MIT School of Engineering

Civil and Environmental Engineering

CAREER: Resilient Design of Networked Infrastructure Systems: Models, Validation, and Synthesis

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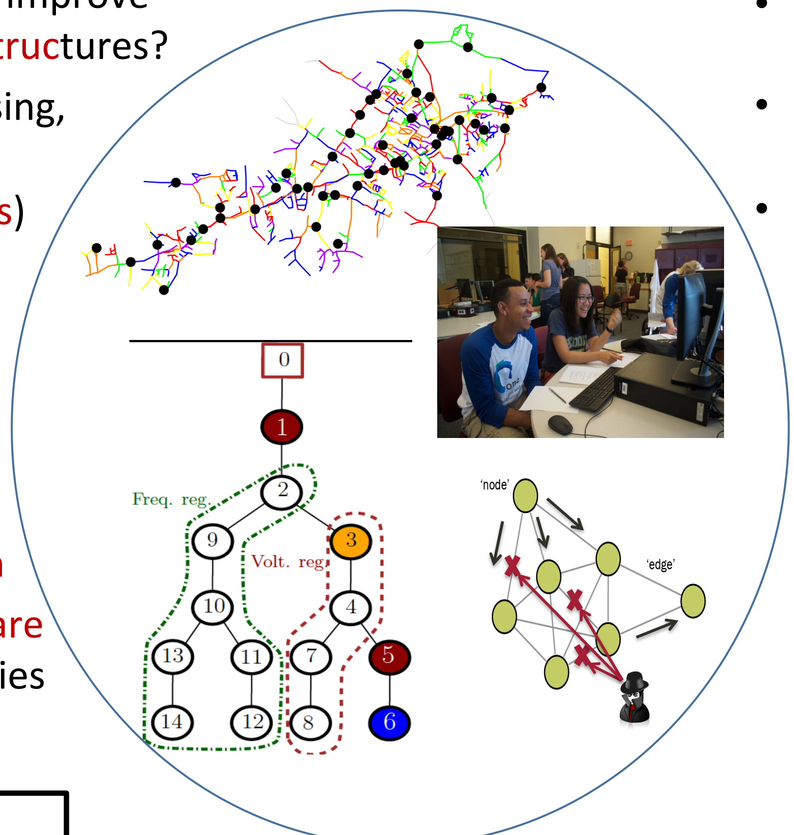
CAREER: Resilient Design of Networked Infrastructure Systems: Models, Validation, and Synthesis

Challenge:

- Which design methods can improve the resilience of civil infrastructures?
- Strategies for network sensing, routing, and control under disruptions (faults & attacks)

Solution:

- **Strategic layer**: Attacker-defender games for design of strategic sensing and optimal resource allocation
- **Control layer**: Incident-aware control and routing strategies in traffic flow networks



Scientific Impact:

- Estimating social welfare of traffic information systems
- Structural characterization of optimal strategies
- Scalable algorithms with performance guarantees

Broader Impact:

- Urban water, Freeway traffic, and Electricity distribution networks
- Google, EPRI, PUB
- New subjects on resilient networks & sustainability
- Online security games

CPS Award: CNS 1453126

Saurabh Amin (MIT)

