Modelling and Control of Load Ensembles

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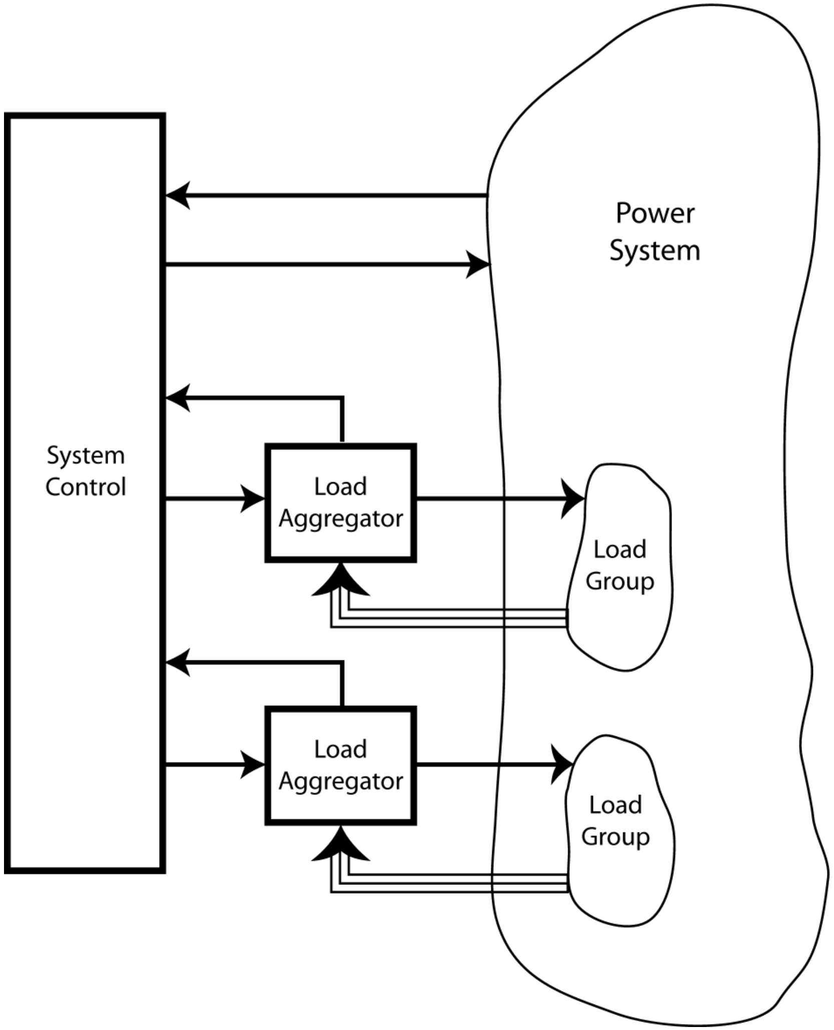
Non-disruptive load control

- Non-disruptive load control is standard in communications so why not in electricity delivery.
- Opportunities for such load control:
  - Large individual loads.
    - Building HVAC control.
  - Large numbers of small devices.
    - Electric vehicle (EV) charging.
      - Prevent undesirable loading patterns.
      - Offer regulation capability for enhancing system operation.
    - Thermostatically controlled loads (TCLs).
      - Air-conditioning, refrigeration, heat pumps.

