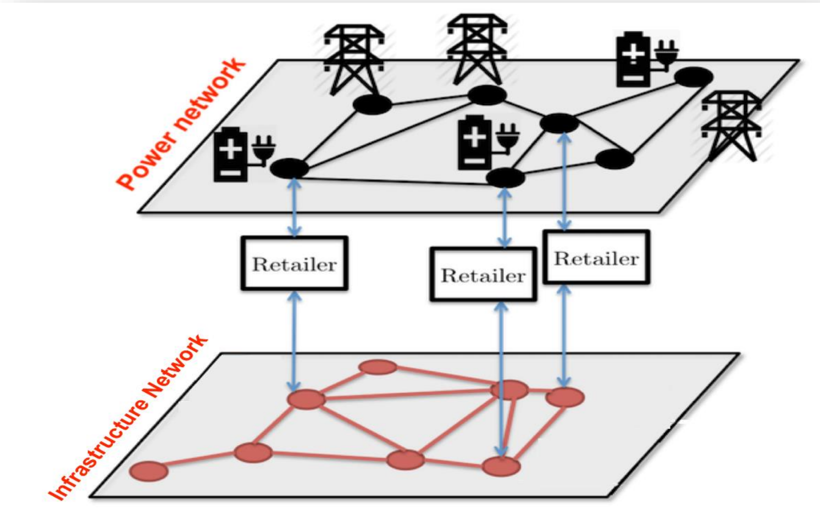
Security Gaps due to Coupling of Energy Delivery Sub-systems

Modeling Secure Coupled Infrastructure Operations

Mahnoosh Alizadeh (UC Santa Barbara), Hoi-To Wai (ASU), Anna Scaglione (ASU), Andrea Goldsmith (Stanford), Eran Schweitzer

GOALS

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



- Examples of coupled infrastructure networks
  - Gas network
  - Water Network
  - Electric vehicles (EVs)
  - Data centers

- ***Goal***: to investigate the way coupled infrastructure can address the issue of resilience in concert
- We start by studying congestion and possible wide area oscillations
  - **In an ideal world**: Maximum Social Surplus solution (or Social Optimum (SO)) finds the optimum settings across the infrastructures (most secure)
  - **Can the systems operate and recover separately and still be secure?**

BACKGROUND STUDIES / FORMULATION

MAX. SOCIAL SURPLUS SOLUTION w/ COUPLED OPTIMIZATION

- Utopia-like, when the infrastructure and IPSO are fully cooperating.

$$\min_{\mathbf{g},\mathbf{e},\boldsymbol{\lambda}} \; J_{\text{Power}}(\boldsymbol{g}) + J_{\text{Infrast./Gas}}(\boldsymbol{\lambda})$$

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

s.t. Power system constraints:

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

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

$$\mathbf{0} = \boldsymbol{f}(\mathbf{e},\boldsymbol{\lambda}) \quad \rightarrow \text{[infrast. to elect. demand map]}$$

Operation constraints for infrastructure

EXAMPLES OF INFRASTRUCTURE SYSTEMS

Electric Vehicle Network

Possible paths: $\mathcal{Q}$

- Decision: **flows** of EVs $\boldsymbol{\lambda} \in \mathbb{R}^{|E|}$

Utility function: $J_{\text{EV}}(\boldsymbol{\lambda}) = \boldsymbol{\lambda}^T \boldsymbol{s}(\boldsymbol{\lambda})$

Coupling constraints: $\boldsymbol{f}(\mathbf{e},\boldsymbol{\lambda}) = \mathbf{E}\boldsymbol{\lambda} - \mathbf{e}$

Operation constraints:

[non-negativity] $\mathbf{d}_q \geq \mathbf{0}$ [individual demand] $\mathbf{1}^T\mathbf{d}_q = a_q$ [map from path flow to total flow] $\boldsymbol{\lambda} = \sum_{q\in\mathcal{Q}} \mathbf{A}_q \mathbf{d}_q$

Gas Pipeline Network

- Decision variables: $\boldsymbol{\lambda} = (\boldsymbol{d}, \boldsymbol{\alpha}, \boldsymbol{\rho}, \boldsymbol{\phi})$

Gas withdrawal

Compressors (controllable)

Pressure

Mass flows

Utility function: $J_{\text{Gas}}(\boldsymbol{\lambda}) = \sum_{(i,j)\in C} |\phi_{\pi_e(ij)}| (\max\{\alpha_{ij}, 1\}^{2m} - 1)$