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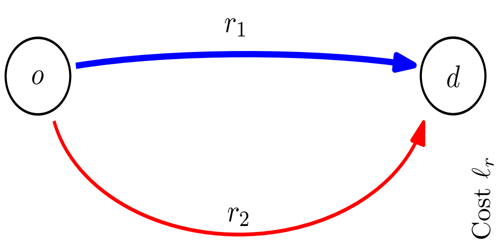
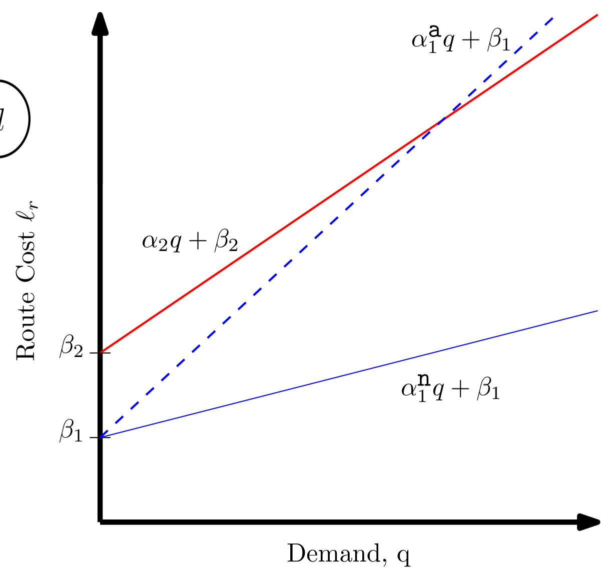
Effects of heterogeneous information on traffic congestion: Motivation

- Traffic information services (TIS) are changing how travelers make routing decisions
    - Inherent heterogeneities in TIS adoption and accuracy
- How does heterogeneous information about traffic incidents affect the travelers' equilibrium route choices and costs?
- Related work:
    - [Arnott, De Palma, Lindsey]: effect of information using Vickrey's bottleneck model, but only for boundary cases (single informed player versus entire informed population)
    - [Ben-Akiva, de Palma, Kaysi], [Mahmassani, Jaykrishnan]: identification of potential effects of information using traffic simulations
    - [Acemoglu, Makhdoumi, Malekian, Ozdaglar]: "Informational Braess Paradox" and the effect of asymmetric info about available routes.

Effects of heterogeneous information on traffic congestion: Objectives

- We introduce a Bayesian congestion game, in which players have private information about incidents, and each player chooses her route on a transportation network
- We characterize the Bayesian Wardrop Equilibrium (BWE) of the game, and study how the cost to individual players and the social cost as a function of the fraction of highly-informed players.





State-dependent route costs
- r_1: normal/accident states
- Drawn by Nature w/ fixed probability

Two commuter populations
- "H": receives signal
- "L": no signal

 [Liu, Wu, Amin, Schwartz. *Transp. Science, ACC 17* (under review)]

Effects of heterogeneous information on traffic congestion: Model outline

Bayesian Congestion Game:

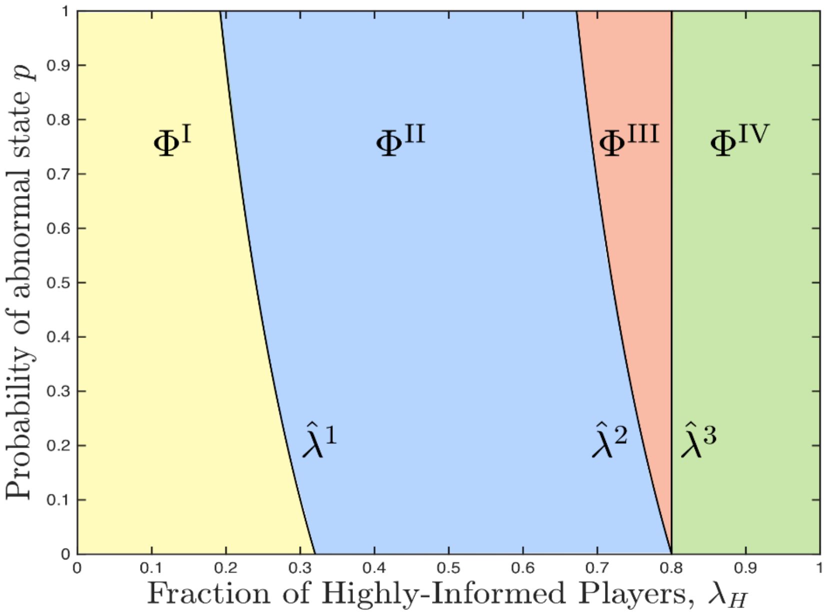
- Models heterogeneous information about incidents and beliefs about other players
- Populations of players that receive different private information from respective information systems (H and L)
- Key features of the model:
  - Probability of incident
  - Fraction of players with information
  - Accuracy of information: high versus low

