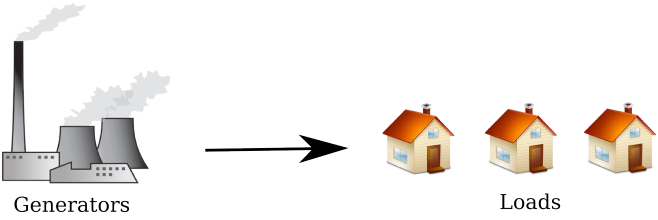
A Control System Framework for Privacy Preserving Demand Response of Thermal Inertial Loads

Abhishek Halder

Department of Electrical and Computer Engineering
Texas A&M University
College Station, TX 77843

Joint work with X. Geng, G. Sharma, L. Xie, and P.R. Kumar

Demand Response: what, why, how

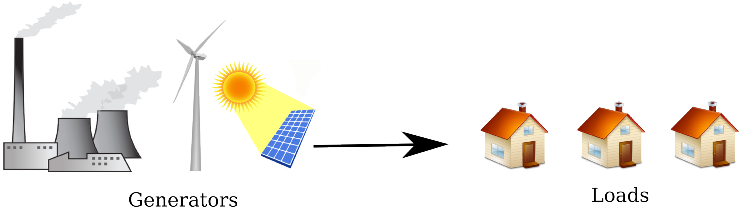


Traditional paradigm: demand is uncertain

Operational model: supply follows demand

Mechanism: operating reserve

Demand Response: what, why, how

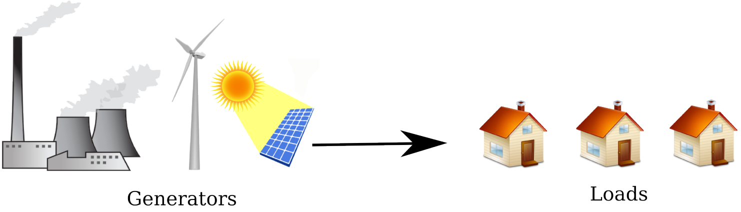


New paradigm: both supply and demand are uncertain

Operational model: demand follows supply

Mechanism: demand response

Demand Response: what, why, how

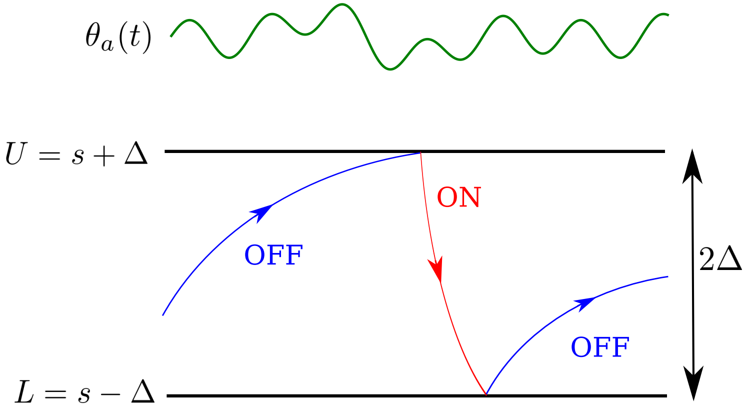


New paradigm: both supply and demand are uncertain

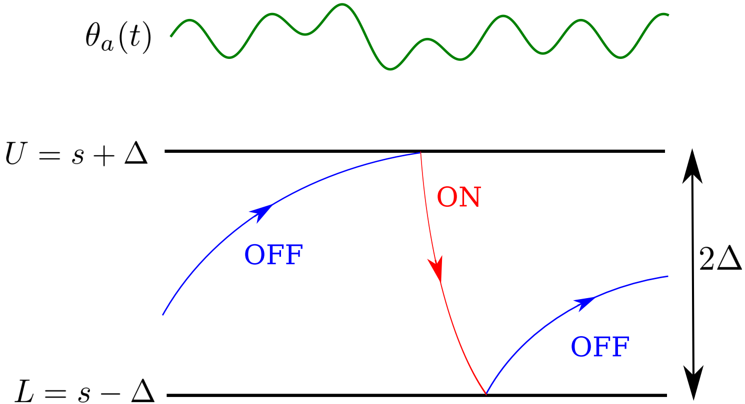
Operational model: demand follows supply

