Event-Based Information Acquisition, Learning, and Control in High-Dimensional Cyber-Physical Systems

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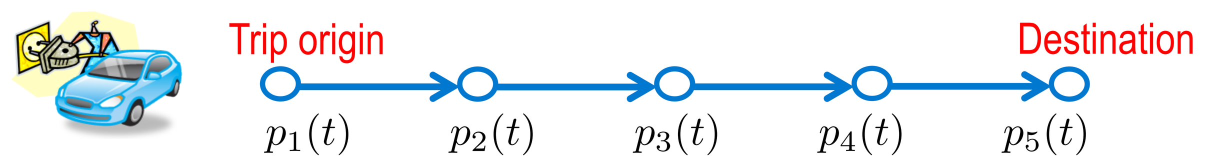
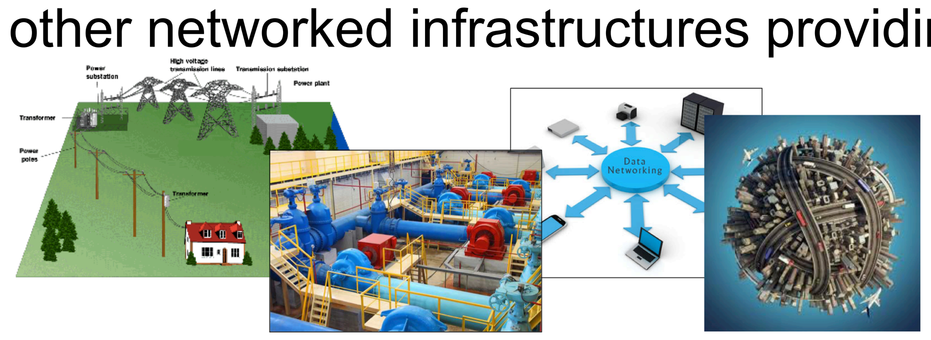
Motivation

- **Target CPS: power systems + networked infrastructure providing demand response (DR), e.g., electric transportation, data networks, etc.**
- Concrete example: Electric Vehicles → electric loads with the primary goal of serving transportation needs



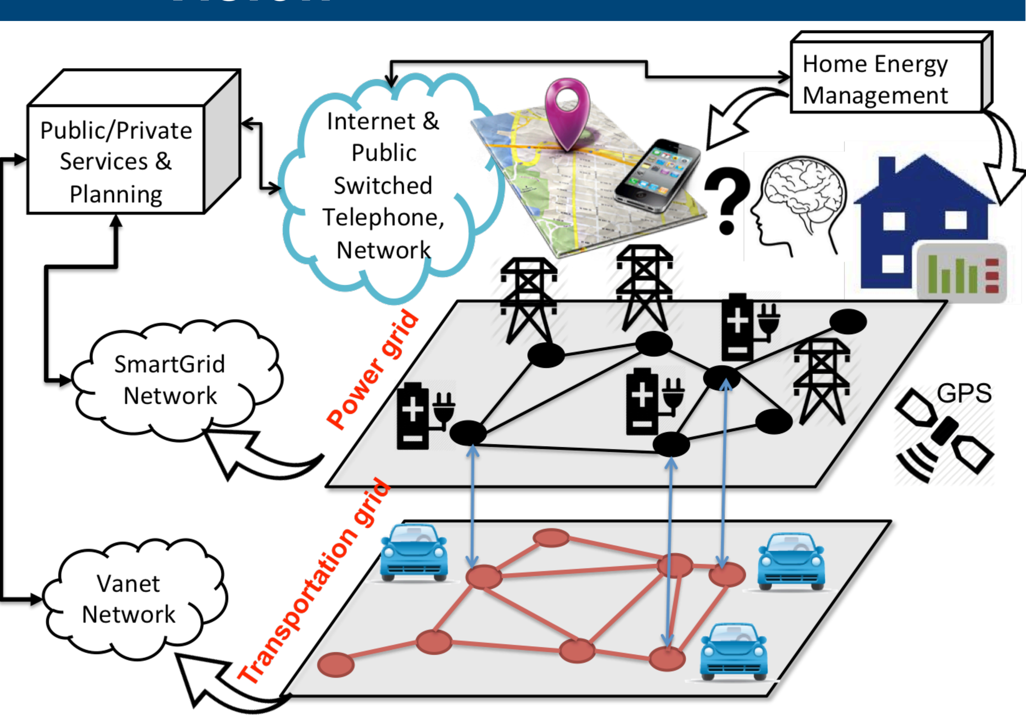
- Battery charging demand at geographically distributed stations affected by locational electricity pricing mechanisms
- Coupling between transportation needs and power grid load needs to be modeled for **reliable price design**
- Same for other networked infrastructures providing DR



Vision

We have developed results to model the effect of electricity costs in optimizing societal networked infrastructure operations management.

