COHORT: Coordination of Heterogeneous Thermostatically Controlled Loads for Demand Flexibility

Bingqing Chen, Jonathan Francis, Marco Pritoni, Soummya Kar, Mario Bergés

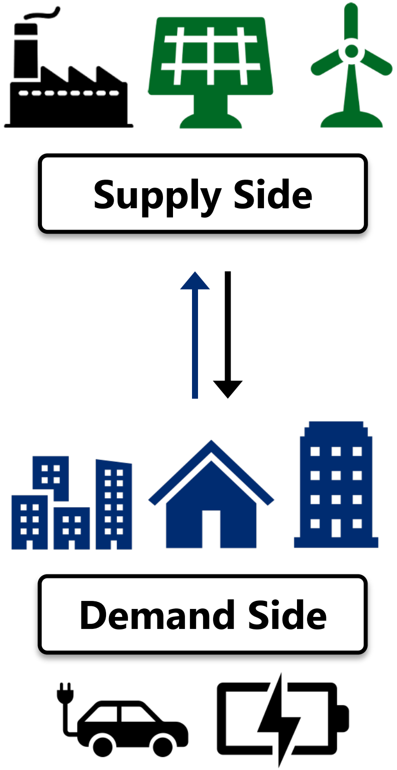
Carnegie Mellon University

Motivation: There are emerging challenges for grid operators to balance supply and demand.

For instance, increasing penetration of **renewable generation** can be problematic, due to its variable and intermittent nature.

Demand-side resources can alleviate these problems through their inherent flexibility.

Vision: **Flexible building loads** autonomously coordinate with each other for efficient, resilient, and robust grid operation.



Carnegie Mellon University

Scope: We focus on thermostatically controlled loads (TCLs), which account for about 20% of electricity consumption in the U.S.

electric water heater

refrigerator

air conditioner (AC)

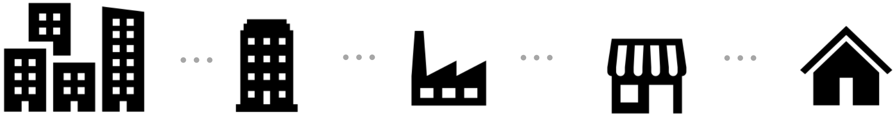
11% of households in the U.S. are already equipped with smart thermostats (King, 2018).

Challenge: Large state-action space

Heterogeneous building loads must be aggregated across a population to be a meaningful resource at the grid-level.

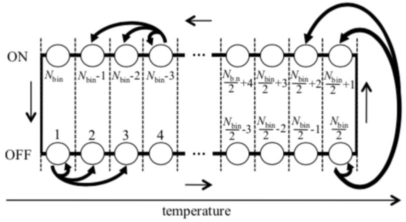
A popular approach in the literature is to develop an aggregate model for the population.

However, these models cannot incorporate detailed dynamics and system-specific constraints.



e.g. At least **0.1MW** / (1kW x 10%) = **1000** ACs

(PJM Interconnection)



State Bin Transition Model

(Koch et al., 2011)

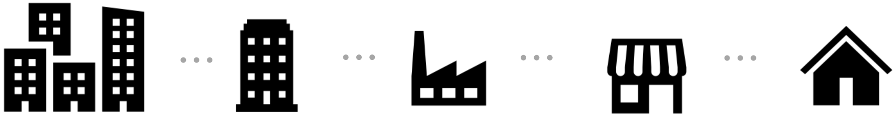
Virtual Battery Model

(Hao et al., 2015; Zhao et al., 2017)

Eric M Burger and Scott J Moura. 2017. Generation following with thermostatically controlled loads via alternating direction method of multipliers sharing algorithm. *Electric Power Systems Research* 146 (2017), 141–160

Challenge: Large state-action space

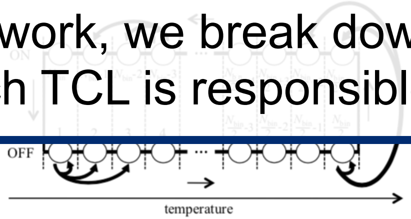
Heterogeneous building loads must be aggregated across a population to be a meaningful resource at the grid-level.



e.g. At least **0.1MW** / (1kW x 10%) = **1000** ACs
(PJM Interconnection)

A popular approach in the literature is to develop an aggregate model for the population.

