Resilience Assessment of Hyperconnected Parcel Logistic Networks Under Worst-Case Disruptions

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Joint work with

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School of Industrial and Systems Engineering, Georgia Institute of Technology

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Georgia Tech College of Engineering
H. Milton Stewart School of Industrial and Systems Engineering

Physical Internet Center

Problem Motivation

- Parcel delivery industry is one of the **fastest growing industries** in the world.
  - Last year, 87 billion parcels were shipped and delivered.
  - Parcel volume is expected to reach 200 billion in next 5 years.

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  - Speed and accuracy of parcel delivery
  - Customers spread out across wide geographical area

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- Moreover, logistics networks designed with only efficiency considerations
  - Not ideal as disruptions occur

Disruptions

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Parcel Delays Incoming: Floods Causing Deliveries To Slow Down

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- Parcel delivery networks face disruptions:
  - Major traffic jams
  - Power outages
  - Pandemics

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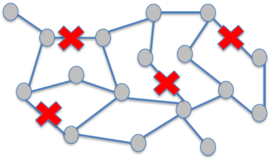
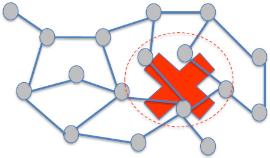
- Disruptions lead to:
  - Excess pressure on functional resources
  - Late parcel deliveries
  - Increased costs

Resilience Evaluation

- **Simulation Models:** Simulation of disruptive events in which the network components fail
  - Random or localized failures
  - Total or partial failures





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  - Centrality measures
  - Path lengths, edge-disjoint paths

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Stochastic disruptive events only - requires disruption data

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- Need to also develop a tool to assess resilience of the **large-scale** networks under such **worst-case disruptive events**
  - Intelligent fictitious adversary (Game-theory based)

Resilient Assessment of Parcel delivery Networks

- **Aim:** To devise a tool that assess the resilience of large-scale logistics networks under worst-case disruptions
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- We study a **two-person Stackelberg game**:
  - Network components are disrupted to cause most harm (fictitious adversary)
  - Best response to minimize the effects of disruptions (logistics company)

- **Contributions:**
  - Bi-level mixed integer linear program (Network Interdiction Problem)
  - Exact solution technique to assess the resilience
  - Resilience analysis of networks

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- **Contributions:**
  - Bi-level mixed integer linear program (Network Interdiction Problem)
  - Exact solution technique to assess the resilience
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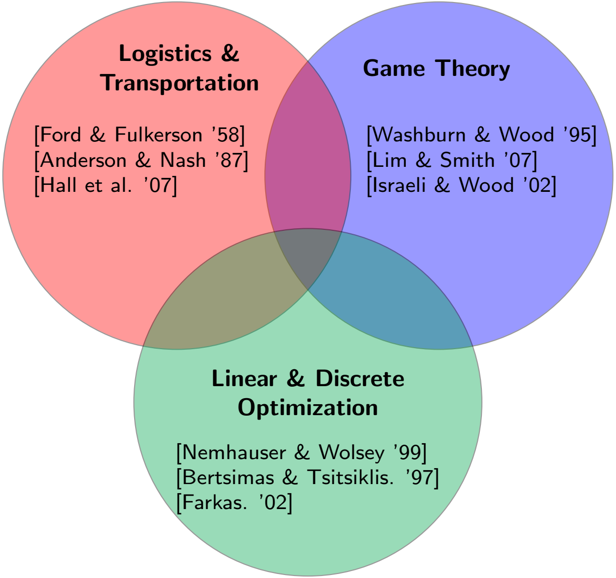
- **Agenda:**

To leverage tools from optimization, network science, and game theory to assess the resilience of logistics networks under worst-case disruptions.