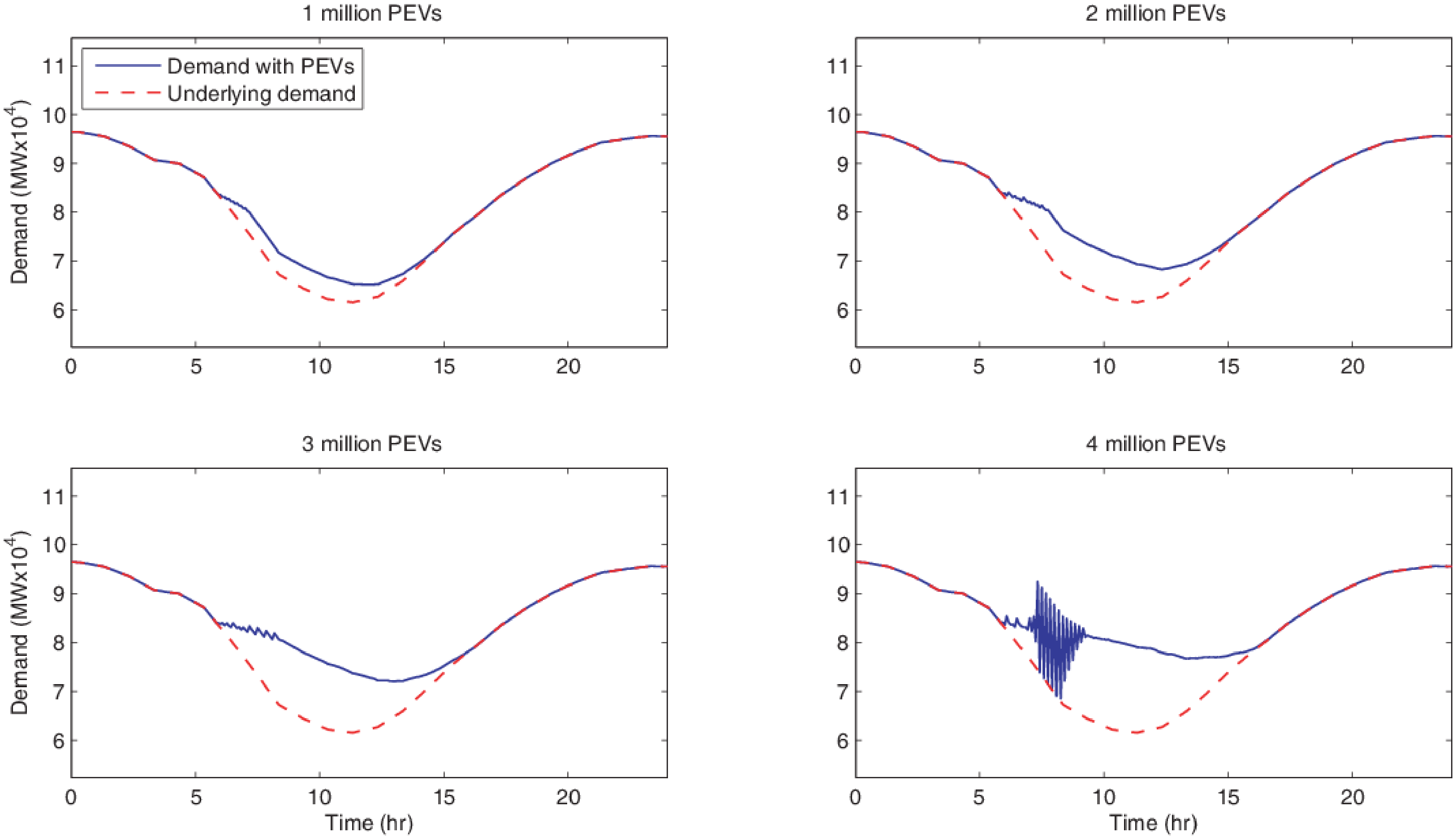
Load control

- Competing objectives:
  - Local control objective, e.g. maintain temperature close to set-point.
  - System service, e.g. balance renewable generation output.
- Load control strategies must be consistent with the legacy system operating philosophy.
- Centralized control of large numbers of loads is impractical.



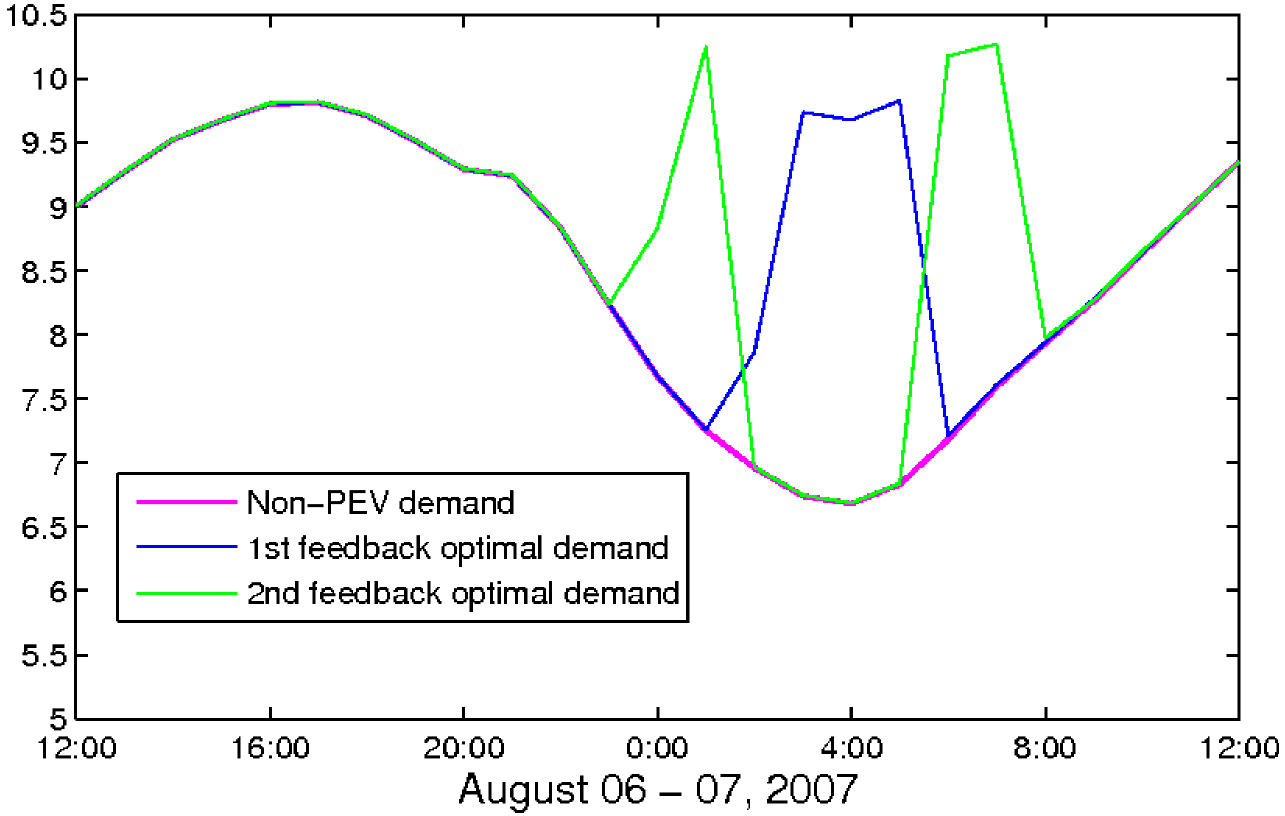
What can go wrong?