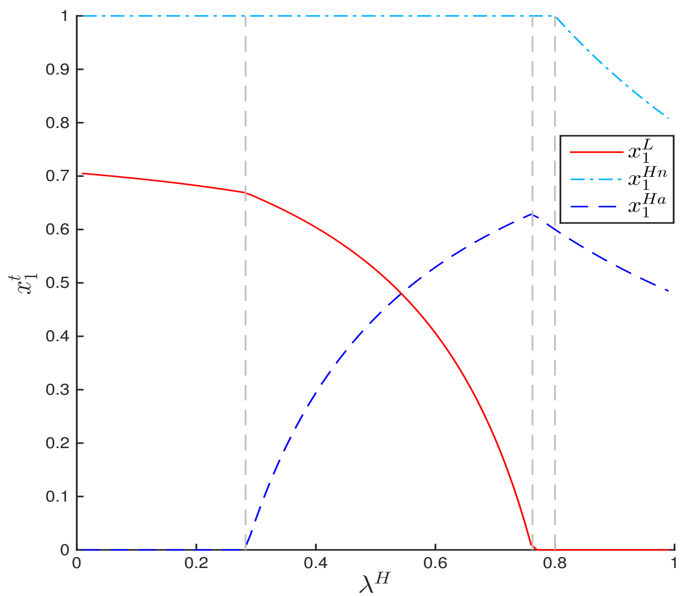
Bayesian Wardrop Equilibrium (BWE):

For each player type, the expected costs of all utilized routes are equal and less than the expected cost of each unutilized route.

Equilibrium characterization

- Four qualitatively different equilibrium regimes
- Recover classical equilibria:
  - Complete info game when everyone is in population H
  - Imperfect info game when everyone is in population L

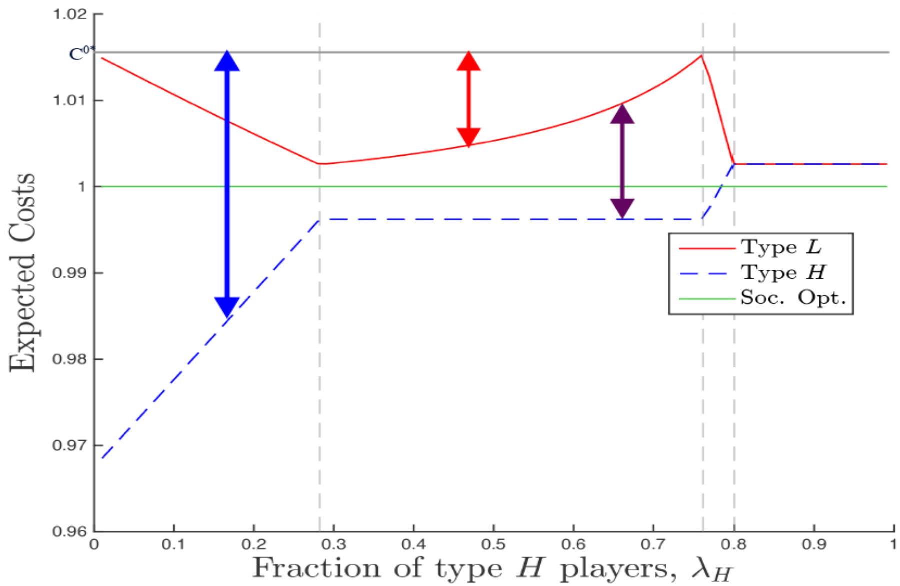




Individual value of information

Theorem:

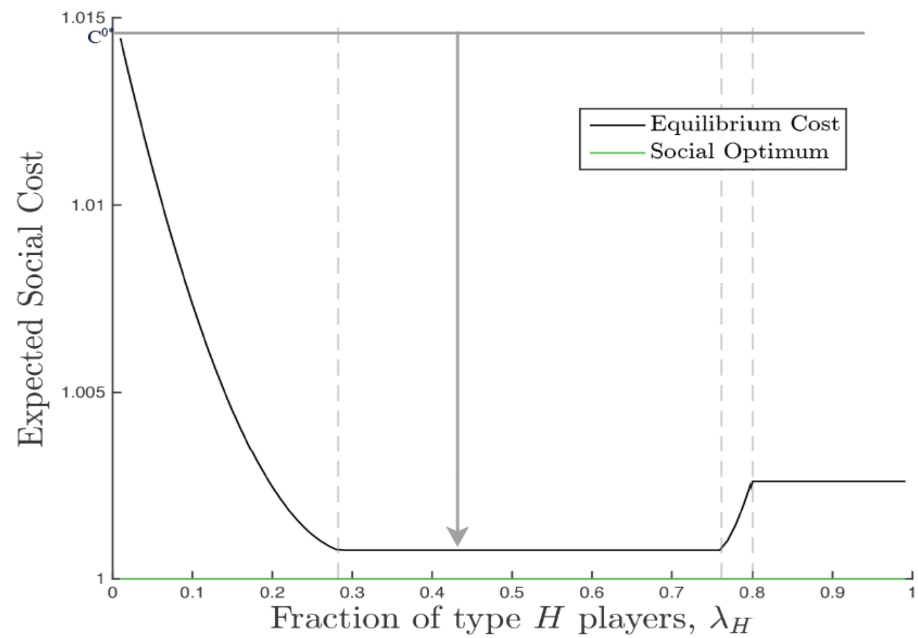
- Value for Population H: as more players gain access to information, the value of information for population H players decreases
- Value for Population L: Benefits from other players having information *even though they don't receive information*
- Relative value of information: Positive up to a threshold, zero above, i.e. *there is no benefit of information if many others have it*



Social value of information

Theorem:

- There exists an "optimal" fraction of players with information
- This threshold is lower than the threshold where relative individual value goes to zero
- There exists a range of λ_H where it is individually advantageous for population L players to gain access to information, but harmful to society for them to do so



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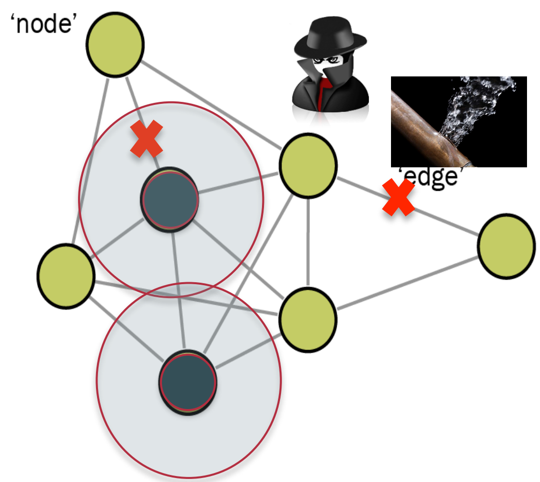
Infrastructure network security games

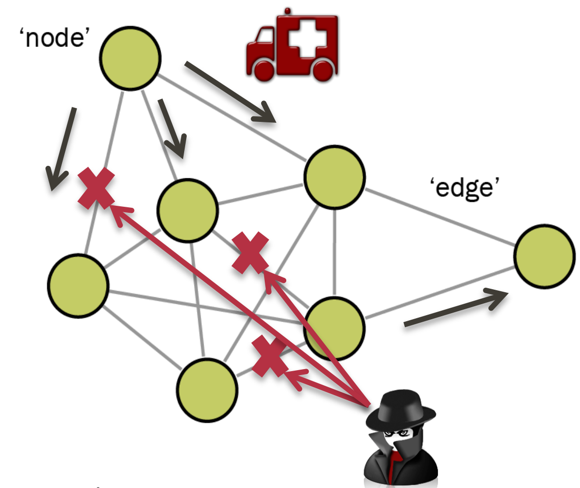
II.(a)-(b) Water distribution:

network sensing under disruptions due to faults **[part II (a)]** or malicious attacks **[part II (b)]**