Using a distributed control framework, we break down the grid-level problem into subproblems, where each TCL is responsible for its own control.



State Bin Transition Model
(Koch et al., 2011)

Virtual Battery Model
(Hao et al., 2015; Zhao et al., 2017)

However, these models cannot incorporate detailed dynamics and system-specific constraints.

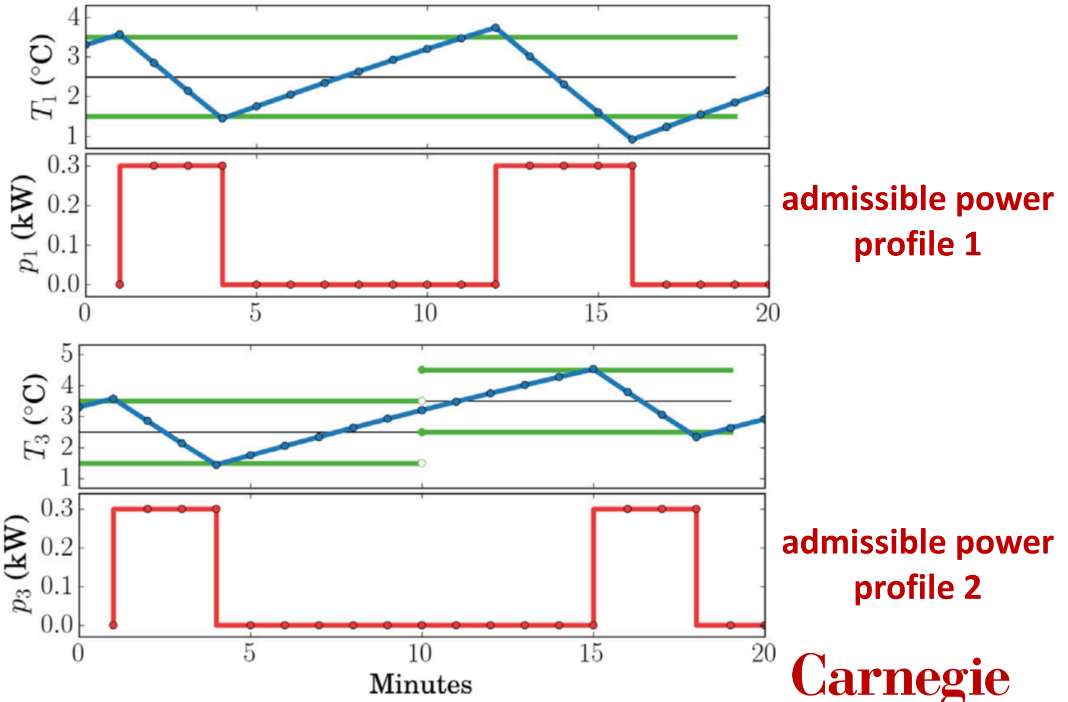
Eric M Burger and Scott J Moura. 2017. Generation following with thermostatically controlled loads via alternating direction method of multipliers sharing algorithm. *Electric Power Systems Research* 146 (2017), 141–160

Challenge: The flexibility of a TCL is combinatorial, and its size grows exponentially with the planning horizon.

Flexibility of a system is defined as the set of all **admissible power profiles** (Zhao et al., 2017).

A TCL operates in discrete action space, i.e. **on or off**.
The flexibility is **coupled over time** through the thermodynamics.

The number of admissible power profiles grows **exponentially** with the planning horizon.