- Price-based strategy for charging electric vehicles: charge when price falls below a lower threshold, cease charging when price rises above an upper threshold.



Decentralized decision-making

- Each EV seeks to minimize its energy cost over its charging horizon, based on the latest prediction of energy price.



Desirable coordination of EV charging

- A decentralized approach to scheduling EV charging that considers trade-offs between:
  - Energy price.
  - Battery degradation.
  - Distribution network effects.
- The resulting collection of EV charging strategies should be efficient (socially optimal).
- Reliable convergence in a few iterations.

- This can be achieved by introducing local costs:
  - A demand charge to mitigate coincident high charger power demand.
  - Cost associated with battery degradation due to high charging power.

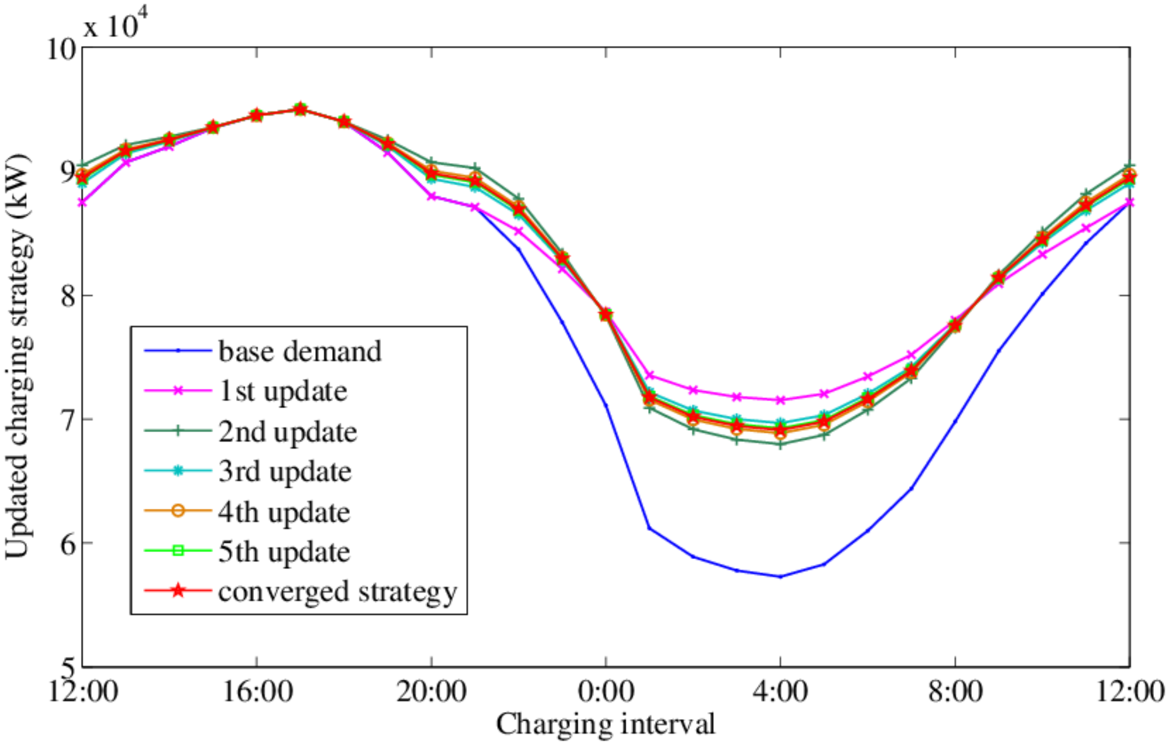
Charging coordination algorithm

1) Each EV autonomously determines its optimal charging strategy with respect to a given electricity price profile $\boldsymbol{p} \equiv (p_t, t \in \mathcal{T})$. This optimal strategy takes into account the trade-off between the electricity cost and local (demand and battery degradation) costs over the entire charging horizon.
2) The electricity price profile $\boldsymbol{p}$ is updated to reflect the latest charging strategies determined by the EV population in 1).
3) Steps 1) and 2) are repeated until the change in the price profile at 2) is negligible.

- Using an appropriate individual cost function and price update mechanism, the algorithm is convergent and achieves the socially optimal (centralized) solution.

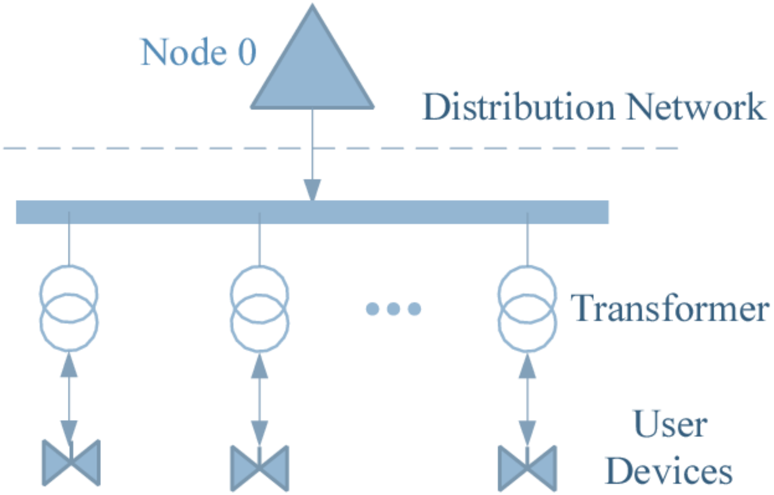
Main result

- Theorem: The decentralized algorithm converges to the efficient (centralized) solution $\boldsymbol{u}^{**}$.
- The proof establishes that $\boldsymbol{p}^{+}(\boldsymbol{p})$ is a contraction map.