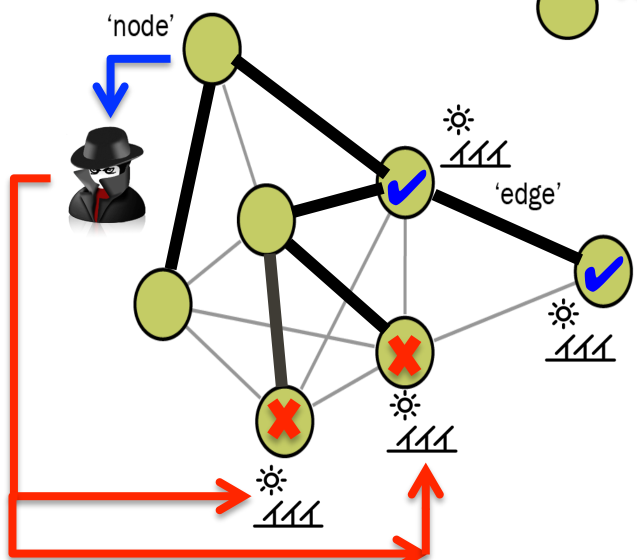
II.(c) Transportation networks:

optimal routing under link disruptions



II.(d) Electricity distribution:

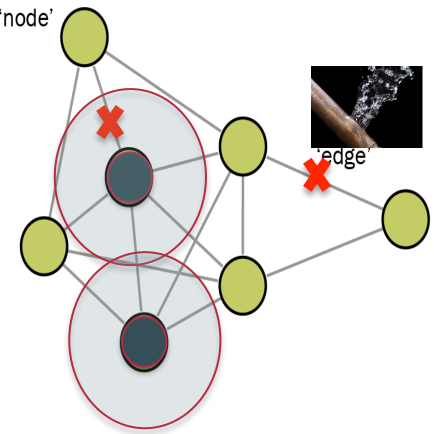
control in the face of strategic node disruptions

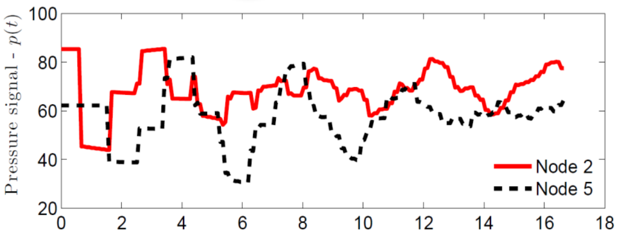


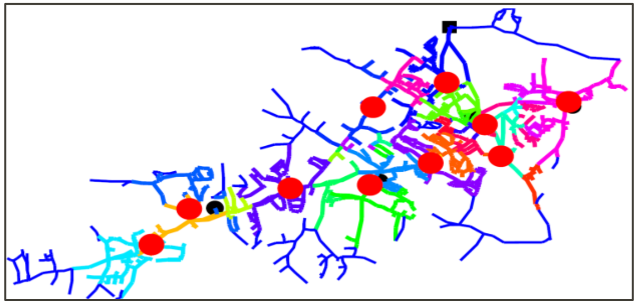
Water network sensing: faults

Objective: For a given network, find minimum number of sensors and their placement:

- Detection: when a detectable event occurs, at least one sensor detects it.
- Location identification: For any pair of events, at least one sensor gives different output for them







Contributions:

- We cast detection problem as Minimum Set Cover (MSC) problem, and Location Identification problem as a Minimum Test Cover (MTC) problem
- We developed an augmented greedy algorithm which provides significant computational improvement while maintaining same approximation ratio as the classical greedy algorithm to solve MSC.