(Burger & Moura, 2017)

Carnegie Mellon University

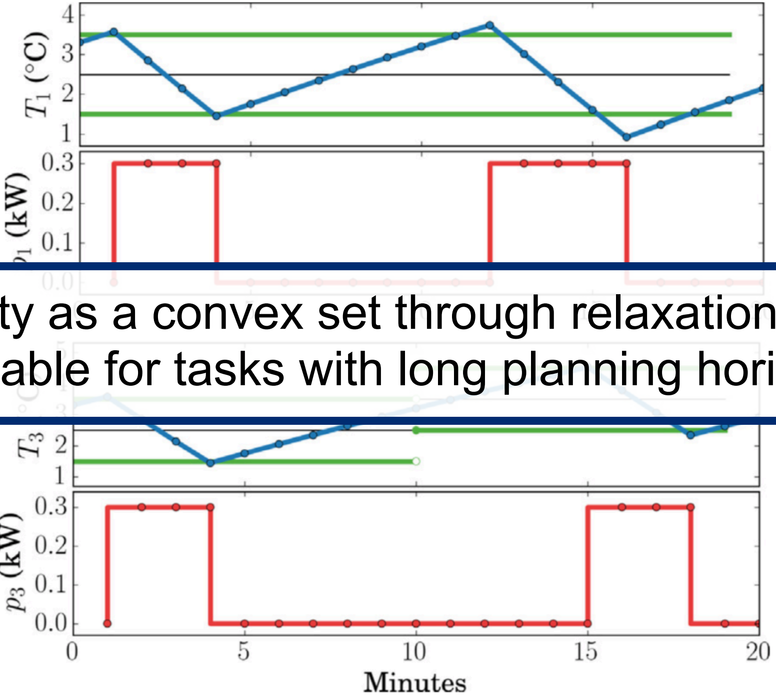
Challenge: The flexibility of a TCL is combinatorial, and its size grows exponentially with the planning horizon.

Flexibility of a system is defined as the set of all **admissible power profiles** (Zhao et al., 2017).

A TCL operates in discrete action space, i.e., on or off.

The flexibility is **coupled over time** through the thermodynamics.

The number of admissible power profiles grows **exponentially** with the planning horizon.



admissible power profile 1

admissible power profile 2

(Burger & Moura, 2017)

We characterize each TCL’s flexibility as a convex set through relaxation, such that COHORT is computationally viable for tasks with long planning horizons.

Carnegie Mellon University

TCL Model and Flexibility

Dynamics

After convex relaxation, the TCL dynamics over a planning horizon can be modelled as a linear system.

$$\underbrace{\begin{bmatrix} 1 & & & \\ -a & 1 & & \\ & \ddots & \ddots & \\ & & -a & 1 \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} T_{t+1} \\ T_{t+2} \\ \vdots \\ T_{t+T} \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} aT_t \\ 0 \\ \vdots \\ 0 \end{bmatrix}}_{\mathbf{x}_0} + \mathbf{B_u} \boxed{\underbrace{\begin{bmatrix} u_t \\ u_{t+1} \\ \vdots \\ u_{t+T-1} \end{bmatrix}}_{\mathbf{u}}} + \underbrace{\begin{bmatrix} T_{a,t} \\ T_{a,t+1} \\ \vdots \\ T_{a,t+T-1} \end{bmatrix}}_{\mathbf{D}} \underbrace{[1-a]}_{\mathbf{b_d}}$$

$\mathbf{u} \in \mathbb{R}^T$ is the power consumption of a TCL over a planning horizon.

Flexibility

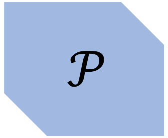
Flexibility is the set of all admissible power profiles that satisfy the end-use requirements and operational constrains.

$$\mathcal{P} = \left\{ [u_{t:t+T-1}] \;\middle|\; \begin{array}{l} x_{k+1} = \mathcal{T}(x_k, u_k); \\ \underline{u}_k \le u_k \le \overline{u}_k; \quad \forall k \in \{t, \ldots, t+T-1\} \\ \underline{x}_{k+1} \le x_{k+1} \le \overline{x}_{k+1}; \end{array} \right\}$$