Coupling constraints: $\boldsymbol{f}(\mathbf{e},\boldsymbol{\lambda}) = q_0 + q_1\mathbf{e} + q_2\mathbf{e}^2 - \boldsymbol{d}$

Operation constraints:

[gas withdrawal demand] $\boldsymbol{d} = \boldsymbol{A}_d\boldsymbol{\phi}$ [compressors limit] $\mathbf{1} \leq \boldsymbol{\alpha} \leq \boldsymbol{\alpha}^{max}$ [pressure limit of pipelines] $\boldsymbol{\rho}^{min} \leq \boldsymbol{\alpha\rho} \leq \boldsymbol{\rho}^{max}$

[*steady state* of gas flow equations]

$$\mathbf{B}_s(\boldsymbol{\alpha})\boldsymbol{s} + \mathbf{B}_d(\boldsymbol{\alpha})\boldsymbol{\rho} = -\boldsymbol{\Lambda}K\boldsymbol{g}(\boldsymbol{\phi}, |\mathbf{B}_s(\boldsymbol{\alpha})|\boldsymbol{s} + |\mathbf{B}_d(\boldsymbol{\alpha})|\boldsymbol{\rho})$$

MULTIPLE INFRASTRUCTURE OPERATORS

- Assume *multiple* retailers operating the infrastructure.
- The retailers individually choose their flow on the **same** network.

$$\boldsymbol{\lambda}^r = \arg\min_{\hat{\boldsymbol{\lambda}}^r \in \mathcal{F}^r} J(\hat{\boldsymbol{\lambda}}^r; \boldsymbol{\lambda}^{-r}; \mathbf{p})$$

Retailer *r* has only control of its virtual flow and has its private demand to satisfy.

SECURITY CONCERNS:

- Static Model Oscillations? → Any Nash Equilibrium (NE)?
- Dynamic Model? → Resonant frequencies for the pipelines!

RESEARCH RESULTS – STEADY STATE MODEL

EXISTENCE OF NASH EQUILIBRIUM & UNIQUENESS

- For the special case of EV network, the multi-retailer problem is a special case of the competition game in network routing.
- Therefore an NE will always exist[a]. Furthermore, the NE is unique[b] if

$$s_a(\lambda_a) \propto (\lambda_a)^\alpha \quad \text{with } \alpha \leq (3R-1)/(R-1)$$

[a] A. Orda, R. Rom, and N. Shimkin, "Competitive routing in multiuser communication networks," IEEE ToN, 1993.
[b] E. Altman, T. Basar, T. Jimenez, and N. Shimkin, "Competitive routing in networks with polynomial costs," *IEEE TAC*, 2002.

As number of retailers, R, increases, the NE may be non-unique for large α.

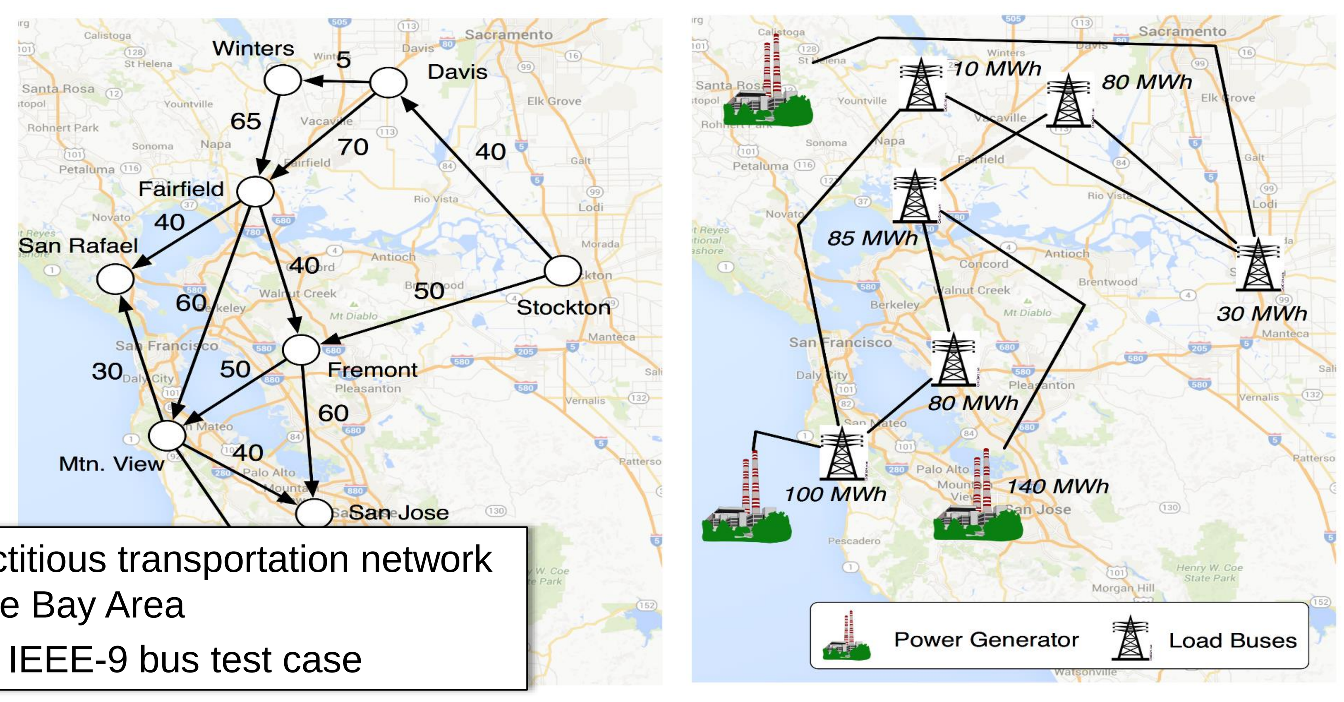
FINDING THE NE VIA BI-LEVEL OPTIMIZATION