Related Work



Problem Setting

- **Goal:**
  1. **Leader:** Interdict edges to maximize the commodity delivery costs between all OD pairs
  2. **Follower:** Minimize the commodity delivery costs after edge-interdiction

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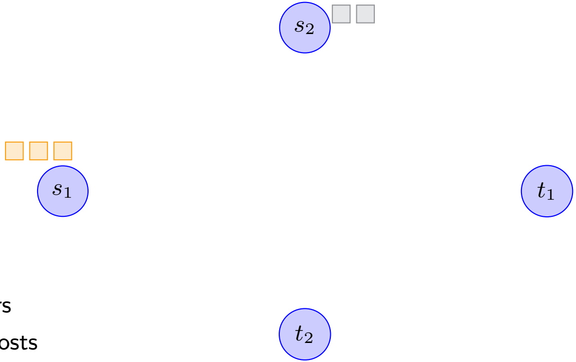

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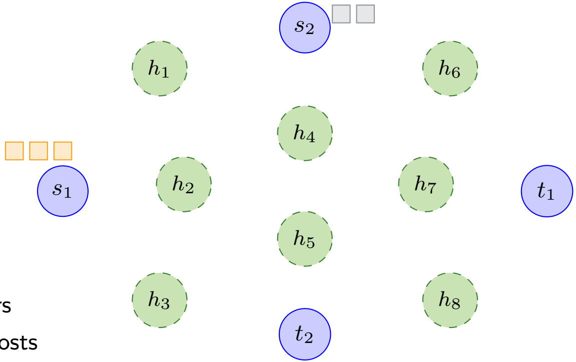

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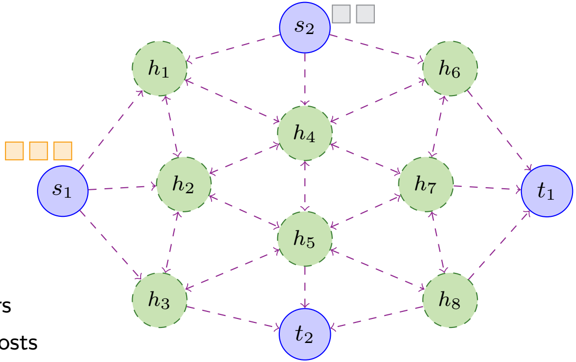

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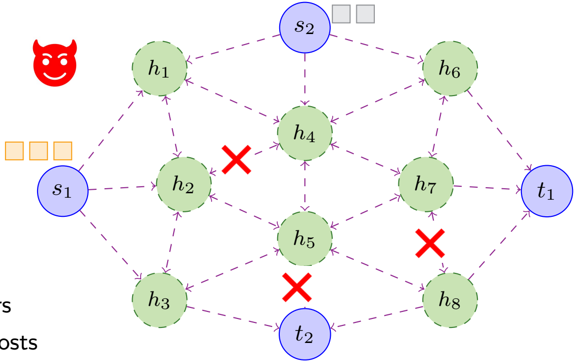

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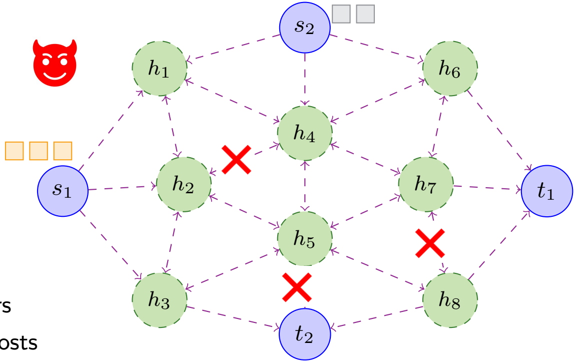

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  - $x_{i,j} \in \{0, 1\}$: Arc (i, j) is interdicted .