Control mechanisms in these infrastructures can affect grid prices through temporal and geographical load shifting. This leads to a feedback loop between these coupled networks.



- Feedback not modeled for power grid price design → harder to balance system → danger to system reliability
- We need to enable the system operator to model these infrastructures' response to posted electricity prices

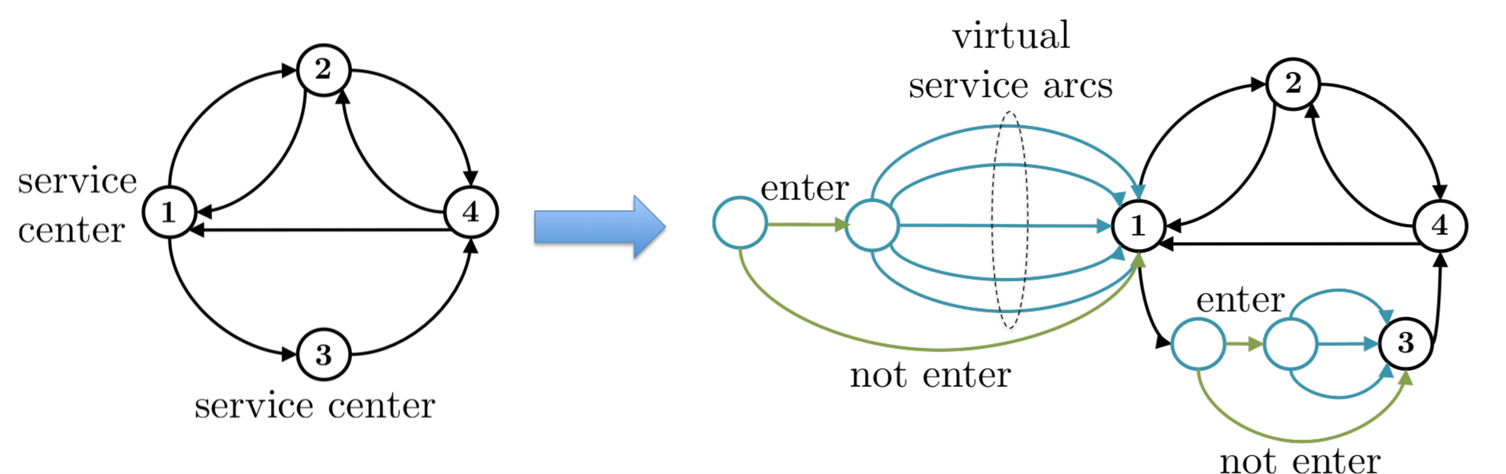
Research goals

- Develop reduced-state and decentralized network control frameworks and pricing mechanisms that
  - ensure reliability within acceptable margins of error
  - model retailers and human behavior in the control loop
  - enable layered solutions that need minimal coordination between various players in these complex systems
  - learn user behavior and protect user privacy
- Design control signals to extract desired demand response both at the transmission level as well as the distribution level
- Optimal placement of resources based on data analytics

Individual user decision model

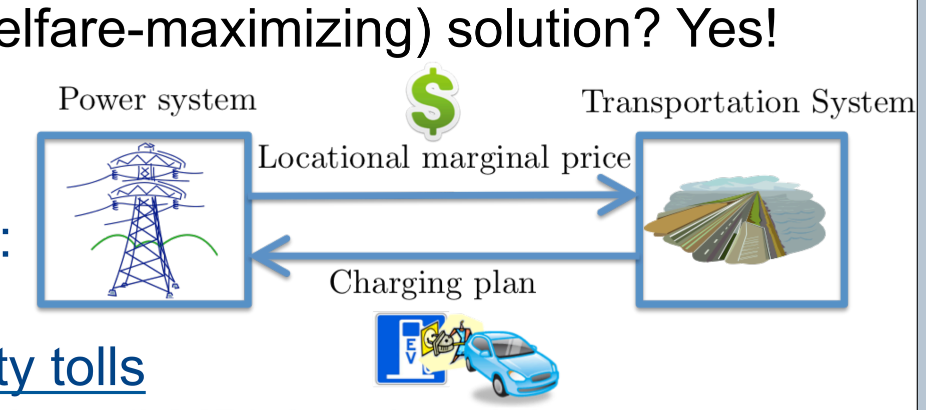
- Problem: jointly decide best transportation path and service type (e.g., charge amount) to receive at one or more service centers en route

- **Proposed solution: Extended infrastructure network with virtual service links** → find shortest path (that is resource-feasible, e.g., never run out of charge or charge battery above capacity)



Optimal control and marginal pricing with no retailers

- Heterogeneous demand → different O-D + request types
- Aggregate effect of individual decisions → Equilibrium flow in two infrastructure networks
- Can two independent system operators collaboratively design control mechanisms such that selfish user network equilibrium turns into an efficient (welfare-maximizing) solution? Yes!