Mechanism: demand response **of thermal inertial loads**

Dynamics of AC state $(s, \theta, \sigma) \in \mathbb{R}^2 \times \{0, 1\}$



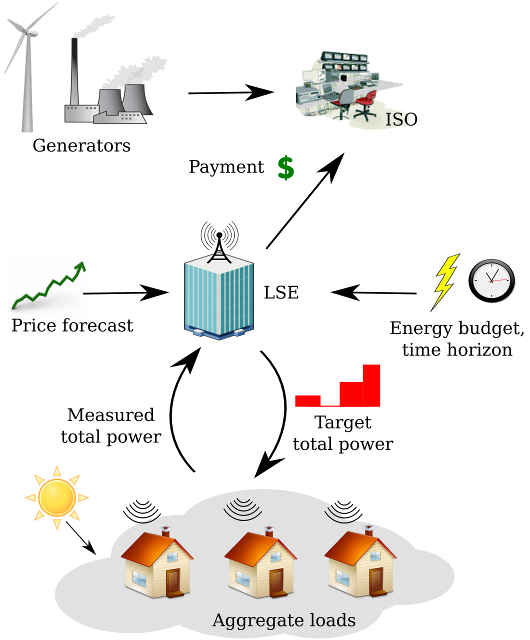
Dynamics of AC state $(s, \theta, \sigma) \in \mathbb{R}^2 \times \{0, 1\}$



Newton's law of heating/cooling: $\dot{\theta} = -\alpha\,(\theta(t) - \theta_a(t)) - \beta P \sigma(t)$

ON/OFF mode switching: $\sigma(t) = \begin{cases} 1 & \text{if} \quad \theta(t) \geq U \\ 0 & \text{if} \quad \theta(t) \leq L \\ \sigma(t^-) & \text{otherwise} \end{cases}$

Proposed architecture



Research scope

Objective: A theory of operation for the LSE

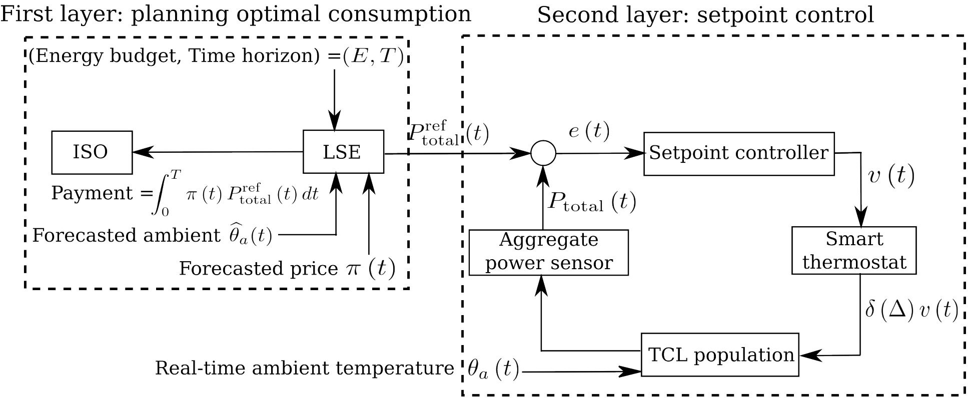
Challenges:

1. How to design the **target consumption as a function of price**?

2. How to control so as to preserve **privacy** of the loads' states?

3. How to respect loads' **contractual obligations** (e.g. comfort range width Δ)?

Two layer block diagram



First layer: planning optimal consumption

price forecast

$$\underset{\{u_1(t),\ldots,u_N(t)\}\in\{0,1\}^N}{\text{minimize}} \quad \int_0^T P \;\; \pi(t) \;\; (u_1(t)+u_2(t)+\ldots+u_N(t))\ \mathrm{d}t$$

subject to

(1) $\dot{\theta}_i = -\alpha\left(\theta_i(t) - \widehat{\theta}_a(t)\right) - \beta P u_i(t) \qquad \forall\, i = 1,\ldots,N,$

