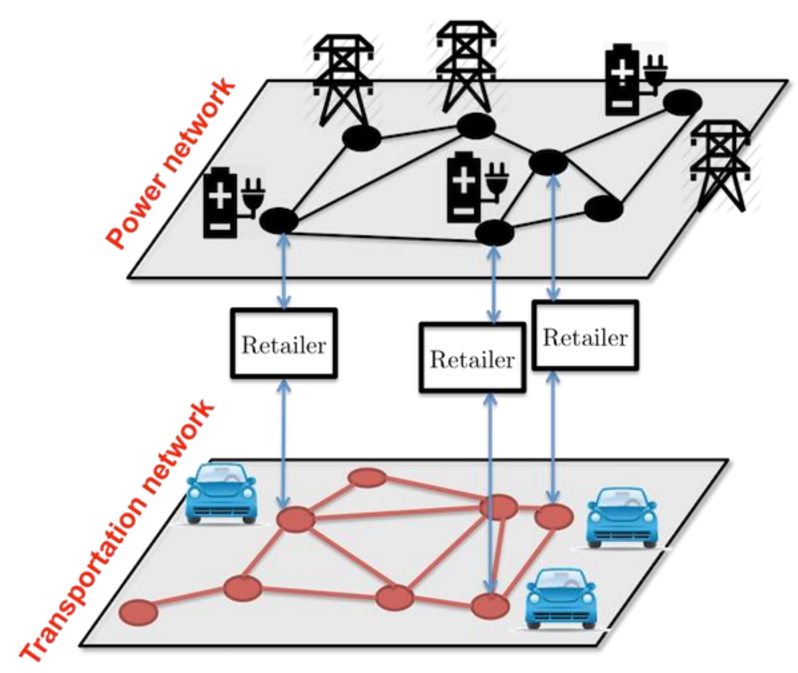
Security Gaps Arising due to Large Infrastructures Coupled with Energy Delivery Systems

Modeling Instabilities in Infrastructures Coupled with the Grid

Mahnoosh Alizadeh, Hoi-To Wai, Anna Scaglione, and Andrea Goldsmith

GOALS / CHALLENGES

Many large infrastructure networks are ***COUPLED*** *with power networks!*



- Examples of coupled infrastructure networks:
  - Electric vehicles (EVs).
  - Data centers.
  - Gas and water networks.

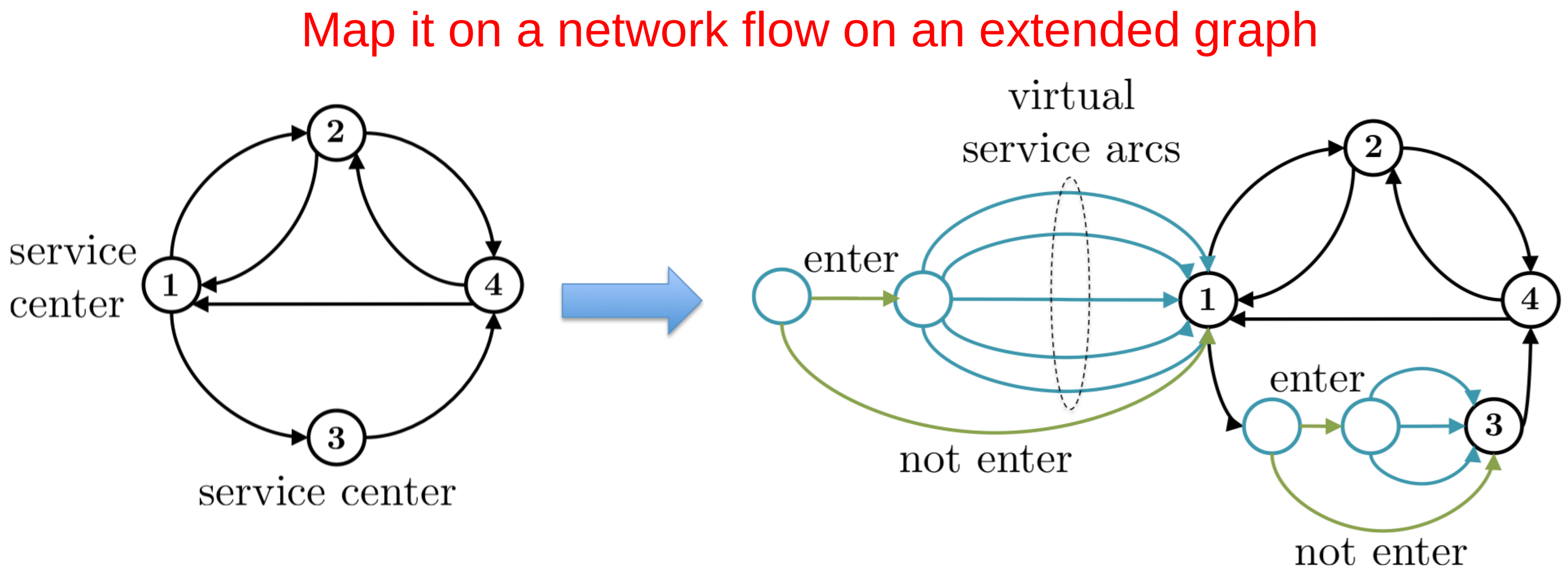
- *Problem:* Adopting a naïve, disjoint pricing strategy may result in **insecure** and **unstable** behavior for both infrastructures: shortages/congestion or waste
- *Goal*: to investigate *optimal interaction* strategies for coupled infrastructure to avoid "predator prey" behavior. We propose:
  - Stable Maximum Social Surplus
  - Distributed algorithm for achieving stable optimum