- Aim: find optimal pricing for IPSO that leads to a Nash Equilibrium.

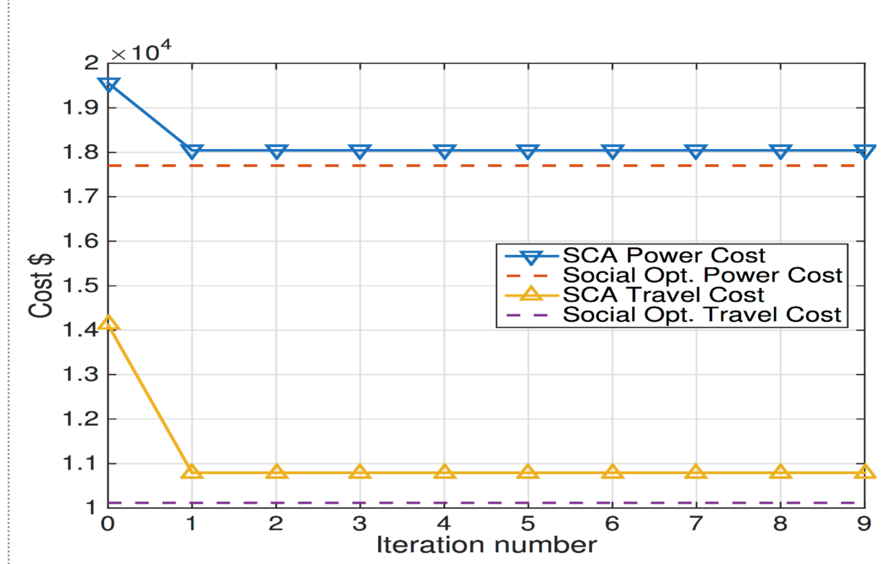
$$\begin{aligned} \min_{\mathbf{g},\mathbf{p}} \quad & \mathbf{1}^T\mathbf{c}(\mathbf{g}) \\ \text{s.t.} \quad & \mathbf{g} \geq \mathbf{0}, \; \mathbf{p} = \mathbf{H}^T\boldsymbol{\mu} + \gamma\mathbf{1}, \\ & \gamma : \mathbf{1}^T(\mathbf{d} + \boldsymbol{\ell} - \mathbf{g}) = \mathbf{0}, \; \boldsymbol{\mu}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

Bi-level *optimization problem*

- Leader-Follower structure --- leader: IPSO, follower: retailers
- The bi-level problem can be solved as a mixed integer program.
- Invokes convex approximation to handle the non-convex constraints.



