CPS Synergy: Collaborative Research: Boolean Microgrid (# 1239116)

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A Theory of Operation for the Load Serving Entity

Research Objective

Design architecture and algorithms for a Load Serving Entity (LSE) to elicit demand response by direct control of its customers' thermostatically controlled loads such as residential air conditioners (ACs).

Research Challenges

1. How to design the *reference* total power trajectory as a function of the forecasted price of energy?
2. The room temperature, setpoint, and ON/OFF binary state of any individual AC cannot be measured for privacy reasons.
3. The LSE may have different contractual obligations for different ACs in terms of their comfort ranges.

Key Questions: What is the *optimal* plan for the LSE to schedule the purchase of power? How to control the AC population in real-time to track the reference *aggregate* power, while respecting *individual* privacy and QoS constraints?

Idea: Two hierarchical control problems:
– *How* to control the ACs? [Real-time output feedback control]
– *What* to control them to? [Day-ahead open-loop control]

Proposed Two Layer Architecture

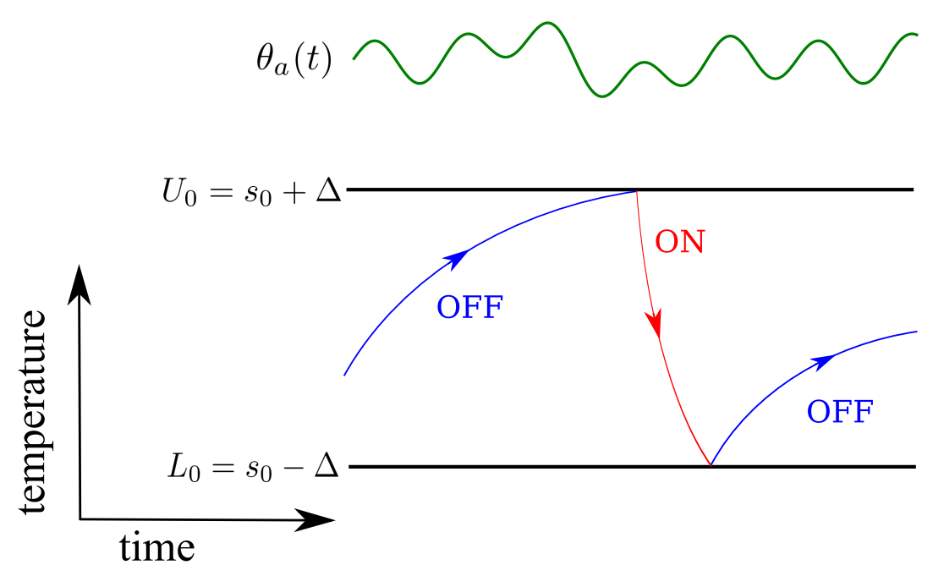

Fig. 1. Uncontrolled dynamics of an AC.

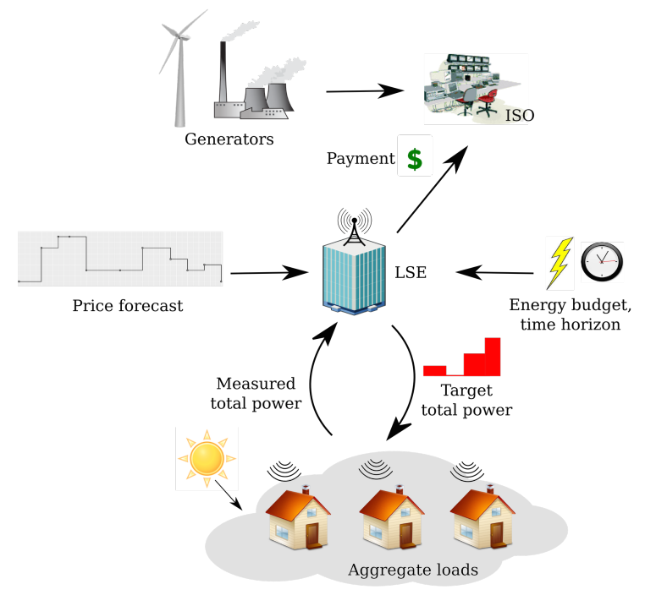

Fig. 2. Proposed direct load control architecture for the LSE.