Results:

- Operators jointly design:
  - Link congestion tolls
  - Service center capacity tolls
  - Locational marginal prices (LMP) for electricity

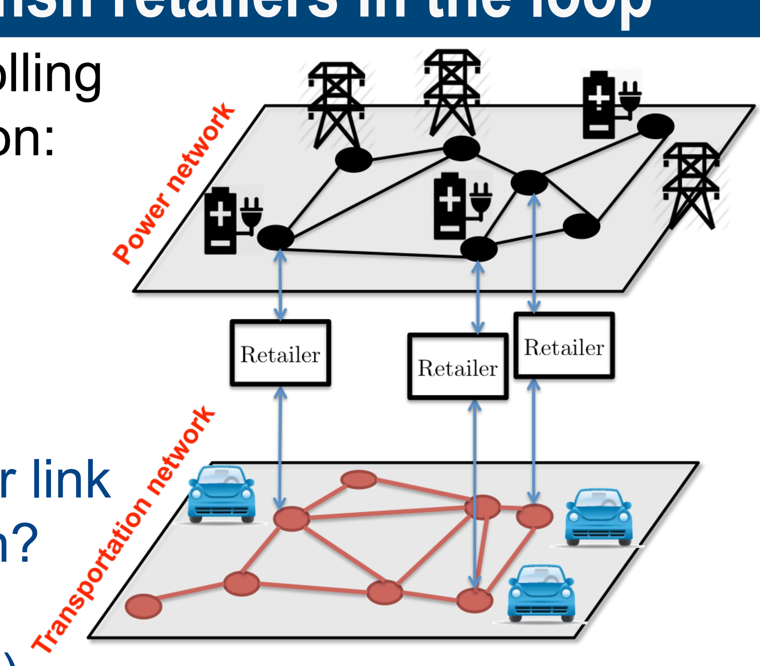
  such that the Wardrop equilibrium is socially optimal
- Operators can use Lagrangian dual decomposition to calculate optimal prices while keeping system data private
- No operator collaboration: we calculate the ``reserve generation capacity" so grid operator can learn user response

Optimal pricing with selfish retailers in the loop

- Effect of selfish retailers controlling significant portions of population:

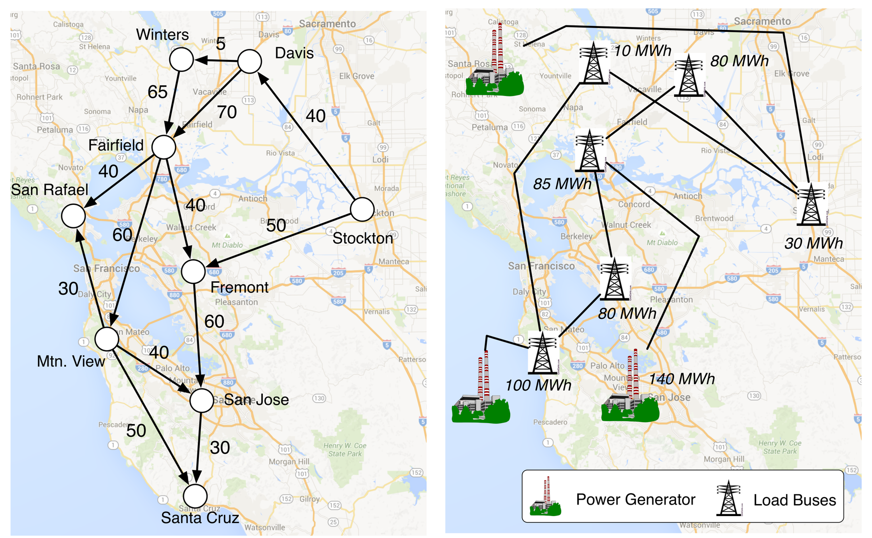
Results:

- The social optimum can be enforced as a Nash eq. iff all virtual links can be taxed.
- Service center capacity tolls or link congestions tolls not an option? Equilibrium problem with equilibrium constraints (EPEC)



Example illustrating importance of research

- Question: what happens if transportation and power systems are disjointedly managed like today?
- Prices (LMPs and tolls) updated iteratively