MODELING COUPLED INFRASTRUCTURES

MATHEMATICAL MODEL FOR COUPLED NETWORKS

- The infrastructure owner's decision is a *network flow problem.*
  - Getting service takes time and cost, feasible paths.
- Receiving electricity takes time = Having longer trip (longer service time).
- Idea to characterize the interaction of the two networks:

Map it on a network flow on an extended graph



- How? Adding virtual links at the service centers (= quantization of the services requested from the grid)

COUPLED INFRASTRUCTURES INTERDEPENDENCY

- Objective:
- Minimum service delay+cost

$$\min_{\boldsymbol{\lambda}} \boldsymbol{\lambda}^T \boldsymbol{s}(\boldsymbol{\lambda}) + \mathbf{p}^T \mathbf{E} \boldsymbol{\lambda}$$

- Utopia: infrastructure and the power system operator (IPSO) cooperating

IPSO solves the economic dispatch problem, with the power demand modulated by services on infrastructure network.

$$\min_{\mathbf{g},\boldsymbol{\lambda}} \boldsymbol{\lambda}^T \boldsymbol{s}(\boldsymbol{\lambda}) + \mathbf{1}^T \boldsymbol{c}(\mathbf{g})$$

s.t. Power system constraints:

$$\mathbf{1}^T(\mathbf{e}+\mathbf{u}-\mathbf{g}) = 0, \quad \rightarrow \text{[balance]}$$

$$\mathbf{H}(\mathbf{e}+\mathbf{u}-\mathbf{g}) \preceq \mathbf{c}, \quad \rightarrow \text{[line flow limit]}$$

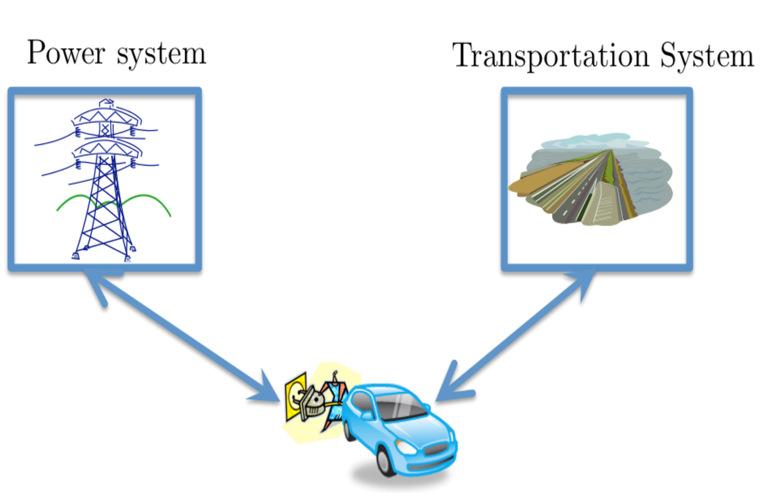
$$\mathbf{e} = \mathbf{E}\boldsymbol{\lambda} \quad \rightarrow \text{[virtual flow to demand mapping]}$$

Flow as a function of path decisions:

$$\mathbf{d}_q \succeq \mathbf{0}, \quad \mathbf{1}^T \mathbf{d}_q = a_q, \quad \boldsymbol{\lambda} = \sum_{q \in \mathcal{Q}} \boldsymbol{\Delta}_q \mathbf{d}_q \quad \rightarrow \text{[service requirement]}$$

- In real world, the two systems are operated separately.