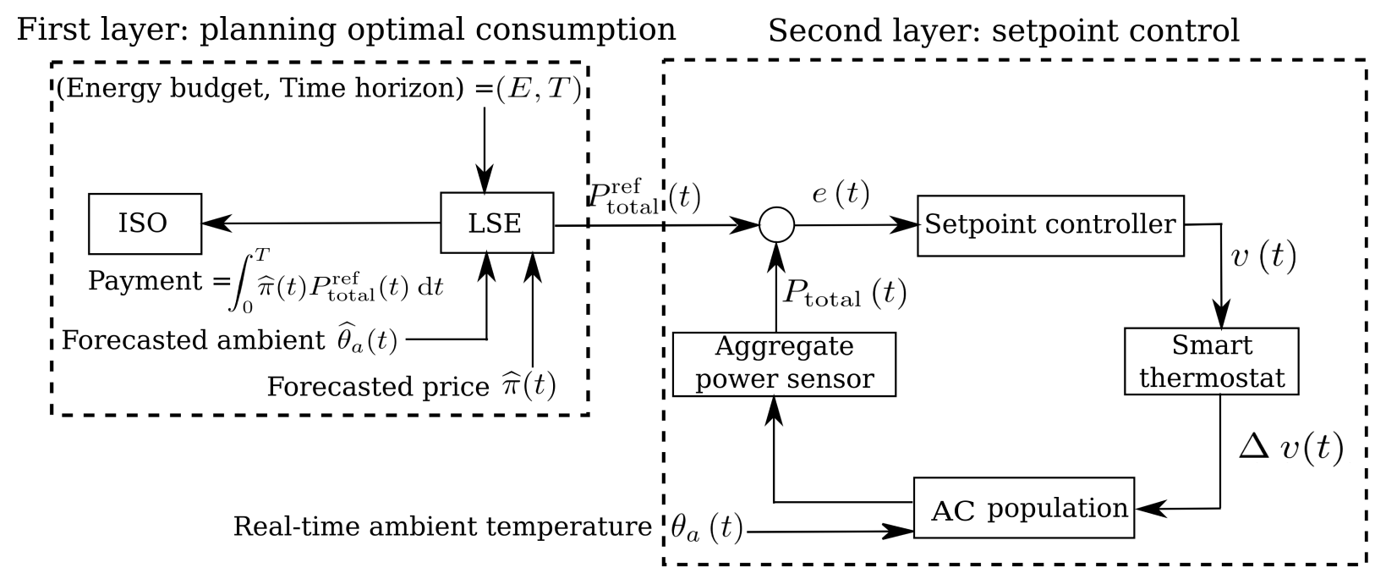

Fig. 3. Block diagram for the two layer control strategy.