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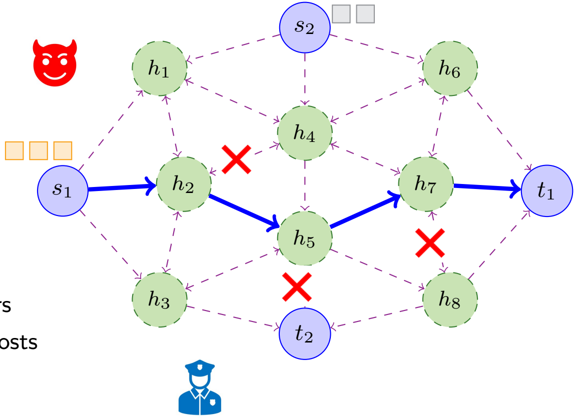

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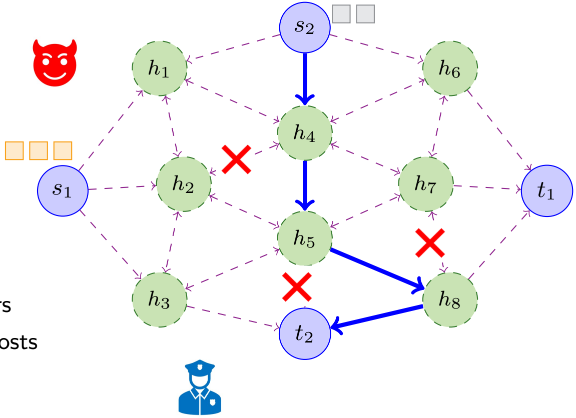

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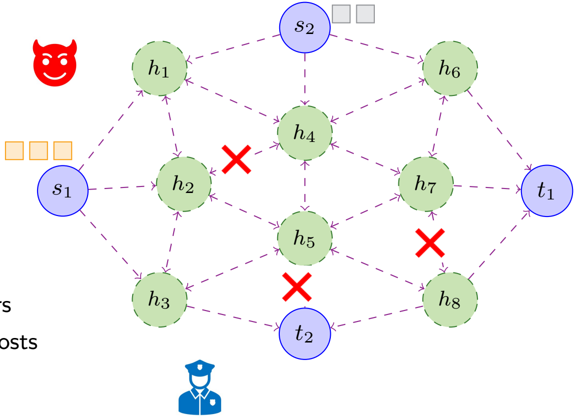

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- **Decision Variables:**
  - $x_{i,j} \in \{0, 1\}$: Arc (i, j) is interdicted .
  - $f^p_{i,j} \in \mathbb{R}_{\geq 0}$: Commodity flow on arc (i, j) for O-D pair p.

Network Interdiction Problem - Formulation

$\mathcal{P}$: Set of O-D pairs

$\mathcal{H}$: Set of hubs

$\mathcal{A}$: Set of transportation arcs

d_p : Commodity demand for O-D pair p

Network Interdiction Problem - Formulation

subject to:

$$x_{i,j} \in \{0, 1\}, \qquad \forall (i, j) \in \mathcal{A} \qquad \text{Arc interdiction variables}$$

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subject to:

$$\sum_{(i,j)\in\mathcal{A}} x_{i,j} \leq \beta$$ Interdiction budget

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Commodity flow balance

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$$\max_{x} \left\{ \min_{f} \, (c_{i,j} + M \cdot x_{i,j}) f^p_{i,j} \right\}$$ Total commodity delivery costs

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Bi-level program

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Dual of the inner problem $\longrightarrow$

Single-level mixed integer program

$$\max_{x,\pi} \sum_{p\in\mathcal{P}} (\pi^p_s - \pi^p_t)$$

s.t:

$$\pi^p_i - \pi^p_j \leq c_{i,j} + M \cdot x_{i,j} \qquad \forall p \in \mathcal{P}, \forall (i,j) \in \mathcal{A}$$

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$$\max_{x} \left\{ \min_{f} \left\{ \sum_{p \in \mathcal{P}} \sum_{(i,j) \in \mathcal{A}} (c_{i,j} + M \cdot x_{i,j}) f_{i,j}^{p} \right\} \right\}$$