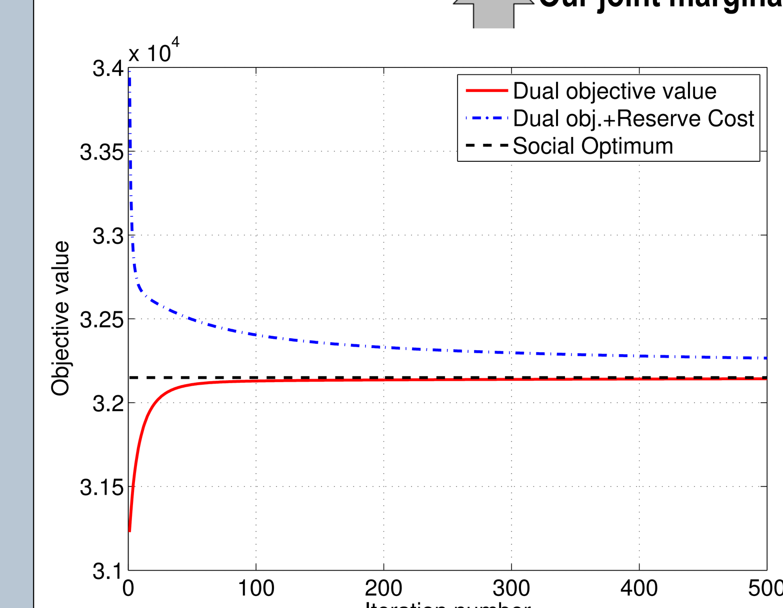
IEEE 9 bus test case overlaid on a simple transportation network modeling San Francisco bay area. The value next to each link is minimum travel time T_a (in minutes) and the base (other than EV) load at each node is in italic. Each node in the network is equipped with a fast charging station.

- Simulation setting: static
  - All EVs consumes 1 kWh each 25 miles
  - Cost of unit time spent en route (γ) = 0.1 cent per 5 min
  - Flow to travel time mapping: $\tau_a(\lambda_a) = T_a + \lambda_a/10^4$
  - Rate of travel: 2000, 10000, 10000 EVs, initial charge of 2,3, and 4 kWh respectively
  - Fast charge rate: 1 kWh to each EV every 5 mins

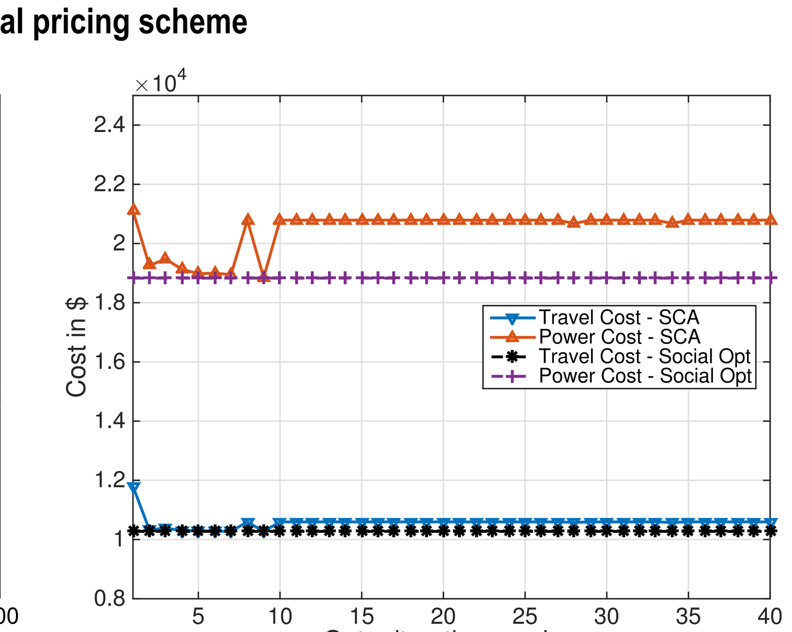
	Joint SO	DP (iter. odd)	DP (iter. even)
Davis	91.67 MWh @$53.43/MWh	110.0 MWh @$54.49/MWh	15.411 MWh @$66.45/MWh
Winters	35.27 MWh @$51.76/MWh	4.921 MWh @$54.49/MWh	46.12 MWh @$44.50/MWh
Fairfield	18.82 MWh @$52.09/MWh	15.93 MWh @$54.49/MWh	84.12 MWh @$48.84/MWh

Notice significant oscillation in LMPs under disjoint model

Our joint marginal pricing scheme



No operator collaboration → Reserve costs to find optimal prices



With retailers in the loop → EPEC SCA → Successive Convex Approx.

Future Work

- Parsing human preference parameters (heterogeneous)
- Stochastic modeling (everything deterministic here)
- Elastic travel demand modeling (customers deciding not to travel if electricity is expensive)
- Profit-maximizing retail price design considering distribution network congestion as well as customer switching decisions

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