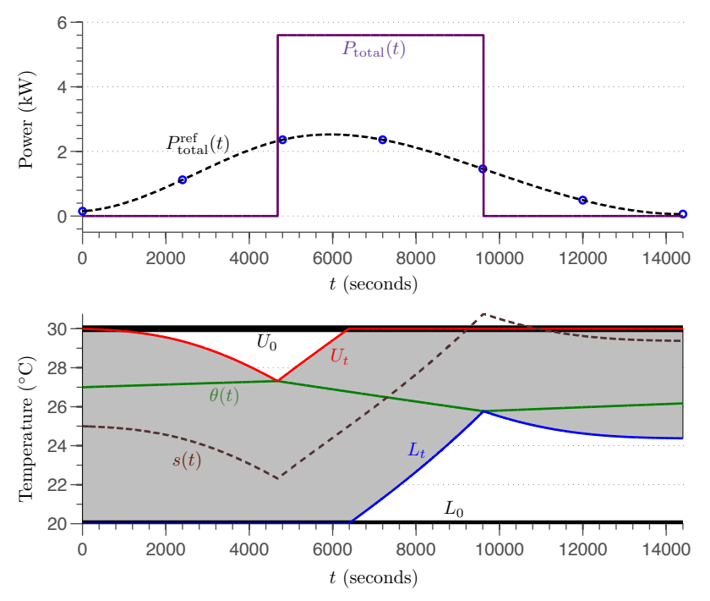

Fig. 4. Deformation $[L_0, U_0] \mapsto [L_t, U_t]$ under setpoint boundary control.

Formulation

First layer: planning optimal consumption

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

subject to

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

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

$$(3)\quad L_{i0} \leq \theta_i(t) \leq U_{i0} \qquad \forall\, i=1,\ldots,N.$$

Second layer: setpoint boundary control

$$P^{\text{ref}}_{\text{total}}(t) = \frac{P}{\eta}\sum_{i=1}^{N} u_i^*(t), \qquad e(t) = P^{\text{ref}}_{\text{total}}(t) - P_{\text{total}}(t),$$

$$v(t) = k_{\text{P}}\, e(t) + k_{\text{I}}\int_0^t e(\varsigma)\mathrm{d}\varsigma + k_{\text{D}}\frac{\mathrm{d}}{\mathrm{d}t}e(t), \qquad \frac{\mathrm{d}s_i}{\mathrm{d}t} = \Delta_i v(t),$$

$$L_{it} = U_{i0} \wedge \left[L_{i0} \vee \left(s_i(t)-\Delta_i\right)\right], \qquad U_{it} = L_{i0} \vee \left[U_{i0} \wedge \left(s_i(t)+\Delta_i\right)\right].$$

Solving the Optimal Planning Problem

1. **Numerically:** difficult to "discretize-then-optimize" since it leads to large MILP (1 million 44 thousand variables for 500 homes with 1 minute time-step-size for Euler discretization). LP relaxation is suboptimal.
2. **Analytically:** turns out to be tractable using maximum principle.

Simulation Setup and Data

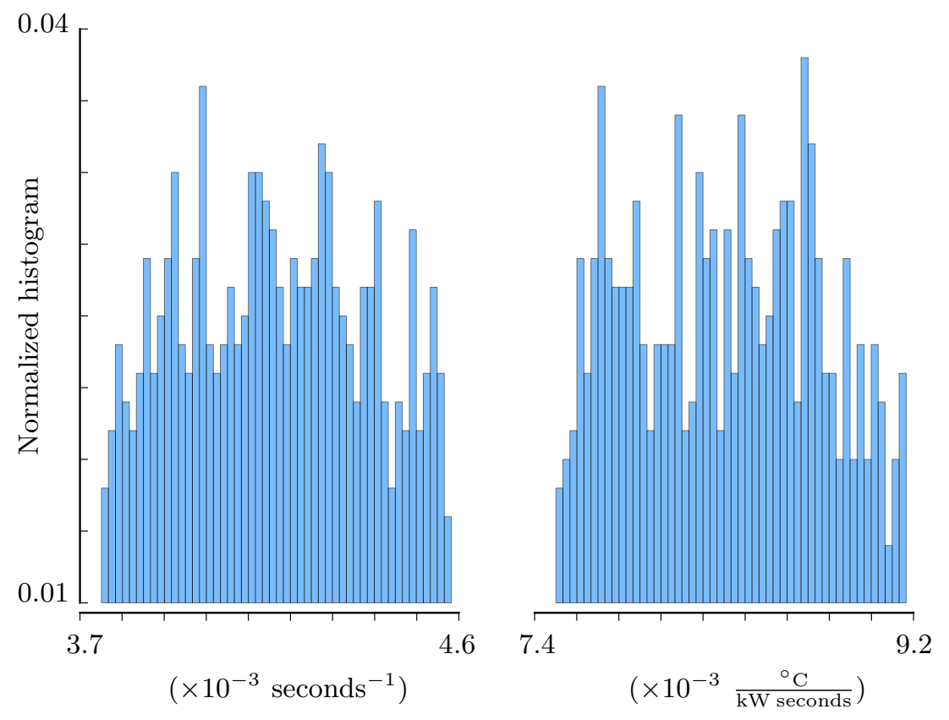

Fig. 5. Histograms of thermal coefficients for the customers' ACs.