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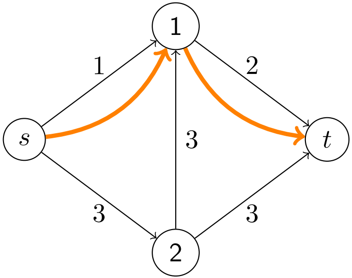
Large # variables: Problem size reduction required

Edge Interdictions

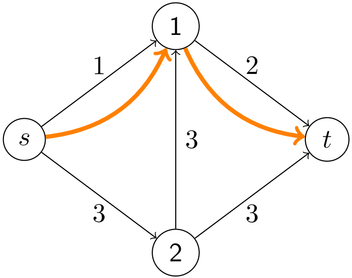
- **Examples:**



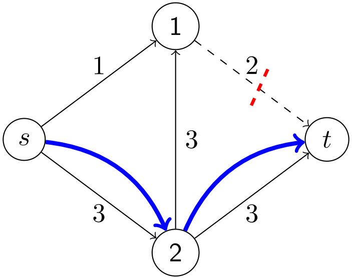
Shortest Path Length: 3
Edge interdictions: 0

Edge Interdictions

- **Examples:**



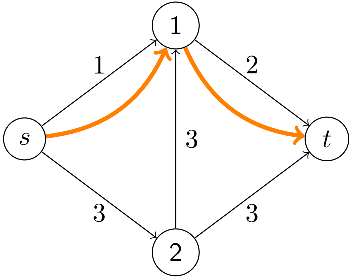
Shortest Path Length: 3
Edge interdictions: 0



Shortest Path Length: 5
Edge interdictions: 1

Edge Interdictions

- **Examples:**



Shortest Path Length: 3
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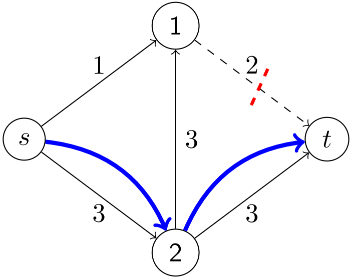
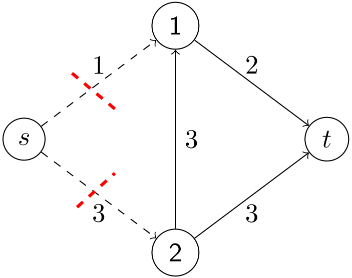


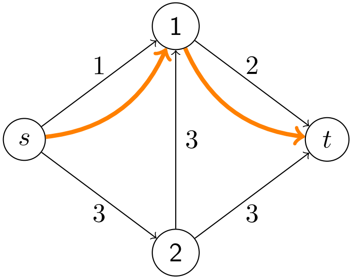
Shortest Path Length: 5
Edge interdictions: 1



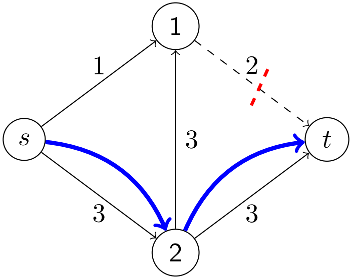
Shortest Path Length: ∞
Edge interdictions: 2

Edge Interdictions

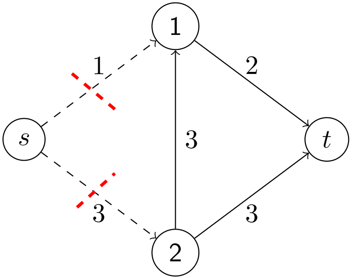
- **Examples:**



Shortest Path Length: 3
Edge interdictions: 0



Shortest Path Length: 5
Edge interdictions: 1



Shortest Path Length: ∞
Edge interdictions: 2

- Which edge(s) to interdict depends upon the **resource availability** at adversary
- **Problem size reduction:** Not generating arc variables that won't be interdicted
  - Search tree to find out such arcs