(2) $\int_0^T (u_1(t)+u_2(t)+\ldots+u_N(t))\ \mathrm{d}t = \tau \doteq \frac{E}{P}(< T, \text{given})$

(3) $L_0^{(i)} \leq \theta_i(t) \leq U_0^{(i)} \qquad \forall\, i = 1,\ldots,N.$

Optimal consumption: $P^*_{\text{ref}}(t) = P\sum_{i=1}^{N} u_i^*(t)$

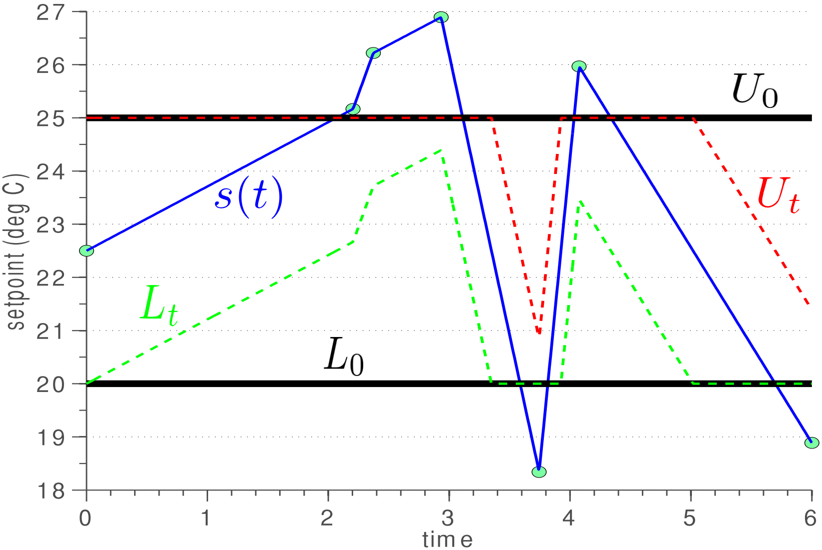
Second layer: setpoint control

$$\underbrace{P^*_{\mathrm{ref}}(t)}_{\text{optimal reference}} = P\sum_{i=1}^{N} u_i^*(t), \quad \rightsquigarrow \quad \underbrace{e(t)}_{\text{error}} = P^*_{\mathrm{ref}}(t) - \underbrace{P(t)}_{\text{measured}}, \quad \rightsquigarrow$$

$$v(t) = \underbrace{k_p e(t) + k_i \int_0^t e(\varsigma)\mathrm{d}\varsigma + k_i \frac{\mathrm{d}}{\mathrm{d}t} e(t)}_{\text{PID velocity control}}, \rightsquigarrow \frac{\mathrm{d}s_i}{\mathrm{d}t} = \underbrace{\Delta_i}_{\text{gain}} \quad \underbrace{v(t)}_{\text{broadcast}},$$

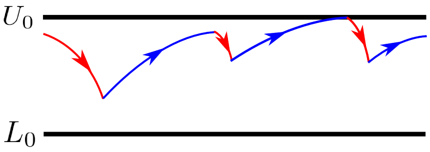
$$\rightsquigarrow \quad L_t^{(i)} = L_0^{(i)} \vee (s_i(t) - \Delta_i), \qquad U_t^{(i)} = U_0^{(i)} \wedge (s_i(t) + \Delta_i).$$

Second layer: setpoint control



Control problems

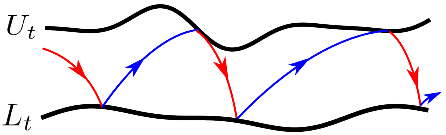
First layer



when to switch?