Extensions

- The central price manager can be replaced by a fully decentralized consensus algorithm.
- The coordination scheme can be extended to a hierarchical architecture that takes into account physical supply constraints, e.g. transformers.



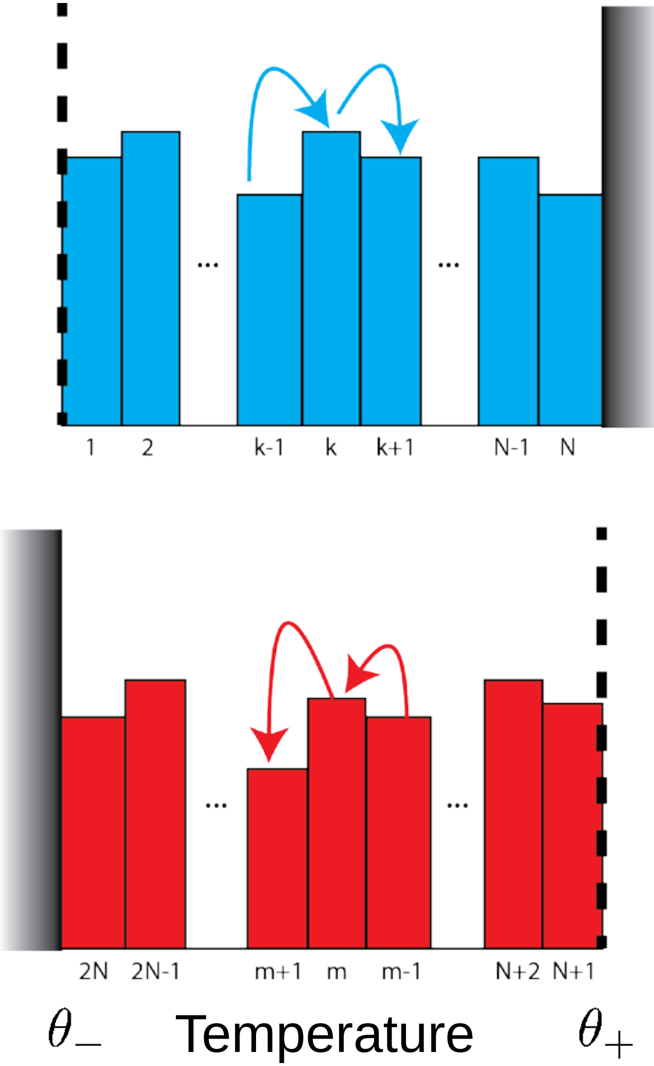
Ensembles with natural dynamics

- The natural (hysteresis-based) dynamics of devices such as TCLs make regulation more challenging.
- A starting point is the development of a simplified model describing aggregate dynamic behaviour.

- The temperature associated with each TCL is influenced by random perturbations, e.g. opening doors/windows.
  - Modelled as noise.
- Every TCL has slightly different characteristics, e.g. thermal capacitance/resistance.
  - The population is heterogeneous.

- Later slides focus on noise and ignore heterogeneity.

Bin model approximation



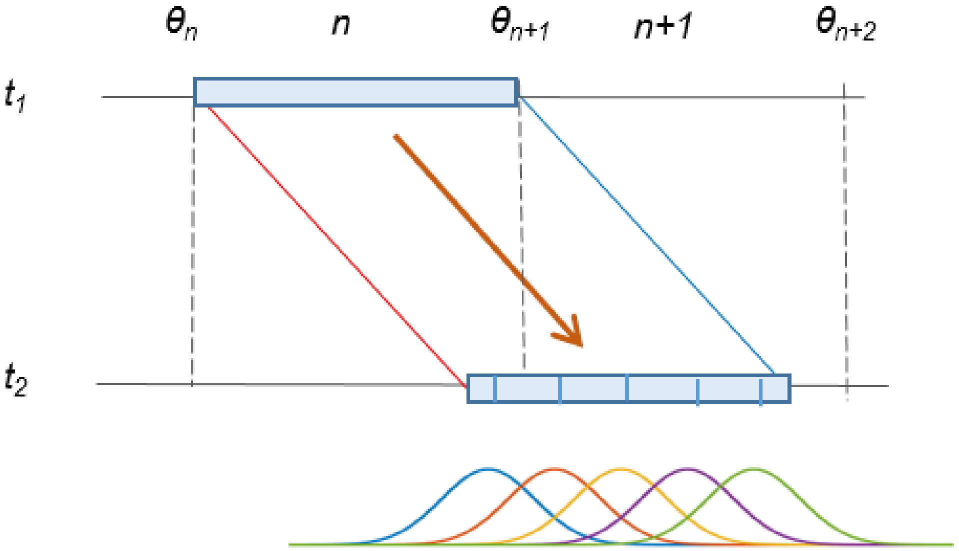
- Regions (for cooling loads):
  - Blue loads are in the off state.
  - Red loads are in the on state.
- Propagation of probability mass from one bin to another can be described by:

$$x_{k+1} = Ax_k, \quad x_0 \text{ given}$$

- where x_k gives the probability mass in each bin at time-step k,
- A is a (transposed) Markov transition matrix.