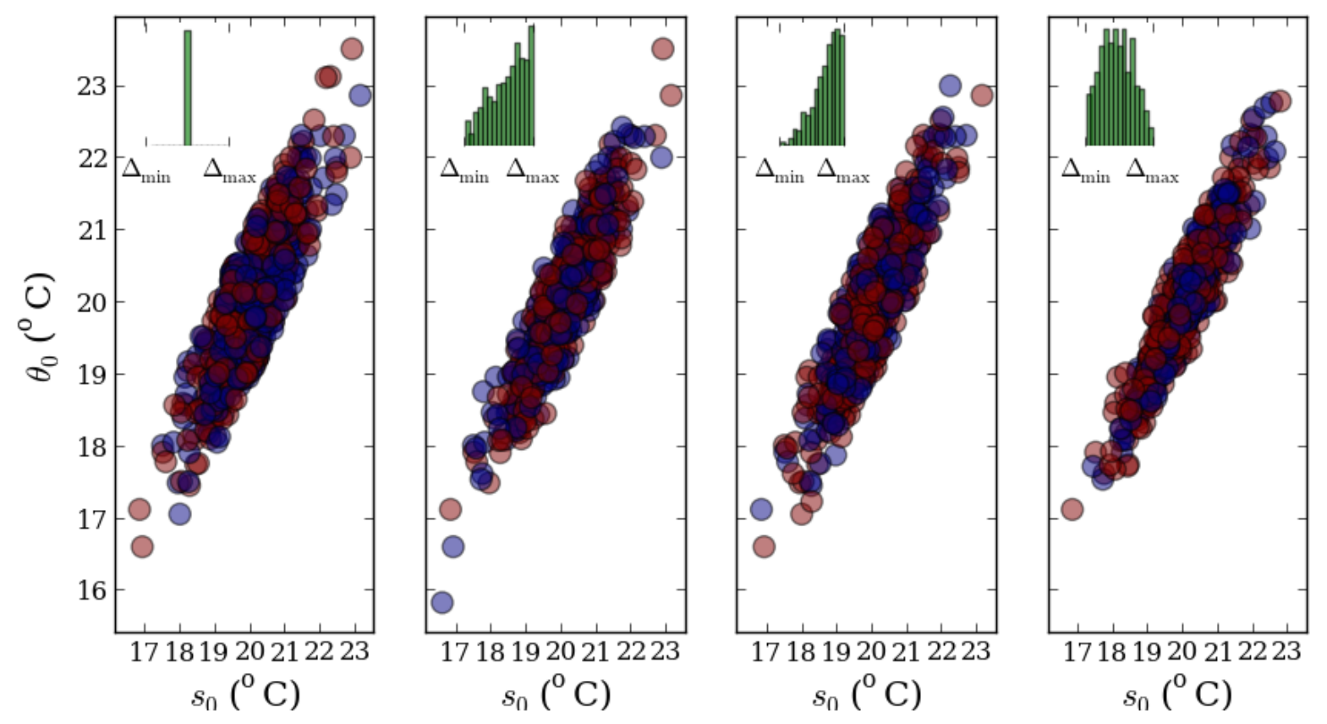

Fig. 6. Initial conditions for the ON *(red)* and OFF *(blue)* ACs for four different contract (Δ) distributions with $N = 500$ homes.