Case Study

- Major Parcel Delivery Company in China
  - Several millions of parcels handled every week
  - **Implementation Scale:** Central China
- Potential locations for logistics hub construction
  - **Logistics significance:** Major cities, highway intersections, and existing city-based inbound/outbound hubs
- Regulations set by Chinese government
  - 11-hour driving limit per day
  - **Allowable transportation edges:** 5.5 hours of travel time
- Topology-optimized networks designed through minimizing
  - single shortest path - Lean network
  - k-shortest paths
  - k-shortest edge-disjoint path

Computational Performance

Computational Performance

Method
Pre-processing + Gurobi
Gurobi

Computational Performance

Method	# Hubs	$\lvert\mathcal{A}\rvert$
Pre-processing + Gurobi	60	1005
	70	1074
	80	1344
	90	1429
Gurobi	60	1005
	70	1074
	80	1344
	90	1429

Computational Performance

Method	# Hubs	$\|\mathcal{A}\|$	$\|\mathcal{A}'\|$
Pre-processing + Gurobi	60	1005	586
	70	1074	656
	80	1344	767
	90	1429	817
Gurobi	60	1005	-
	70	1074	-
	80	1344	-
	90	1429	-

Computational Performance

Method	# Hubs	$\lvert\mathcal{A}\rvert$	$\lvert\mathcal{A}'\rvert$	# Variables
Pre-processing + Gurobi	60	1005	586	3137
	70	1074	656	3227
	80	1344	767	3312
	90	1429	817	3403
Gurobi	60	1005	-	18207
	70	1074	-	18641
	80	1344	-	21290
	90	1429	-	23388

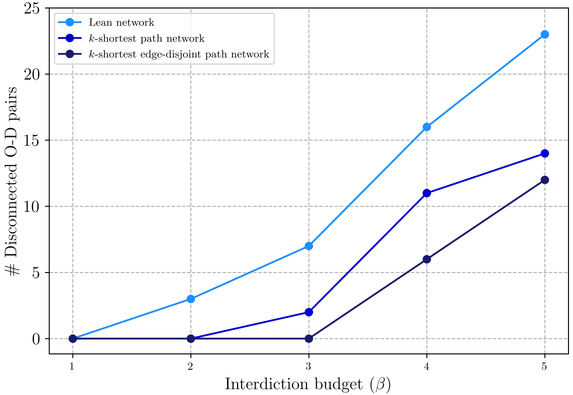
Computational Performance

Method	# Hubs	$\lvert\mathcal{A}\rvert$	$\lvert\mathcal{A}'\rvert$	# Variables	# Constraints
Pre-processing + Gurobi	60	1005	586	3137	4288
	70	1074	656	3227	4571
	80	1344	767	3312	4836
	90	1429	817	3403	5912
Gurobi	60	1005	-	18207	150,976
	70	1074	-	18641	163,420
	80	1344	-	21290	212,830
	90	1429	-	23388	261,777