control variable
$\sigma(t)$

Second layer

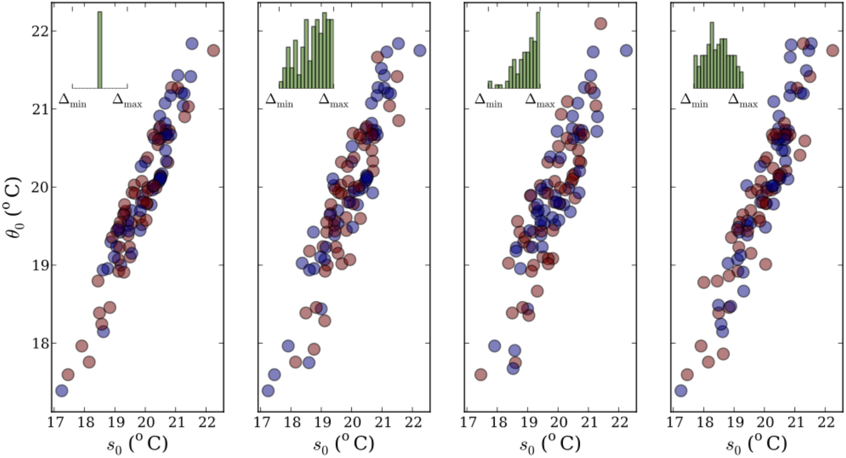


how to move setpoint boundaries?

control variable
$\frac{\mathrm{d}s}{\mathrm{d}t}$

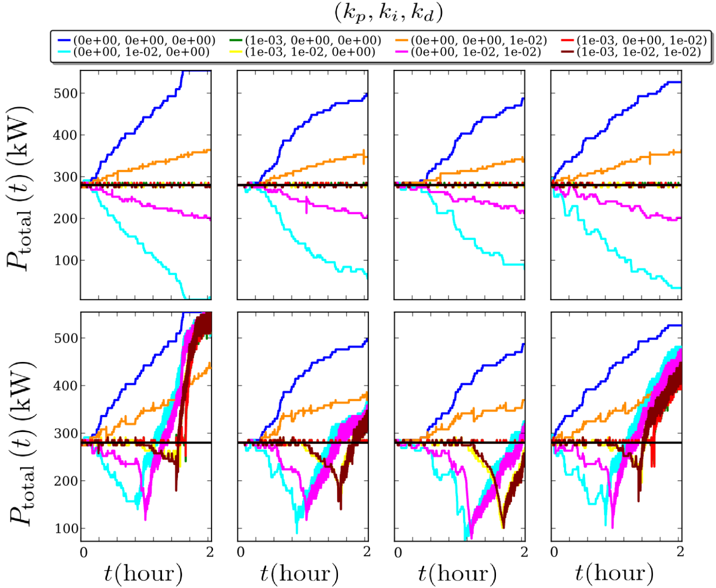
Direct numerical solution

Given: distribution of the $N = 100$ loads' initial conditions $(s_0, \theta_0, \sigma_0)$, and their contracts (Δ)