This will result in oscillating behavior!!!



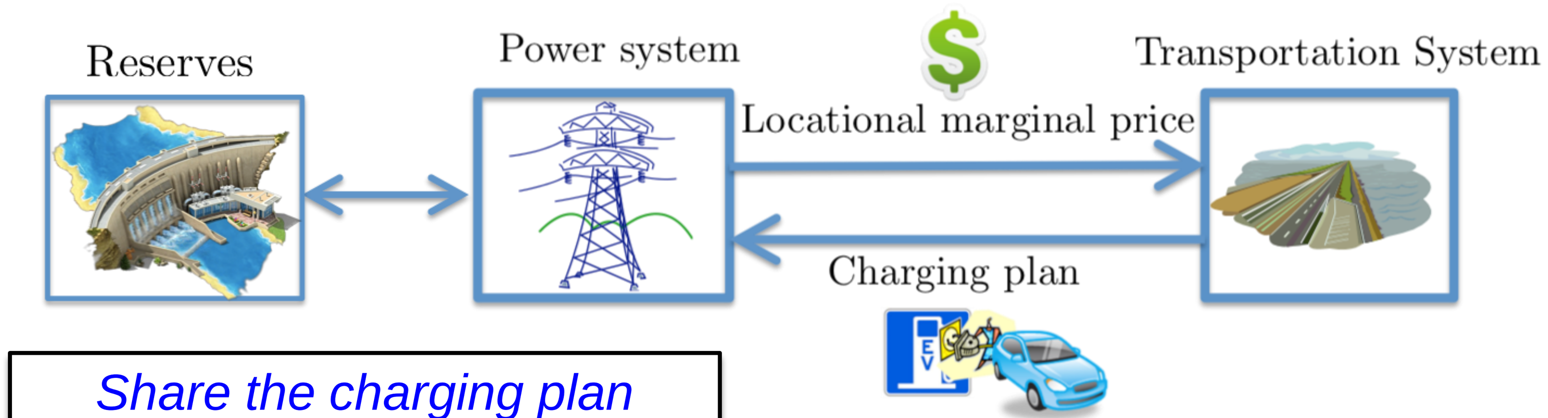
Disjoint pricing mechanism:

1. Design electricity prices while fixing infrastructure decision.
2. Find optimum path on the extended graph (decentralized or centralized)
3. Repeat steps 1 & 2…