Computing the *A* matrix

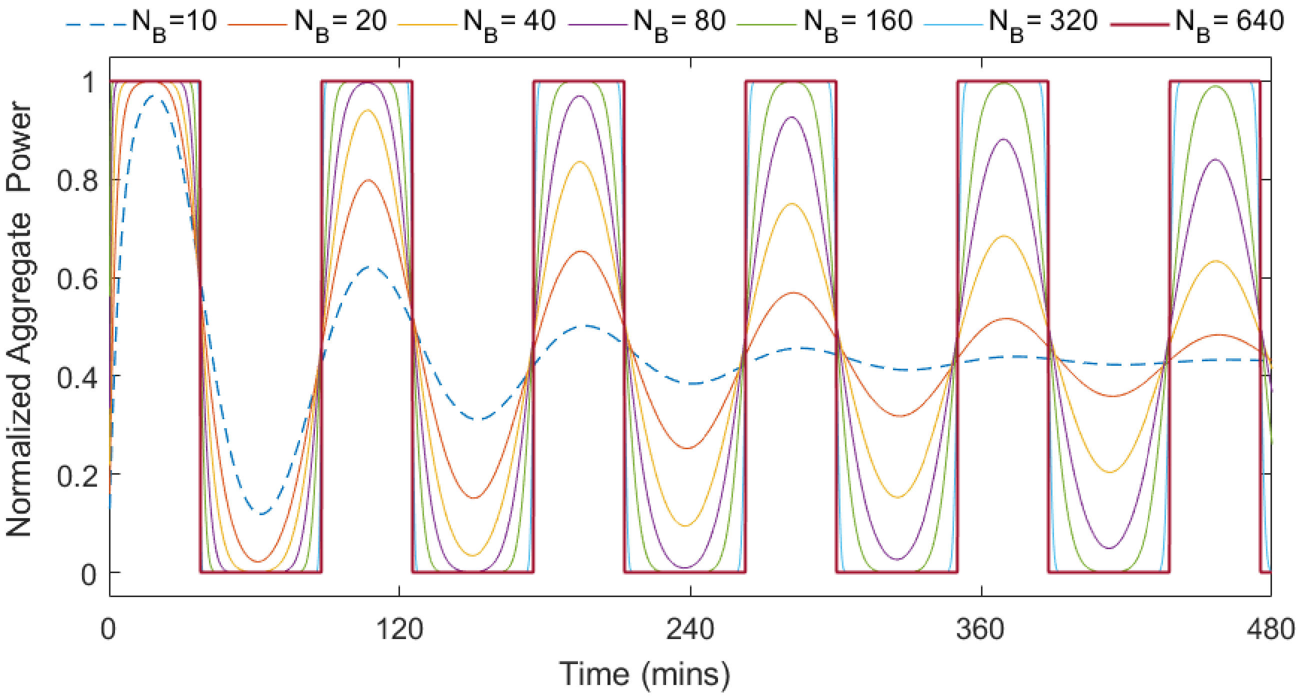
- Assume TCLs are uniformly distributed within a bin.
- Propagation forward is given by convolving the bin distribution with the noise distribution.



- Compute the new probability mass in each bin and distribute uniformly within that bin.
- Bin width and time-step (modelling decisions) affect the outcome.