Thermodynamics

Power Limits

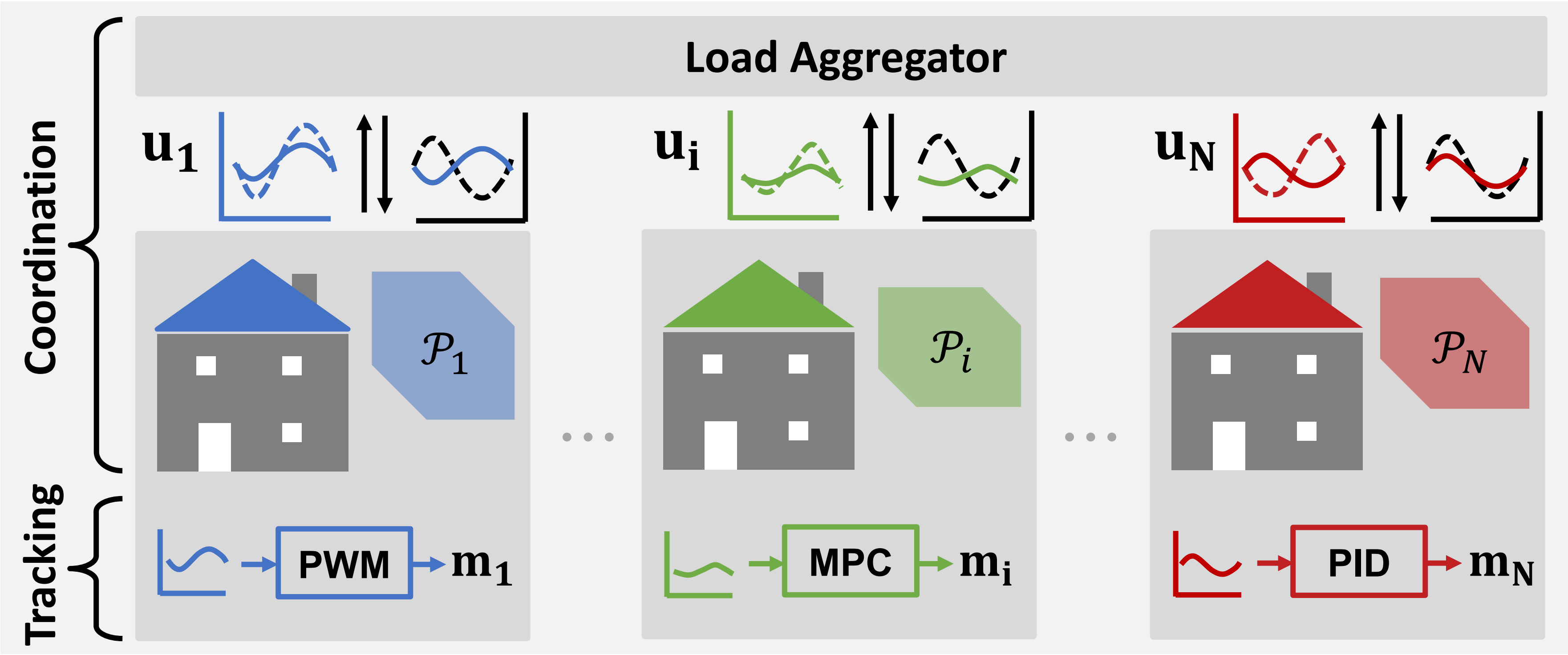
Thermal Comfort



$\mathcal{P}$ is geometrically interpreted as a polytope.

Lin Zhao, Wei Zhang, He Hao, and Karanjit Kalsi. 2017. A geometric approach to aggregate flexibility modeling of thermostatically controlled loads. *IEEE Transactions on Power Systems* 32, 6 (2017), 4721–4731.

COHORT: Coordination Of HeterOgeneous Residential Thermostatically controlled loads



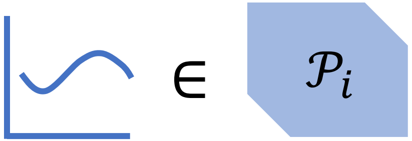
We decompose the grid-level problem into subproblems and coordinate their solutions to find the grid-level optimum.

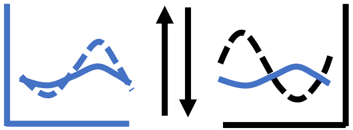
Original Problem

$$\min_{\mathbf{u_i}} \quad g\left(\sum_{i}^{N} \mathbf{u_i}\right)$$
$$\text{s.t.} \quad \mathbf{u_i} \in \mathcal{P}_i, \ \forall i$$

ADMM-Compatible Form

$$\min_{\mathbf{u_i}, \mathbf{v_i}} \quad \sum_i \mathbb{I}_{\mathcal{P}^i}(\mathbf{u_i}) + g\left(\sum_i \mathbf{v_i}\right)$$
$$\text{s.t.} \quad \mathbf{u_i} = \mathbf{v_i}$$