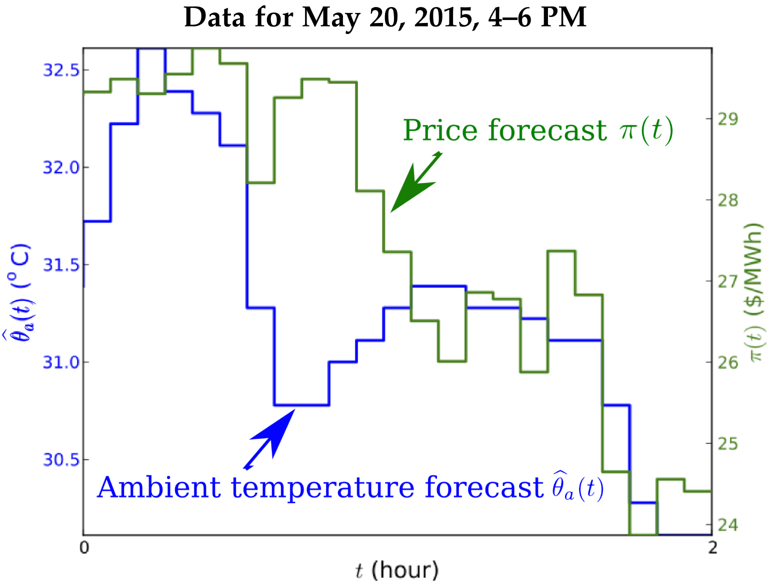


Direct numerical solution: $P^*_{\text{ref}}(t) = 50P$

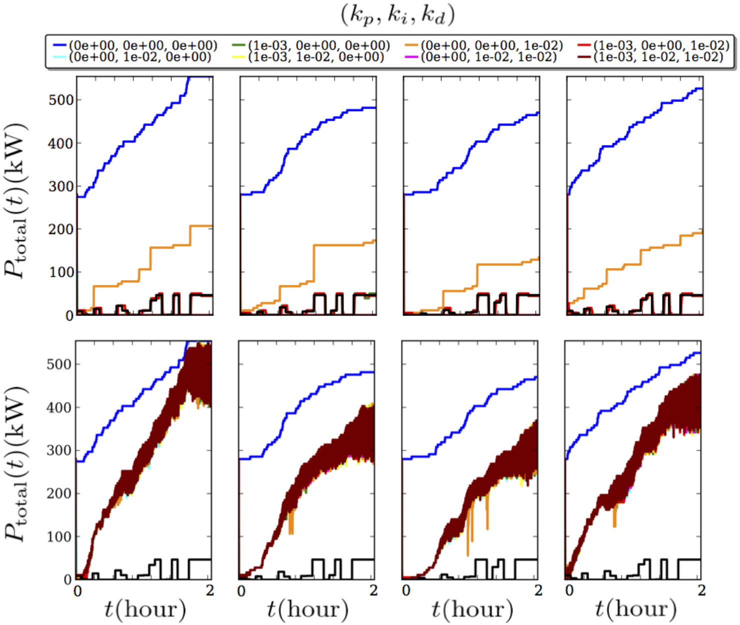
Setpoint velocity control has good tracking performance



Direct numerical solution: Houston data



Direct numerical solution: Houston data



Summary

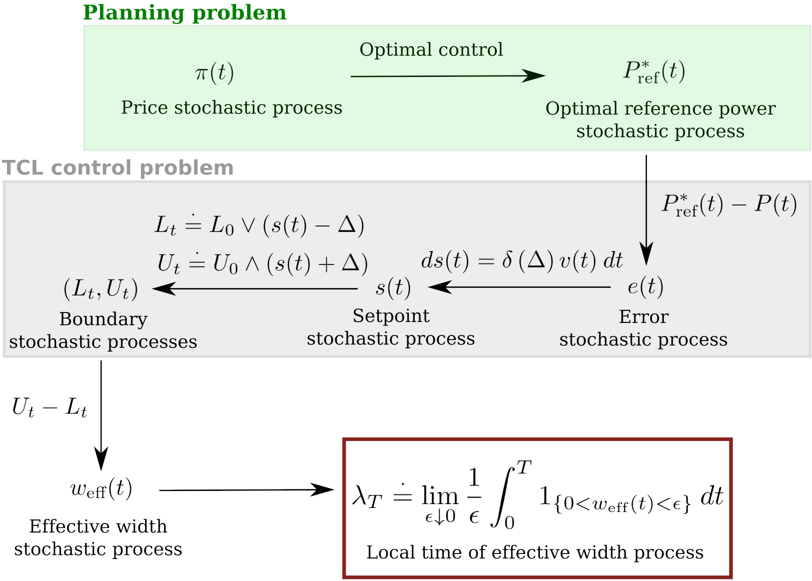
- A simple framework for optimal demand response.
- Designs optimal target consumption using forecast.
- Tracks the designed target consumption in real-time.
- LSE does not need to know individual states $\Rightarrow$ preserves privacy.

Summary

- A simple framework for optimal demand response.
- Designs optimal target consumption using forecast.
- Tracks the designed target consumption in real-time.
- LSE does not need to know individual states $\Rightarrow$ preserves privacy.

Thank you

Performance



Limit of performance