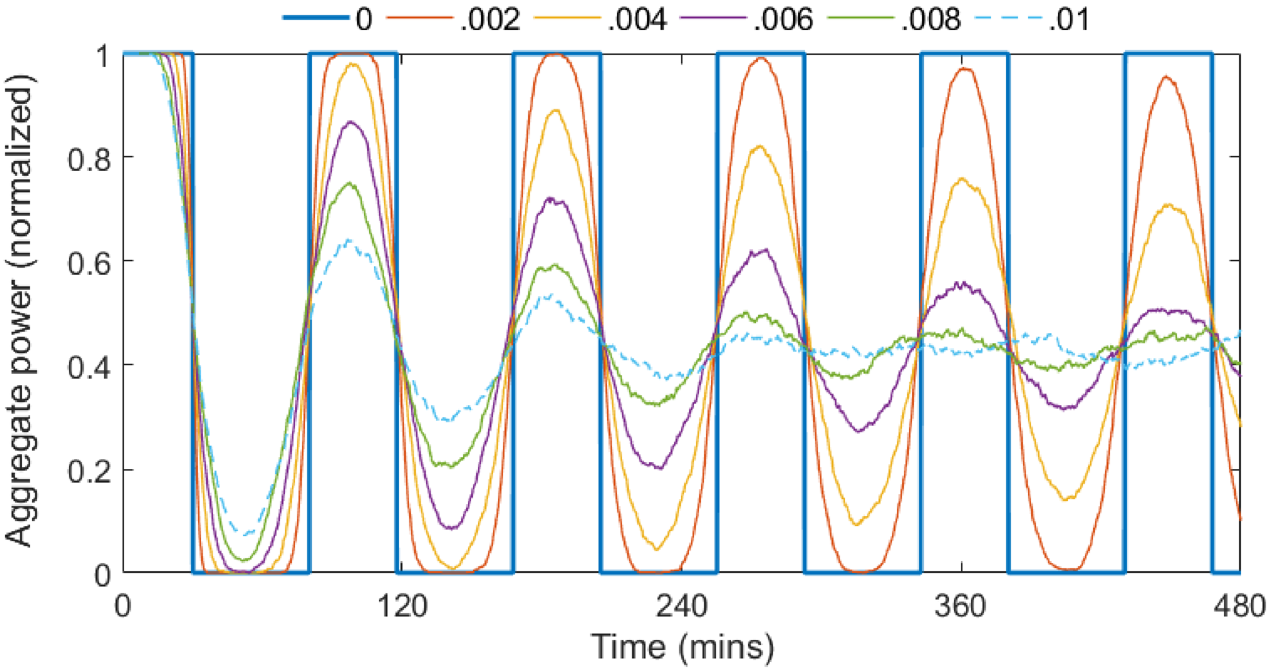
Impact of bin width

- Consider a homogeneous population of TCLs with no noise.
- Assume an initial condition where all TCLs are in the same bin, having just switched on.
- Total power consumed by the ensemble, for different numbers of bins, displays quite different behaviour.



Impact of background noise

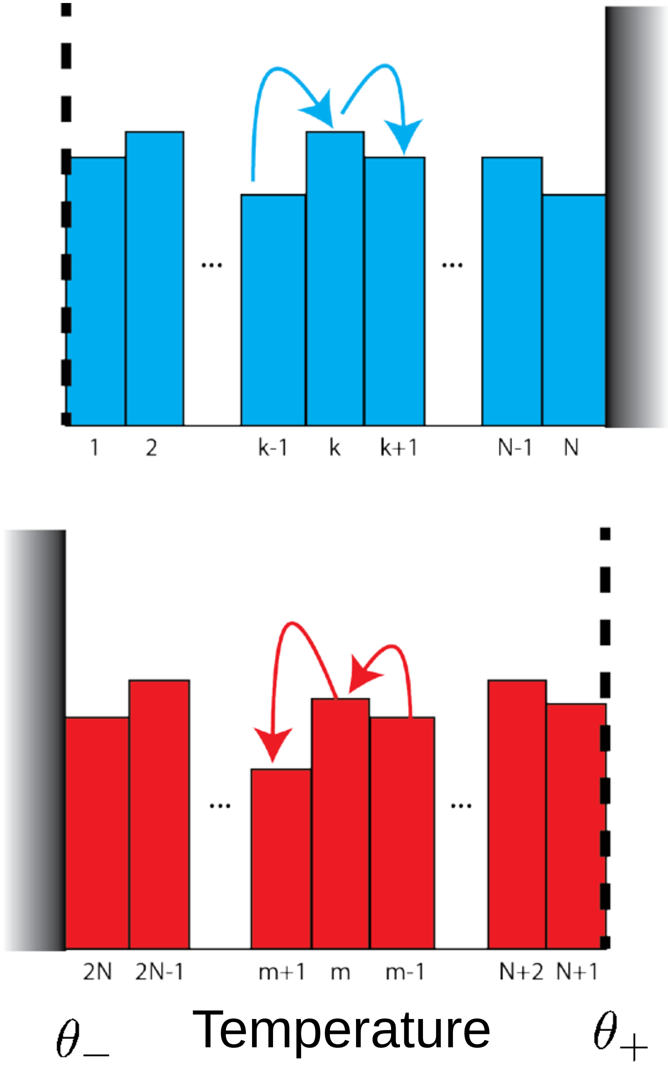
- Homogeneous population but different levels of noise.
- Same initial condition as previously.
- Accurate model (high number of bins).



Strategies for controlling TCL ensembles

- Variation of the set-point.
- “Transactive” control.
- There are (of course) many other possibilities.