$\mathbf{u_i}$ 

$\mathbf{u_i}$  $\mathbf{v_i}$

Where,

- $\mathbf{u_i} \in \mathbb{R}^T$ is the power consumption of a TCL over a planning horizon;
- g is the system level objective;
- $\mathcal{P}^i$ is the convex-relaxed **flexibility** of individual TCL;

Carnegie Mellon University

ADMM Implementation

Load Aggregator

Aggregation: $\bar{\mathbf{u}} = \frac{1}{N}\sum_i \mathbf{u}_\mathrm{i}$

v-update (Eq. 10b)

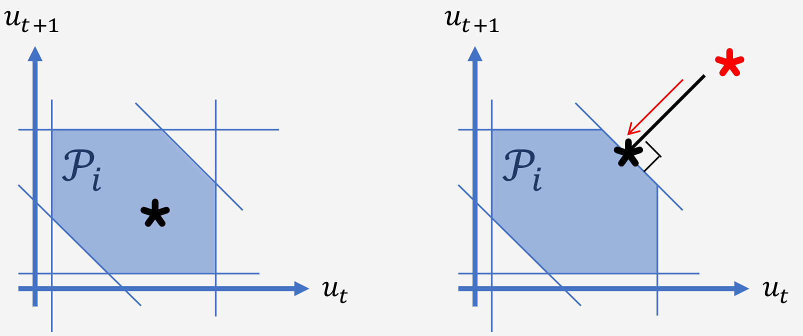
w-update (Eq. 10c)

