure 12(a) imply that between 1.15% to 5.76% of electricity consumption in these sectors can be saved with penetration rates of *just* 20%. As we increase the penetration rates from 5% to 50%, the percentage savings range from 0.87% to 8.68% in the optimistic scenario and from 0.38% to 3.79% in the pessimistic scenario. Overall, these projections illustrate that even with very conservative assumptions, Hawadaar can have an economically meaningful impact on consumption at a macro level.

7 RELATED WORK

Efficient operation of HVAC has been at the forefront of existing literature on *energy conservation* [1, 3, 7, 9, 21, 29, 30] and *thermal comfort* [15, 18, 27, 31] in buildings. Energy conservation is typically achieved by incorporating occupancy patterns [1, 7, 21]

[5] These climate regions were created by the Building America program and are meant to capture the differences in climate and building types in different parts of the country. These regions include cities such as Houston, Dallas, Pheonix, Memphis, and Atlanta, which have climate similar to cities such as Mumbai, New Delhi, Karachi, Lahore, Tehran, Dhaka, Beijing, and Cairo.

[6] The average per capita electricity consumption in lower middle income countries ranges from 500 to 1000 kwh per capita out of which approximately 30% is residential and commercial electricity consumption [8]. Using the midpoint consumption of 750 kwh per capita we can conclude that residential and commercial sectors account for 255 kwh per capita of electricity consumption. Then we can express our total savings in per capita terms and find the percent saved.

and thermal load predictions [5, 9] into HVAC operation schedules, or by exercising more fine-grained control, such as room-level air flow control [29] and stage selection in a multi-stage HVAC [30]. Aswani et al. [5] employ similar predictive techniques for the energy efficient operation of a room-level AC only, thereby addressing a subset of problems considered in this paper. Studies focusing on improving thermal comfort of centralized HVAC try to find improved setpoints based on occupants' feedback [15, 31], or by augmenting HVAC with personal devices to create micro thermal-zones around a user for highly personalized thermal comfort [2, 18, 27]. These personal comfort systems nonetheless rely on HVAC to first achieve a building wide setpoint; this facility is not available in our setup.

Our goal to achieve thermal comfort at low energy budget is aligned with existing literature but the nature of challenges we face is inherently different. For example, the type of buildings, the extreme weather, as well as thermal characteristics and location of conditioning units entail us to build more aggressive control strategies, such as the ones employed by HAWADAAR. This paper thus primarily focuses on developing and evaluating these centralized control strategies. While the current implementation of HAWADAAR is oblivious to occupancy prediction (estimating the number of occupants for determining internal thermal load) due to its reactive control strategy, occupancy detection (if and when the room is occupied) is an orthogonal but well-researched problem outside the current scope of this paper. Thus, we do not foresee any inherent challenges in the seamless incorporation of existing occupancy detection solutions in HAWADAAR, to refine its operation schedules and further reduce energy consumption.

The work that comes closest to our idea of interleaving AC and ceiling fan is the collaboration of NEST with a smart ceiling fan company [17]. The key idea is to adjust fan'speed as temperatures rise, allowing to increase thermostat setpoint of a centralized HVAC while still feeling just as cool. However, we observed that for our range of operating temperature and suboptimal building insulation, simultaneous use of AC and fan results in higher average temperature as the fan forces hot air down.

8 CONCLUSIONS

This paper serves as a proof of concept for the fundamental components of an unconventional, inverted HVAC architecture for older buildings in emerging countries. As an alternative to modern HVAC, we proposed IoT-based retrofits to reinforce legacy air conditioning units for policy driven actuation. HAWADAAR is a practical realization of this proposal, demonstrating its efficacy in achieving a *high* level of thermal comfort at *low* energy budget. Our empirical evaluations, when plausibly scaled to countrywide estimates highlight the worthwhile impact of HAWADAAR, providing energy savings that directly translate into reduced carbon emissions in countries that rely heavily on burning fossil fuels for electricity generation. We see a greater value in pursuing this work further not only to widen its impact, such as by including more device types, but also to improve its implementation and algorithmic aspects.

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