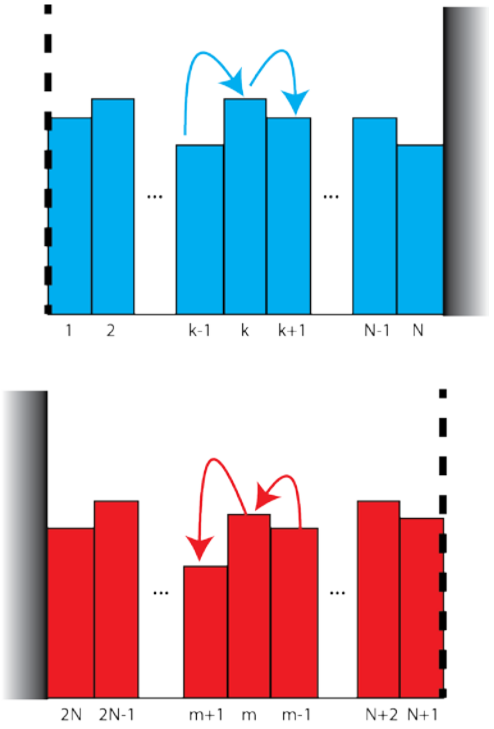
Set-point load control

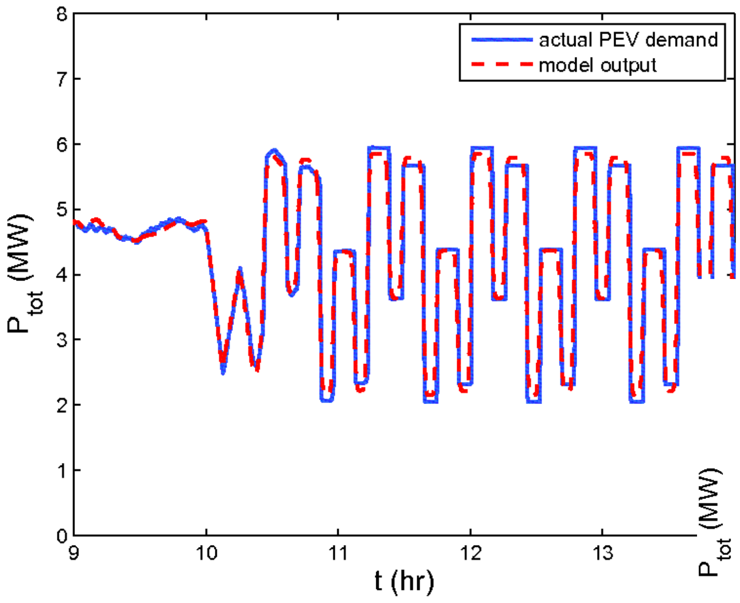


- Control strategy (for cooling loads):
  - Increase load by lowering set-point.
  - Decrease load by raising set-point.

Fast control

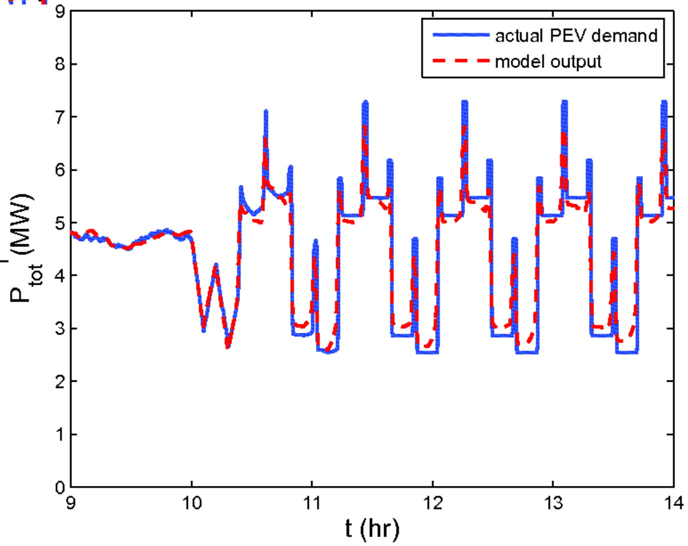
- The model is a nonlinear hybrid dynamical system.
  - Nonlinear because states and inputs multiple together.
  - Hybrid due to the influence of rapidly changing inputs.





Period-3 orbit,
Input period = 15.6 min

Period-4 orbit,
Input period = 12.4 min



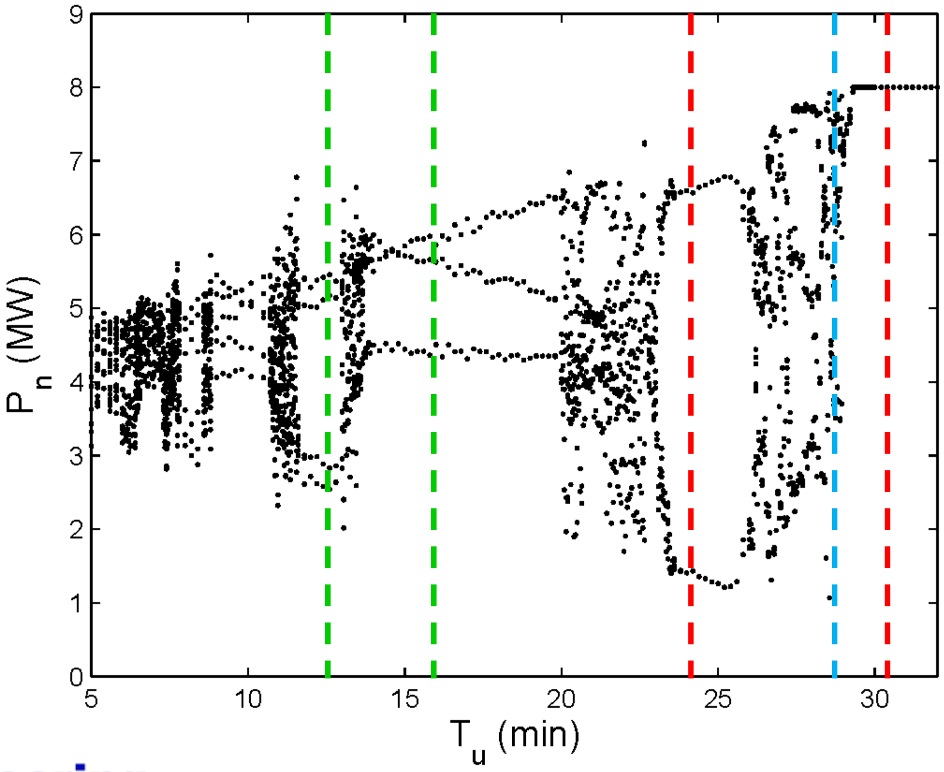
Bifurcation diagram

- Analysis of period-adding bifurcations was achieved using a Poincaré map:

$$P_n := P_{tot}(nT_u)$$

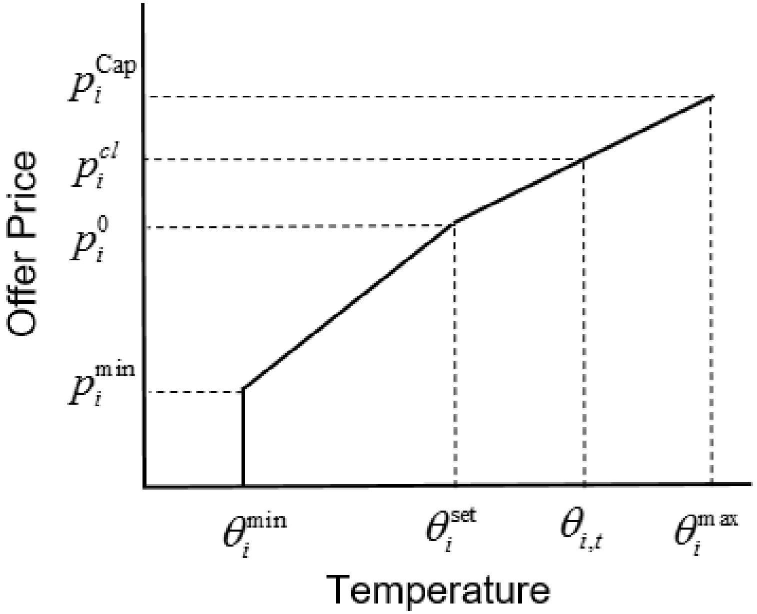
where T_u is the input period.

- Varying the input period T_u gave the bifurcation diagram:



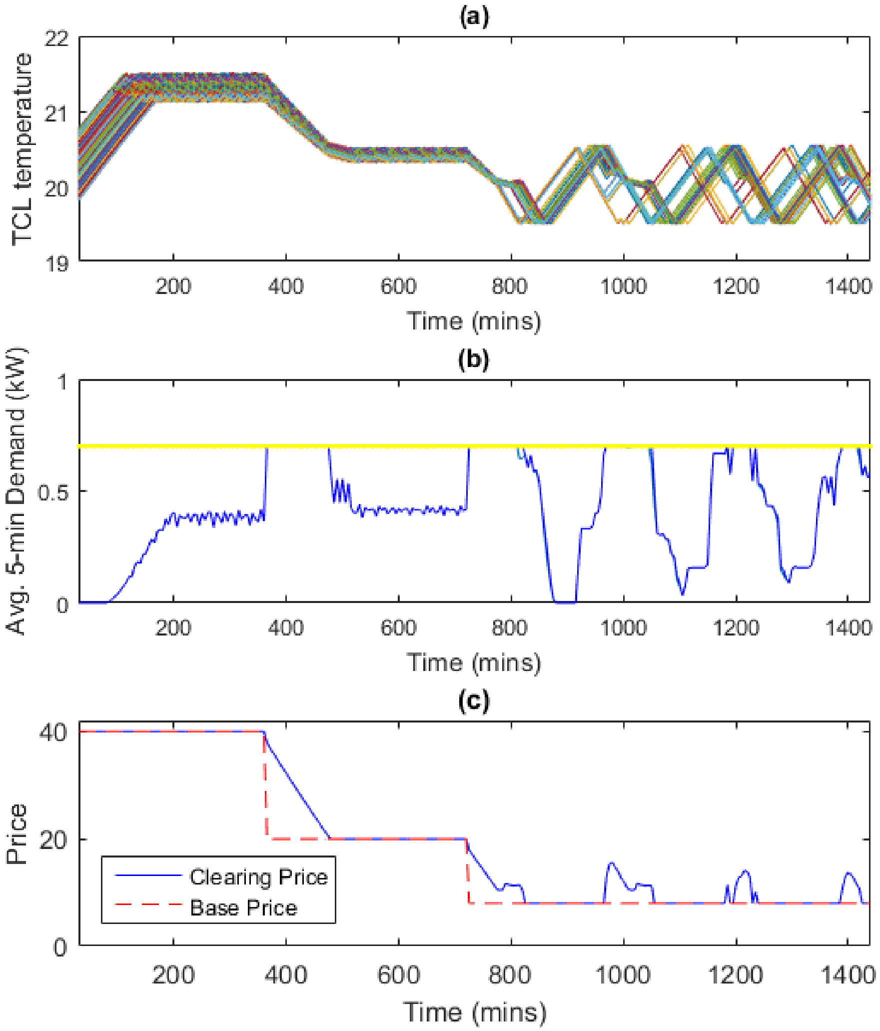
“Transactive” control

- Based on a market mechanism, “prices to devices”.
- TCLs are equipped with “smart” thermostats that relate comfort to bidding price.
  - Determine the bid based on a forecast of temperature in 5 minutes.



- Consider a distribution feeder with two large loads, e.g. EVs that are charging, and numerous air-conditioners.

TCL synchronization



Conclusions

- Significant actuation can be achieved through coordinated non-disruptive control of highly distributed loads.
- Numerous technical issues remain to be addressed:
  - Control structure.
  - Nonlinearity (bifurcations).
  - Latency.
  - Verifiability.
  - Interoperability.
  - Data security.
  - …