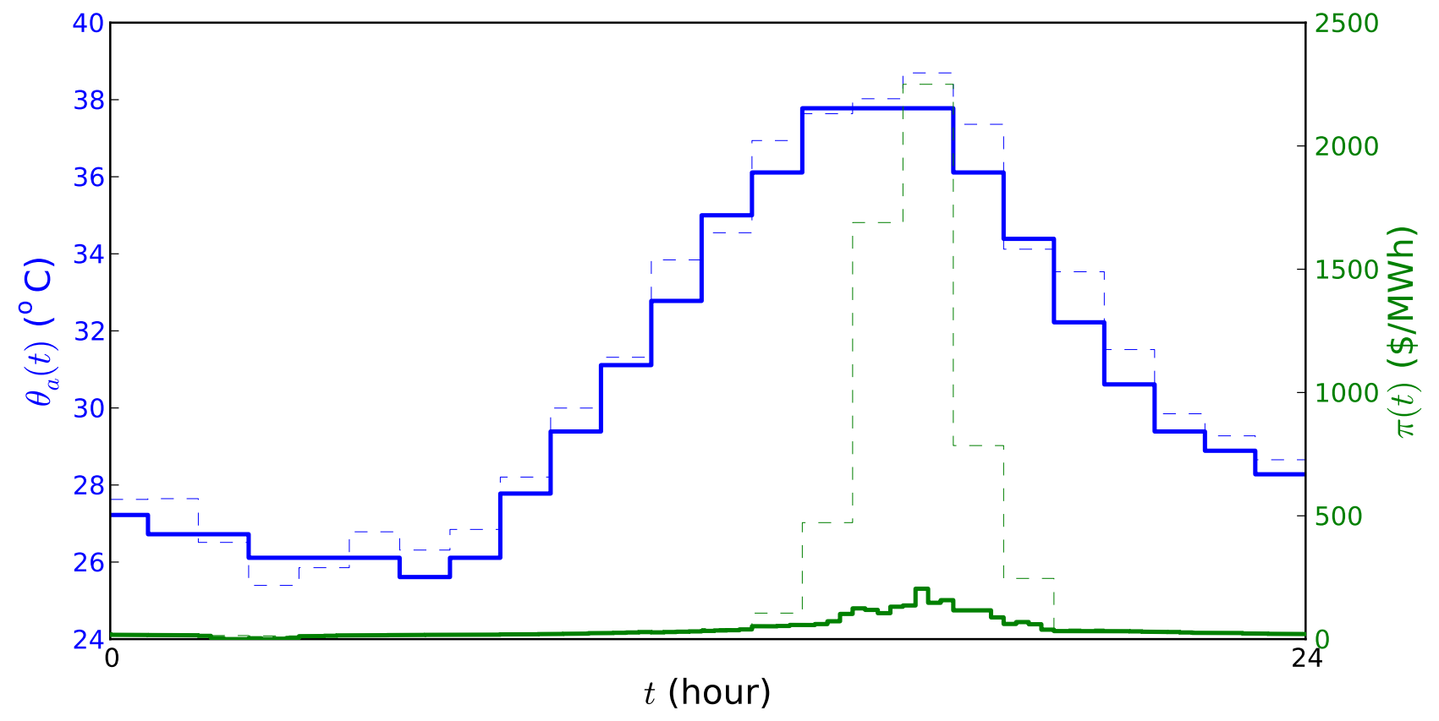

Fig. 7. The ambient temperature forecast ($\widehat{\theta}_a(t)$, *dashed blue*) and real-time ambient temperature ($\theta_a(t)$, *solid blue*) from Houston weather station. ERCOT day-ahead price ($\widehat{\pi}(t)$, *dashed green*) and real-time price ($\pi(t)$, *solid green*) data.