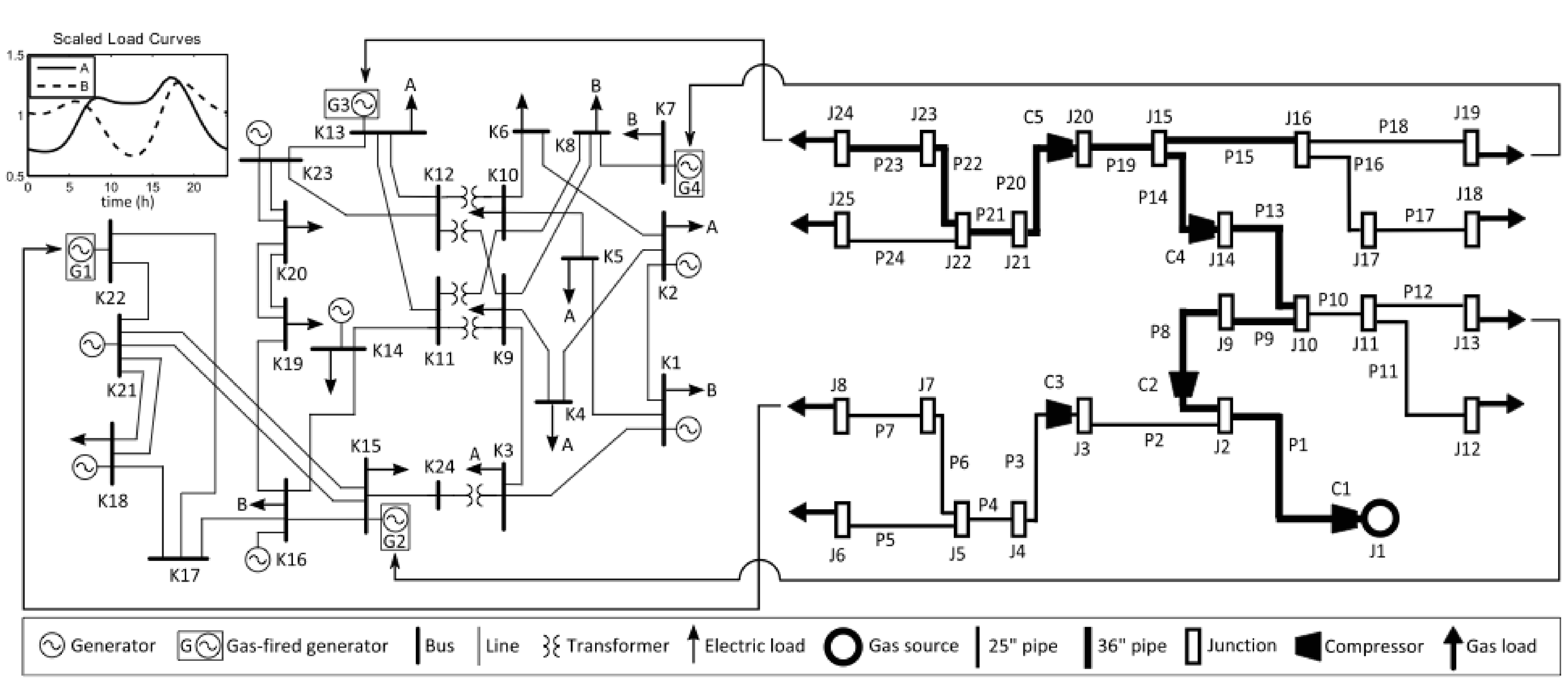
- Infrastructure: fictitious transportation network modeled after the Bay Area
- Power: modified IEEE-9 bus test case



Cost of NE vs Social Optimal solution can be bounded by the Price of Anarchy (PoA), can be calculated in closed form.

- NE exists in the simulated case
- Bi-level optimization does not find the socially optimal solution
- PoA for this case is bounded by 1.46.

GAS PIPELINE SYSTEM COUPLED WITH POWER SYSTEM



[c] A. Zlotnik, L. Roald, S. Backhaus, M. Chertkov, and G. Andersson, "Coordinated scheduling for interdependent electric power and natural gas infrastructures," IEEE TPS, 2016.

- Prior study[c] showed that when the Max Social Surplus problem was solved separately, then system instability may occur.
- We anticipate that the situation can be exacerbated with competitive gas retailers. ➔ Security issue!

FUTURE WORK

- Gas network: do NE points exist?
- Looking at attacks to control system for pipelines or grid that can induce dynamic resonance for pipelines

M. Alizadeh, H.-T. Wai, A. Goldsmith, and A. Scaglione, ``Optimal Electricity Pricing for Societal Infrastructure Systems", in 50th HICSS Conference.
M. Alizadeh, H.-T. Wai, A. Goldsmith, and A. Scaglione, ``Marginal Charging Station Pricing in an Intelligent Electric Transportation System", accepted by ACC 2017.

CYBER RESILIENT ENERGY DELIVERY CONSORTIUM | CRED-C.ORG
FUNDING SUPPORT PROVIDED BY THE U.S. DEPARTMENT OF ENERGY AND THE U.S. DEPARTMENT OF HOMELAND SECURITY