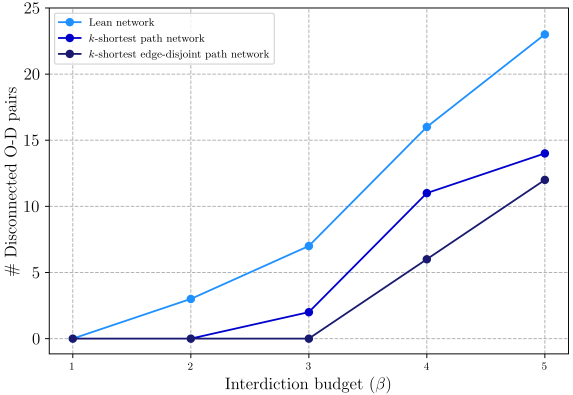
Computational Performance

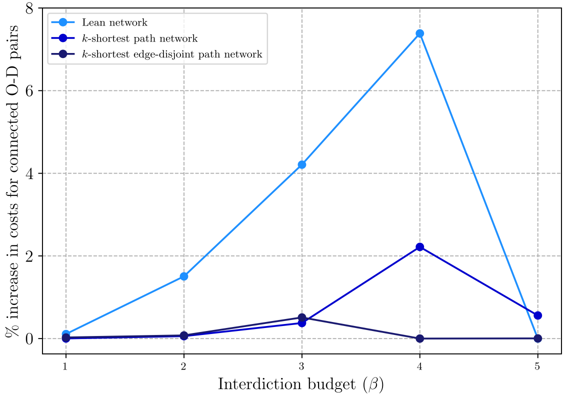
Method	# Hubs	$\lvert\mathcal{A}\rvert$	$\lvert\mathcal{A}'\rvert$	# Variables	# Constraints	Total Time (sec)	Optimality Gap (%)
Pre-processing + Gurobi	60	1005	586	3137	4288	54	0
	70	1074	656	3227	4571	59	0
	80	1344	767	3312	4836	62	0
	90	1429	817	3403	5912	82	0
Gurobi	60	1005	-	18207	150,976	time limit	504.5
	70	1074	-	18641	163,420	time limit	831.4
	80	1344	-	21290	212,830	time limit	1392.5
	90	1429	-	23388	261,777	time limit	1965.2

Resilience Analysis of Networks

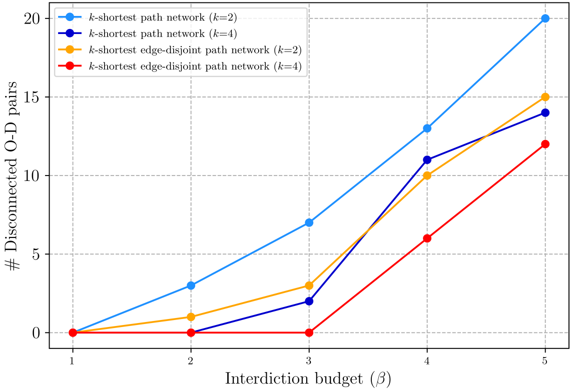


Resilience Analysis of Networks

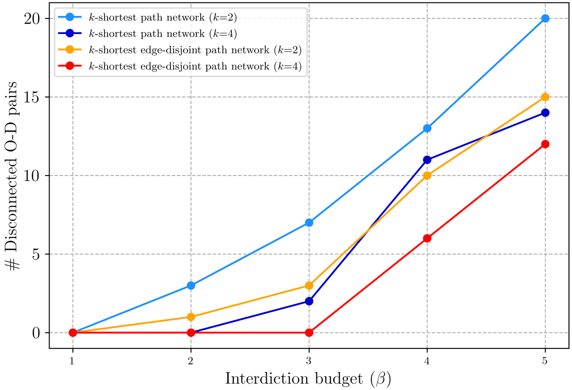


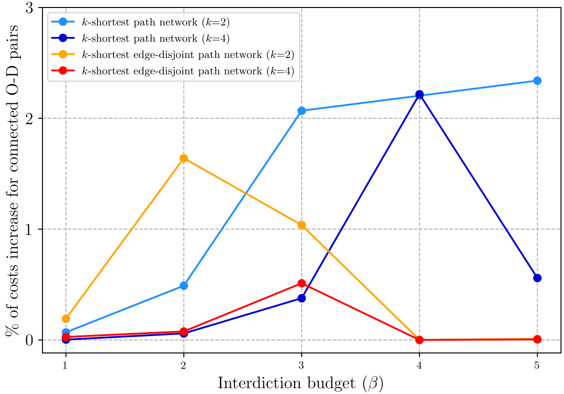


Resilience Analysis of Networks



Resilience Analysis of Networks





Summary

Contributions:

- Resilience assessment of large-scale networks under worst-case disruptions
- Network interdiction problem with a bi-level mixed integer formulation
- Dualization procedure and search tree strategy to reduce the problem size drastically
- Computational performance comparison of the solution methodology against off-the-shelf solver
- Resilience analysis of the topology-optimized networks

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Thank you!

Questions: onkar.kulkarni@gatech.edu