Results

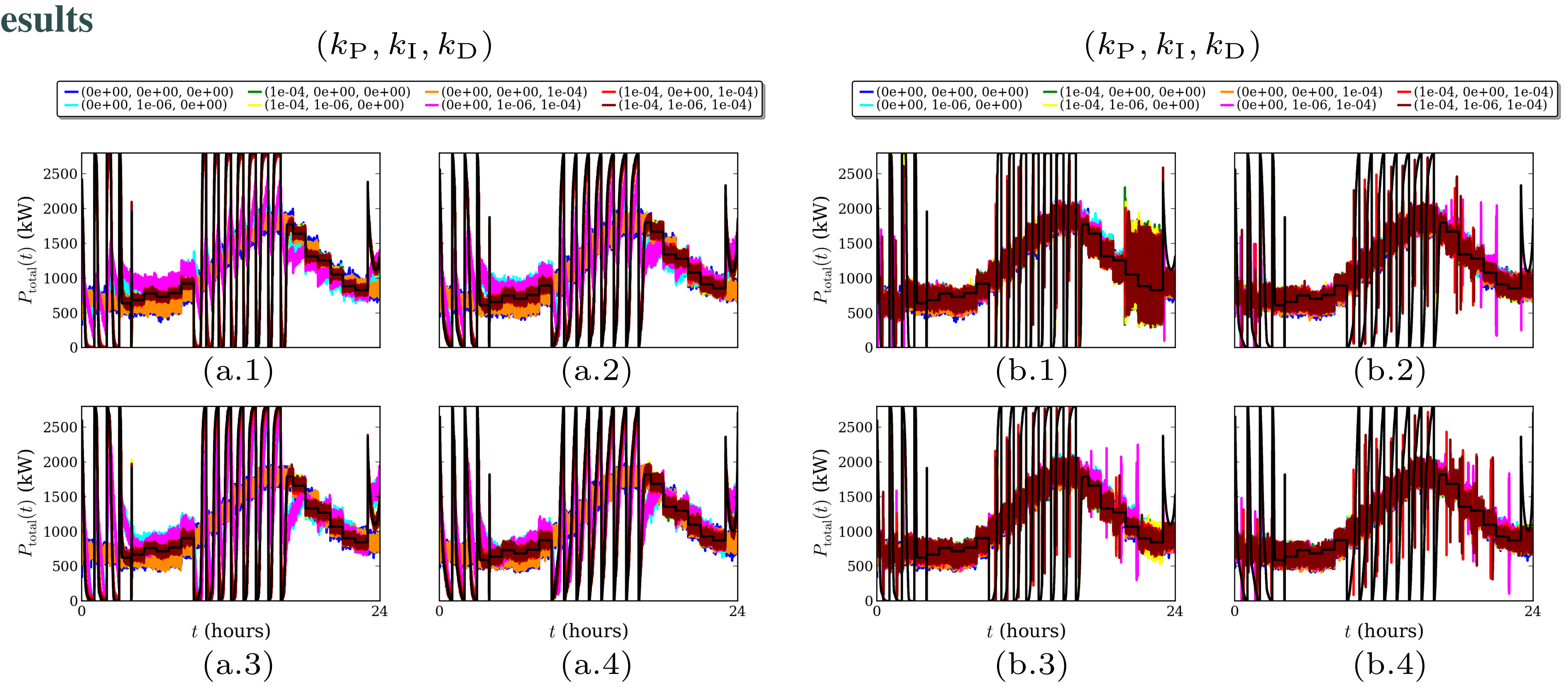

Fig. 8. Real-time tracking performance with (b) and without (a) contractual QoS constraints for four different Δ distributions (as in Fig. 6).