$\leftarrow \mathbf{u}_\mathrm{i}$

$\rightarrow (\bar{\mathbf{u}}, \bar{\mathbf{v}}, \bar{\mathbf{w}})$

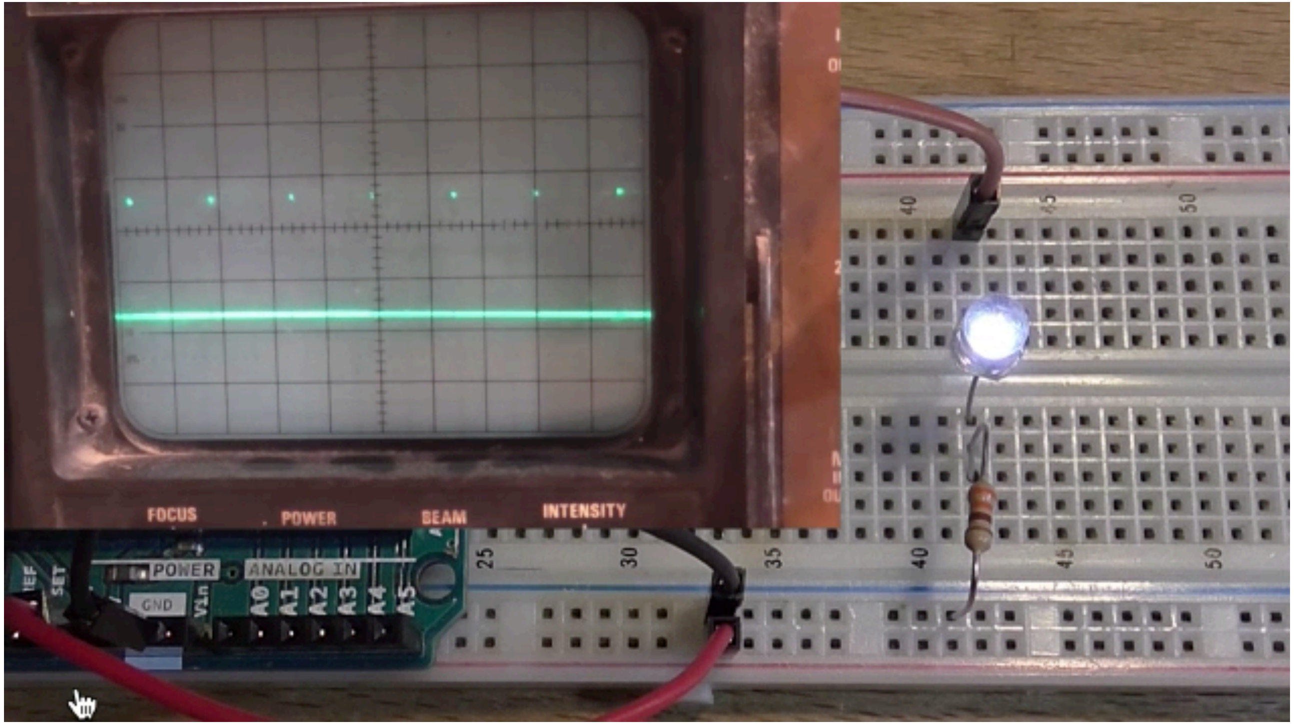
TCL i

u-update: $\mathbf{u}_\mathrm{i} = \mathbf{Proj}_{\mathcal{P}_\mathrm{i}}(\mathbf{u}_\mathrm{i}^+)$



(a) u_i^+ feasible (b) u_i^+ infeasible

We translate continuous power trajectory back to on/off actuation using pulse width modulation.



COHORT is applicable to a variety of use cases.

Generation Following

$$g_{\text{track}}\Big(\sum_i \mathbf{u_i}\Big) = \frac{1}{T}||\tilde{\mathbf{u}} - \sum_i \mathbf{u_i}||_2^2$$

Minimize Ramping

$$g_{\text{tv}}\Big(\sum_i \mathbf{u_i}\Big) = \sum_{k=t+1}^{t+T} |P_{\text{net,k}} - P_{\text{net,k-1}}|$$

where, $\mathbf{P}_{\text{net}} = \mathbf{P}_{\text{total}} - \mathbf{P}_{\text{gen}}$

$$\mathbf{P}_{\text{total}} = \mathbf{P}_{\text{non-shiftable}} + \sum_i \mathbf{u_i}$$

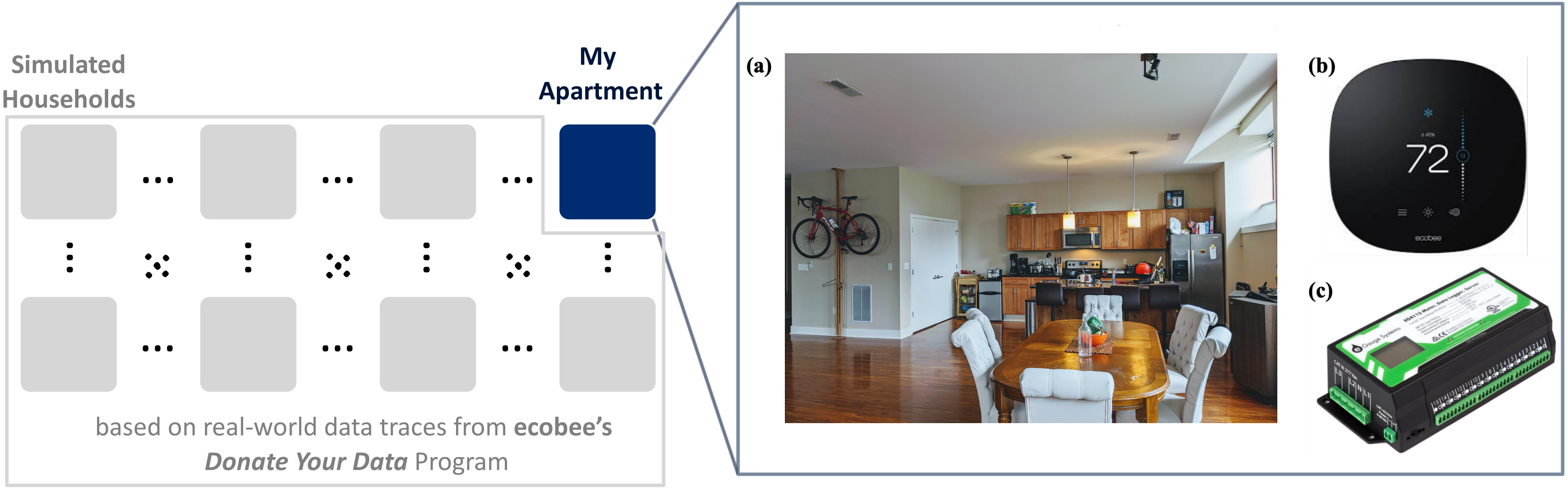
Peak Load Curtailment

$$g_{\text{peak}}\Big(\sum_i \mathbf{u_i}\Big) = ||\mathbf{P}_{\text{total}}||_\infty$$

where, $\mathbf{P}_{\text{total}} = \mathbf{P}_{\text{non-shiftable}} + \sum_i \mathbf{u_i}$