[Sela, Abbas, Koutsoukos, Amin. *Automatica 16, BuildSys 15]*

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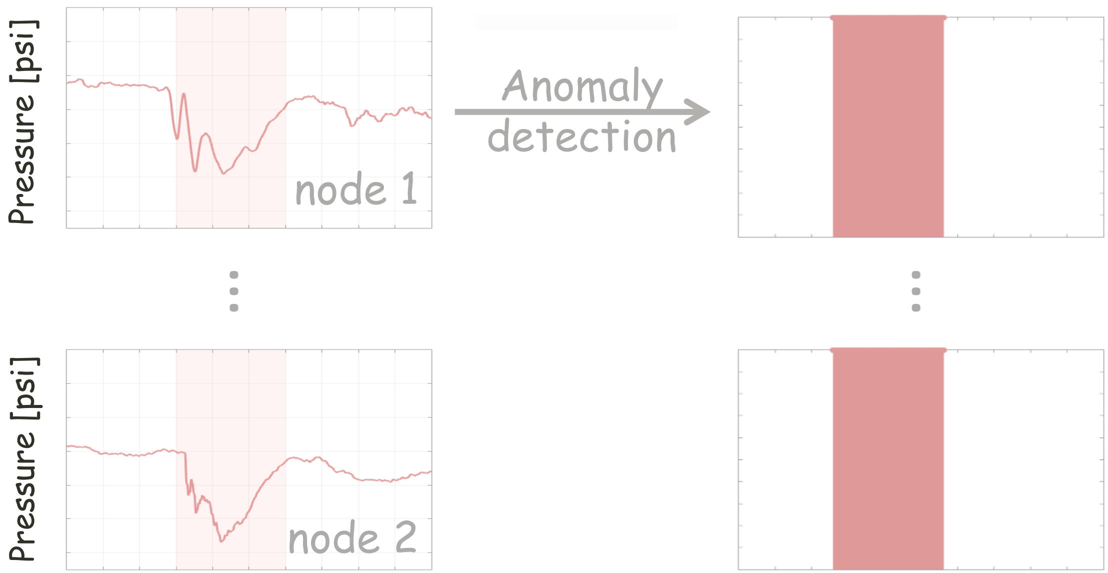
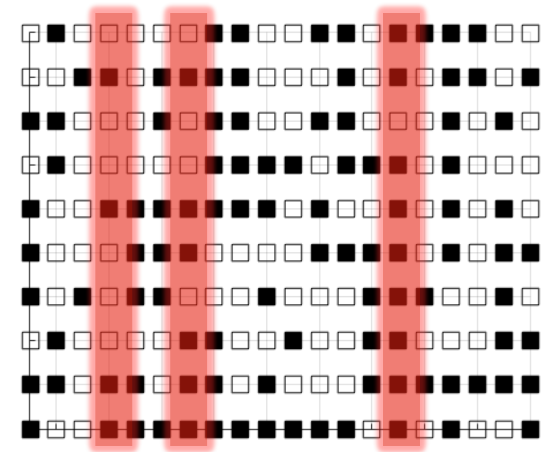
Water network sensing: faults