Privacy preserving sensing of $P_{\text{total}}(t)$

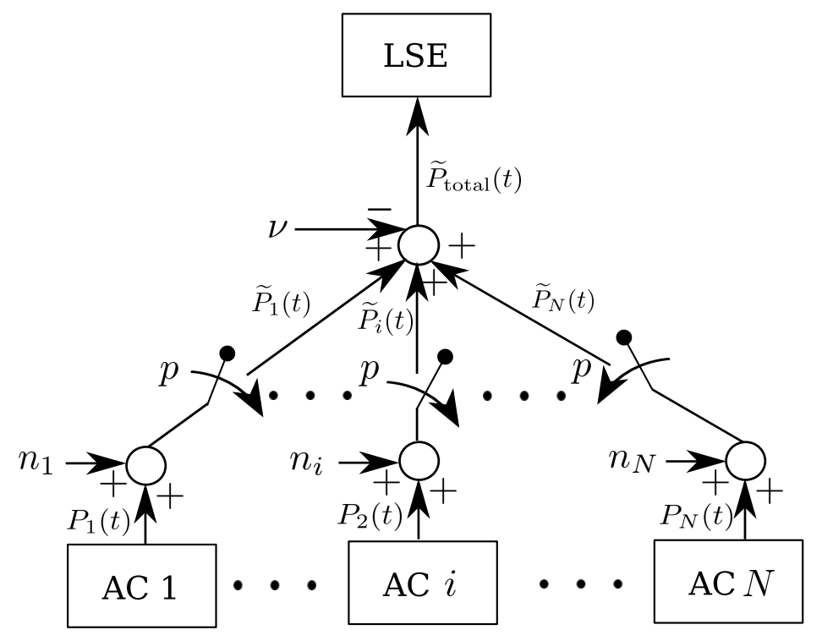

Fig. 9. Differentially private sensing architecture for the LSE to measure $P_{\text{total}}(t)$.

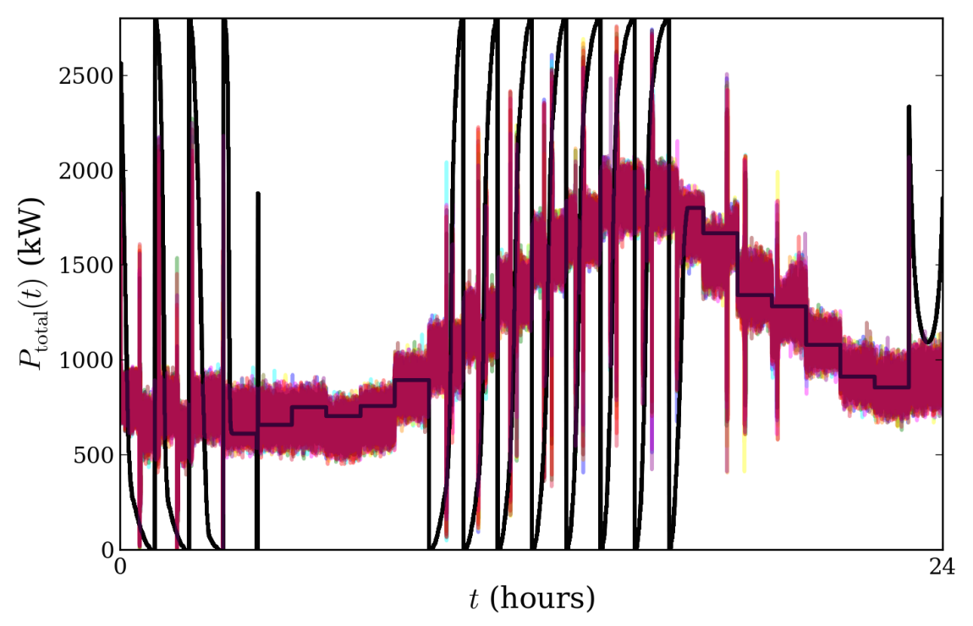

Fig. 10. Real-time tracking performance with differentially private sensing of $P_{\text{total}}(t)$.