Carnegie Mellon University

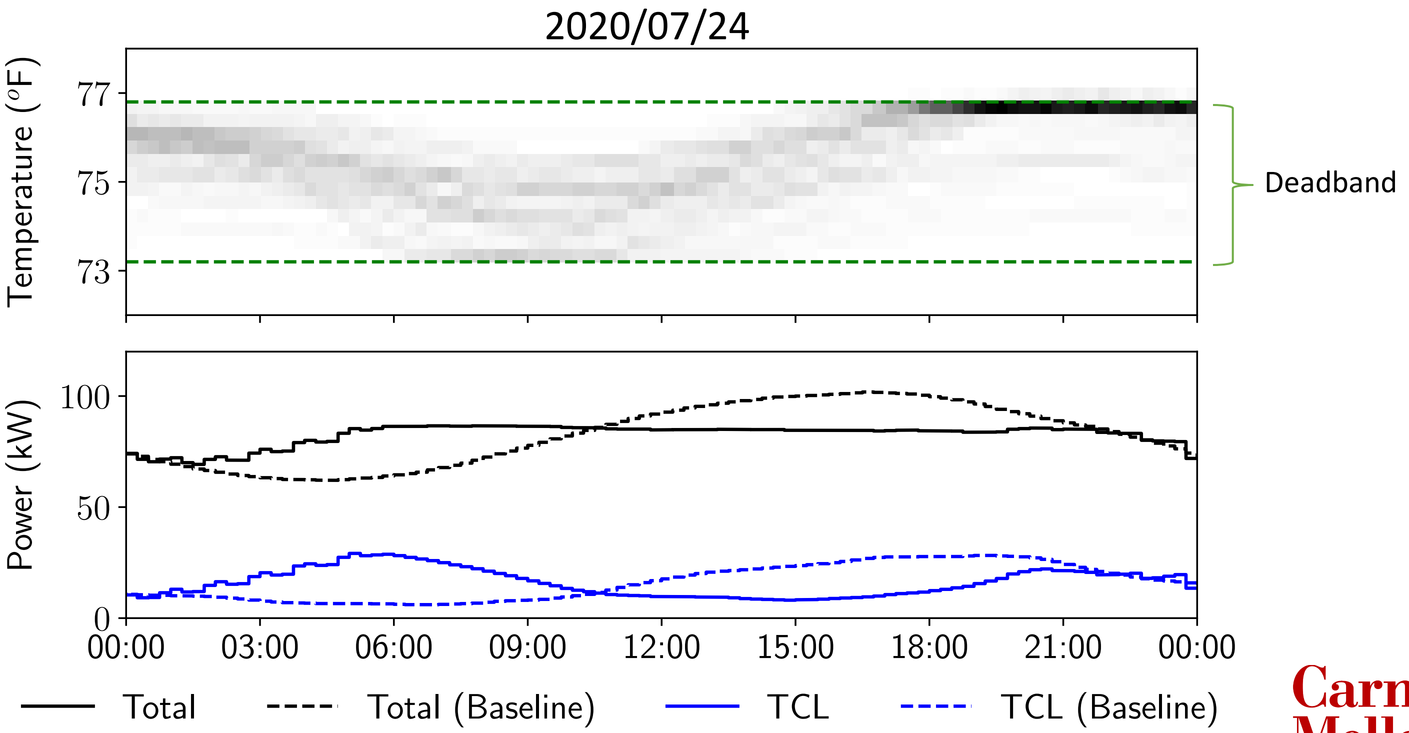
We validated that COHORT is practical for real-world systems through a hardware-in-the-loop simulation.