This does not converge

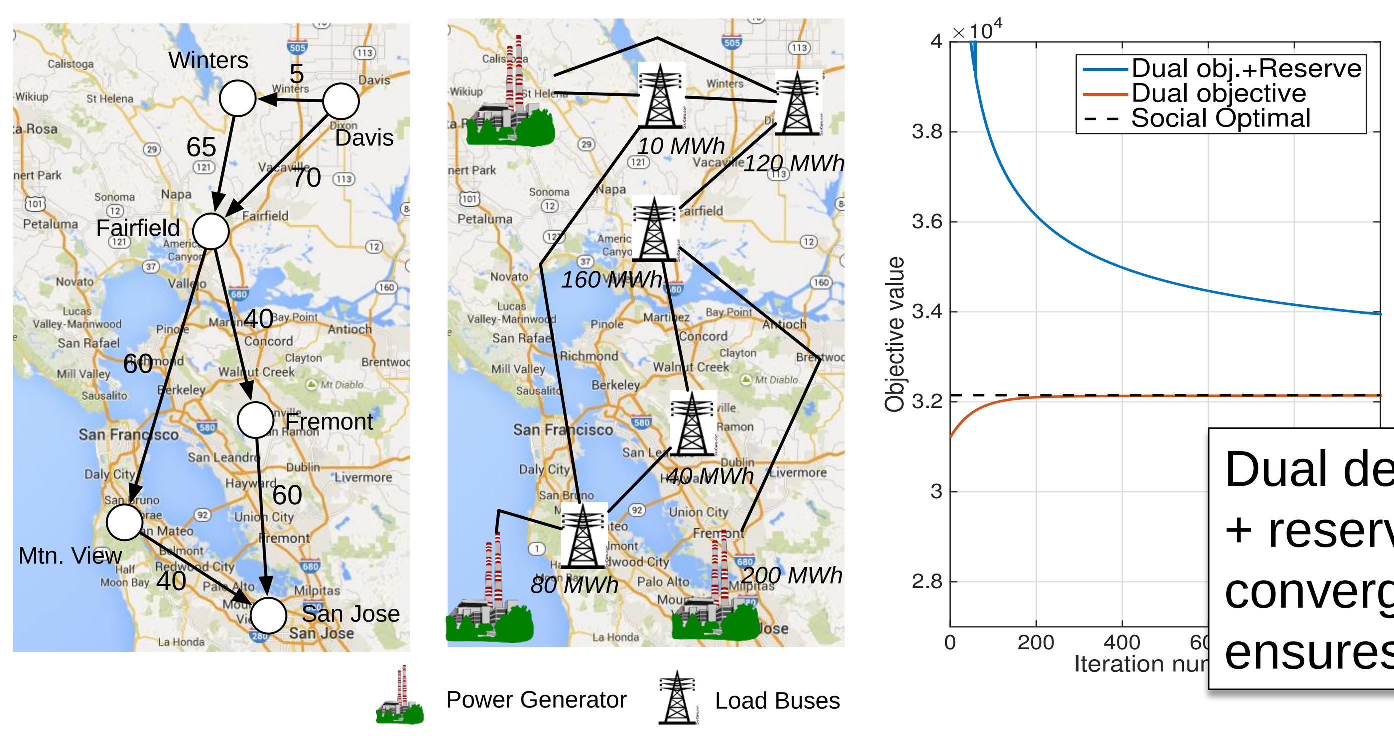
RESEARCH SOLUTION

1) DUAL-DECOMPOSITION ALGORITHM w/ RESERVE OPT.



Share the charging plan for given dual variable (more than metering!)

- Dual decomposition algorithm applied on the SO problem.
  - At each iteration: passing *electricity price* (from IPSO) and the *network flow pattern* (from infrastructure).
  - To tackle infeasibility during the dual decomposition iterations, we propose a reserve optimization strategy.
  - Bounds on the worst-case infeasibility of the IPSO problem.
- Below the test of the dual decomposition method on a fictitious coupled infrastructure network with EVs, modeled after the Bay Area.



Dual decompose + reserve opt. converges and ensures feasibility

	Social Optimum	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
Fremont	0.211 MWh @\$52.33/MWh	7.819 MWh @\$54.49/MWh	0.00 MWh @\$51.93/MWh
Mtn. View	0.103 MWh @\$52.85/MWh	7.326 MWh @\$54.49/MWh	0.00 MWh @\$58.85/MWh

Naïve disjoint electricity pricing scheme may result in **oscillating** behavior!

2) BI-LEVEL OPTIMIZATION FOR OPTIMAL PRICING OF NE

- There are *multiple* retailers operating the infrastructure.
- The retailers individually optimize their flows on the **same** network.
- Aim: optimal pricing for IPSO that leads to a Nash equilibrium (NE).

$$\begin{aligned} \min_{\mathbf{g},\mathbf{p}} \quad & \mathbf{1}^T \mathbf{c}(\mathbf{g}) \\ \text{s.t.} \quad & \mathbf{g} \geq \mathbf{0}, \ \mathbf{p} = \mathbf{H}^T \boldsymbol{\mu} + \gamma \mathbf{1}, \\ & \gamma : \mathbf{1}^T(\mathbf{d} + \boldsymbol{\ell} - \mathbf{g}) = \mathbf{0}, \ \boldsymbol{\mu} : \mathbf{H}(\mathbf{d} + \boldsymbol{\ell} - \mathbf{g}) \leq \boldsymbol{m}, \\ & \mathbf{d} = \boldsymbol{M} \textstyle\sum_{r \in \mathcal{R}} \boldsymbol{\lambda}^r, \\ & \forall\, r \in \mathcal{R} : \boldsymbol{\lambda}^r = \arg \min_{\tilde{\boldsymbol{\lambda}}^r \in \mathcal{F}^r} J(\tilde{\boldsymbol{\lambda}}^r; \boldsymbol{\lambda}^{-r}; \mathbf{p}). \end{aligned}$$

Bi-level *optimization problem*

- The bi-level problem can be solved as a mixed integer program.

BROADER IMPACT

- First mathematical model for characterizing the interaction between the grid and coupled infrastructure networks
- We formulate and propose various solutions for cost optimization under different applications.
- We demonstrated the perils in adopting naïve disjoint pricing scheme in coupled infrastructure problems.

FUTURE EFFORTS

- Investigate the security aspect in the proposed formulations.
- Study the effects on the system when it is not at equilibrium.

M. Alizadeh, H.-T. Wai, M. Chowdhury, A. Goldsmith, A. Scaglione, and T. Javidi, "Joint Management of Electric Vehicles in Coupled Power and Transportation Networks," [Online] http://arxiv.org/pdf/1511.03611.pdf

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