Pricing contracts and performance

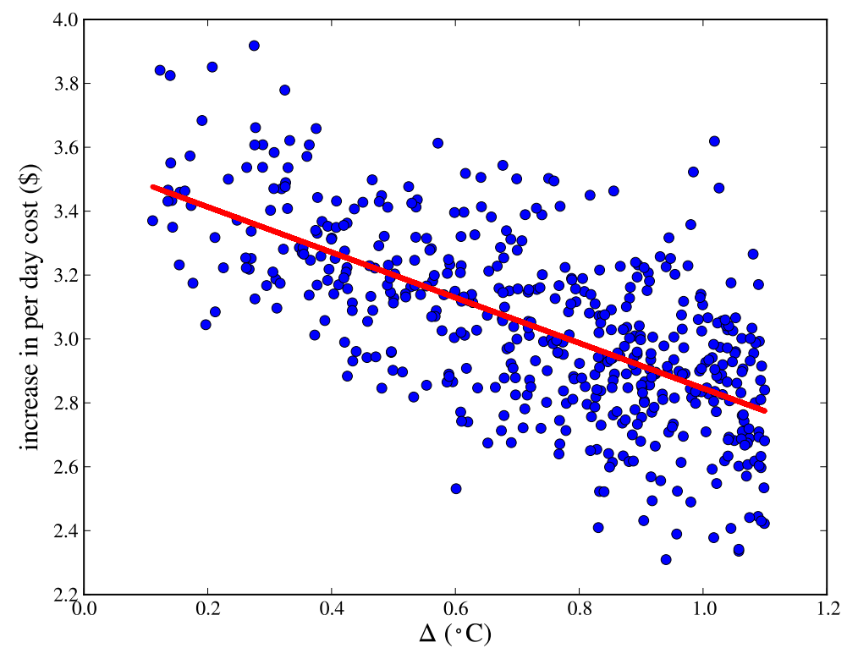

Fig. 11. Sensitivity based contract pricing chart for the LSE.

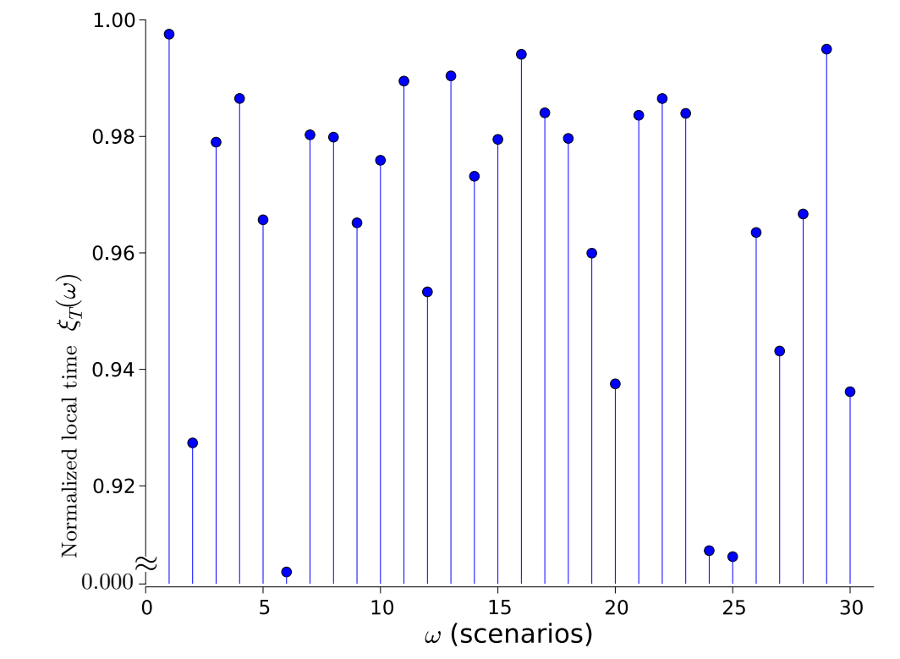

Fig. 12. Limitation of LSE's control performance for 30 days of August 2015 in Houston.

References

[1] A. Halder, X. Geng, P.R. Kumar, and L. Xie, "Architecture and Algorithms for Privacy Preserving Thermal Inertial Load Management by A Load Serving Entity". *arXiv:1606.09564*, 2016.

[2] A. Halder, X. Geng, G. Sharma, L. Xie, and P.R. Kumar, "A Control System Framework for Privacy Preserving Demand Response of Thermal Inertial Loads". *Proceedings of the 6th IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pp. 181–186, 2015.