15-day Experiment Period: 2020/07/11-2020/07/25

Use Case 3: Peak Load Curtailment (Population)

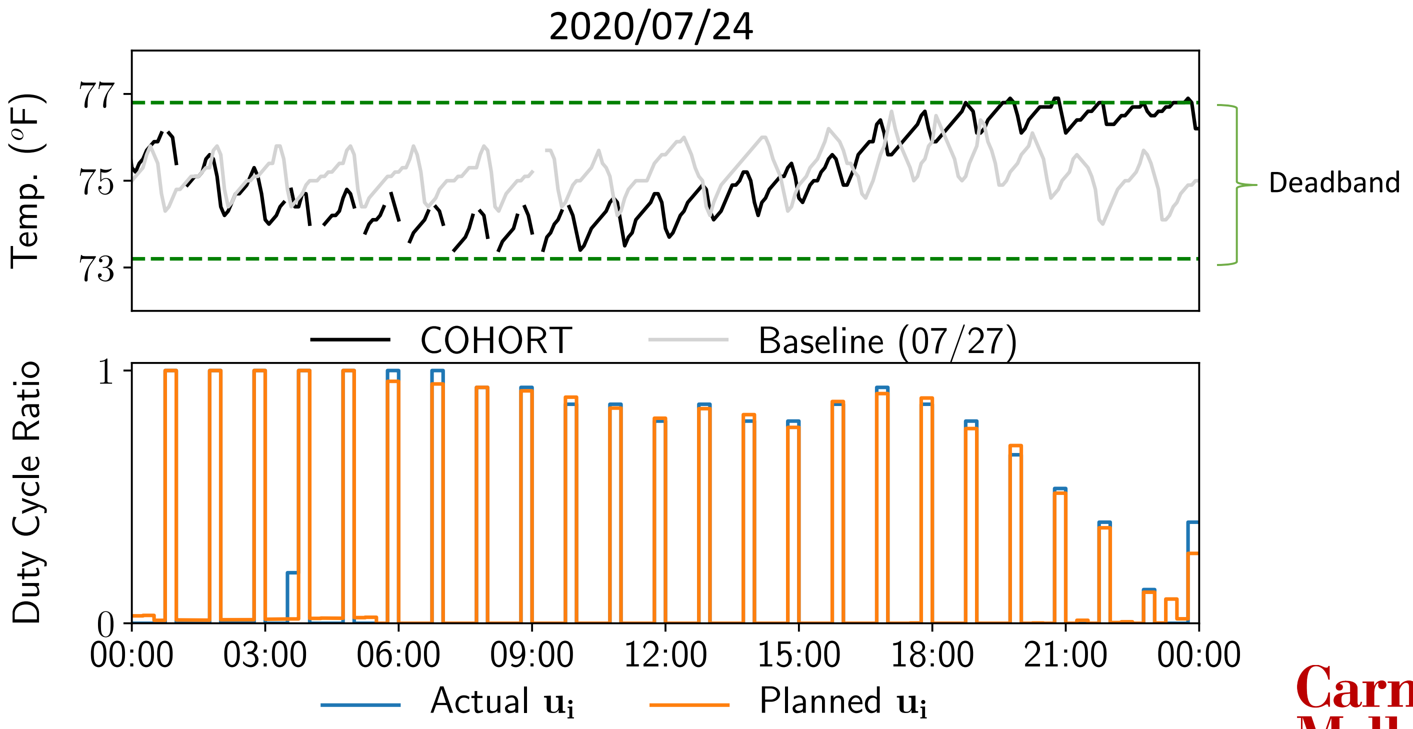
COHORT reduced daily peak loads by an average of **12.5%**.



(From PJM Interconnection)

Carnegie Mellon University

Use Case 3: Peak Load Curtailment (Real-world Testbed)



Carnegie Mellon University

Take-aways

COHORT is a practical, scalable, and versatile solution for coordinating TCLs.

COHORT is validated on a real-world testbed and can be easily integrated with commercial smart thermostats.

COHORT is computationally scalable for both large population sizes and long planning horizons.

COHORT is applicable to a wide variety of grid objectives, which we demonstrated through three distinct use cases.

Thank you!

[Code] **https://github.com/INFERLab/COHORT**
[Contact] **bingqinc@andrew.cmu.edu**