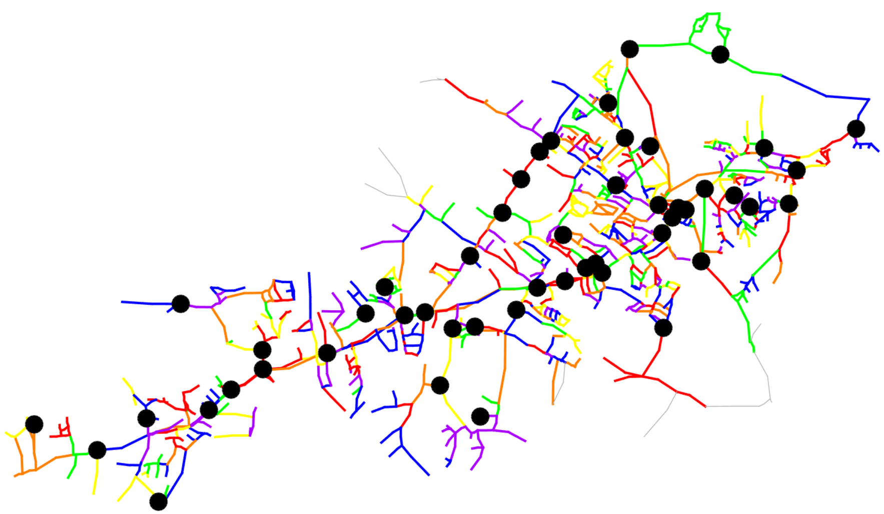
Modeling

Alarms

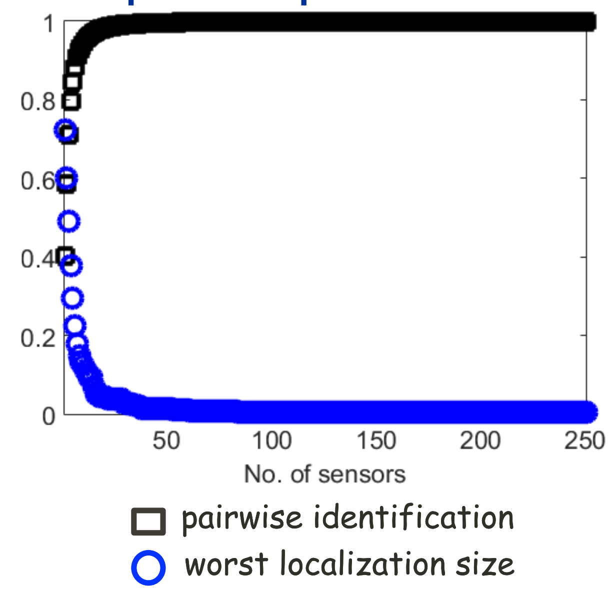


Influence matrix





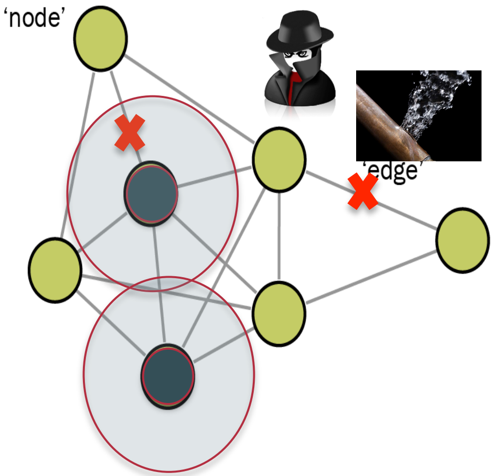
Optimal placement



Data source: SMART project

Water network sensing: attacks

Objective: For a given network that faces adversarial link disruptions, find (randomized) sensing strategies subject to limitations on sensing range and resource constraints.



Approach: We formulate a simultaneous game over the network:

- Attacker: simultaneously disrupts multiple edges
- Defender: strategically chooses a sensor placement

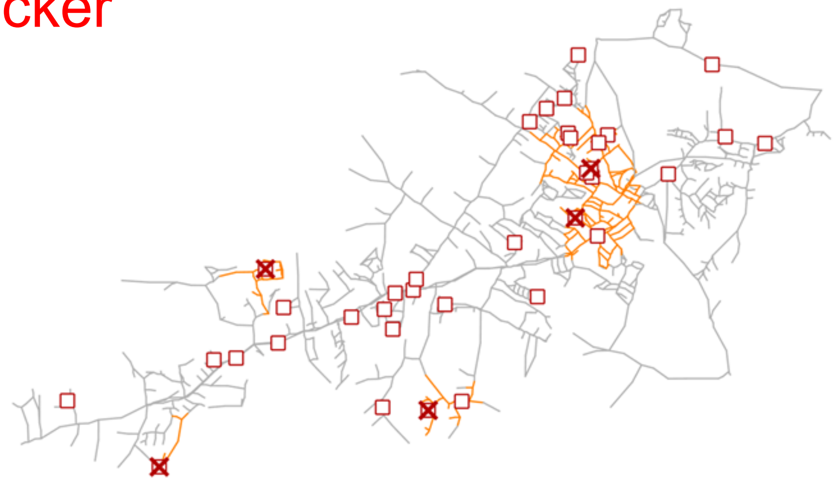
Contributions:

- We consider general sensing model: heterogeneous range
- We study randomized sensing strategies based on mixed Nash equilibria
- Characterization of support of equilibrium strategies in terms of minimum set cover and maximum set packing problem

[Dahan, Sela, Amin, *Allerton 16]*

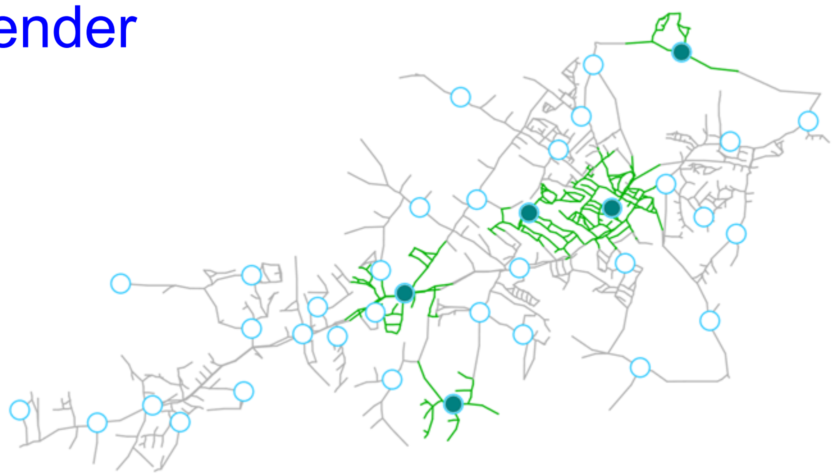
Water network sensing: attacks

Attacker



MSP: maximum set of links that are covered by any node at most once

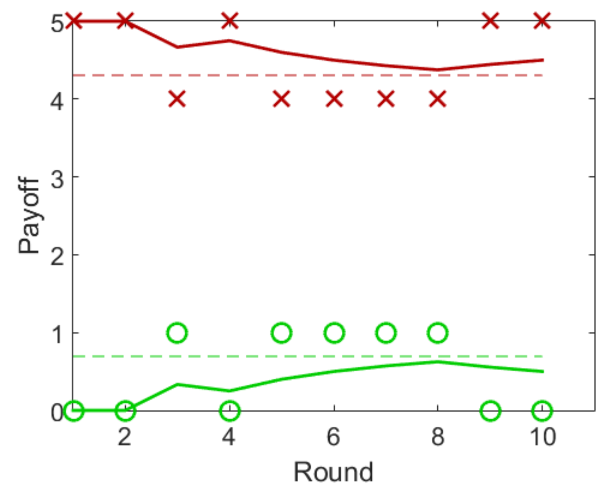
Defender



MSC: minimum set of nodes that cover all edges

Play	ler
Rul	odes
Buc	p_D
Pay	ons
Obj	

Payoffs



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Summary of progress

I. Incident management in traffic flow networks

(a) Estimating social welfare of traffic information systems

[Liu, Wu, Amin, Schwartz. *Transportation Science, ACC 17* (under review)]

(b) Network control under unreliable capacities (stochastic incidents)

[Jin and Amin. *IEEE CDC 14, IEEE TAC* (R&R), *IEEE TAC* (under review)]

II. Security (attacker-defender) games on infrastructure networks

(a)-(b) Network sensing to detect faults **[part (a)]** or attacks **[part (b)]** in water network [Sela, Abbas, Koutsoukos, Amin. *Automatica 16, BuildSys 15*]

[Dahan, Sela, Amin. *Allerton 16*]

(c) Transportation network routing under adversarial link disruptions

[Dahan & Amin. Allerton 15, *Math of OR (*under review]

(d) Optimal control of electricity distribution networks under adversarial compromises of distributed energy resources

[Shelar & Amin. CDC 15, ACC 15, *IEEE CONES 16*]