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

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Joint work with

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

Disruptions


THE WALL STREET JOURNAL.

BUSINESS

FedEx to Ramp Up Spending to Ease Delivery Delays

WORLD ECONOMY

Another shipping crisis looms on

impact mail and parcel deliveries

MALAYSIA

Parcel Delays Incoming: Floods Causing

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

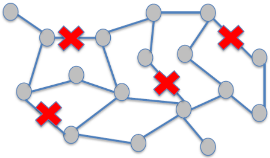
Disruptions

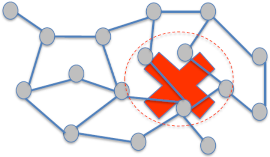
- Parcel delivery networks face disruptions:
  - Major traffic jams
  - Power outages
  - Pandemics

- 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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- 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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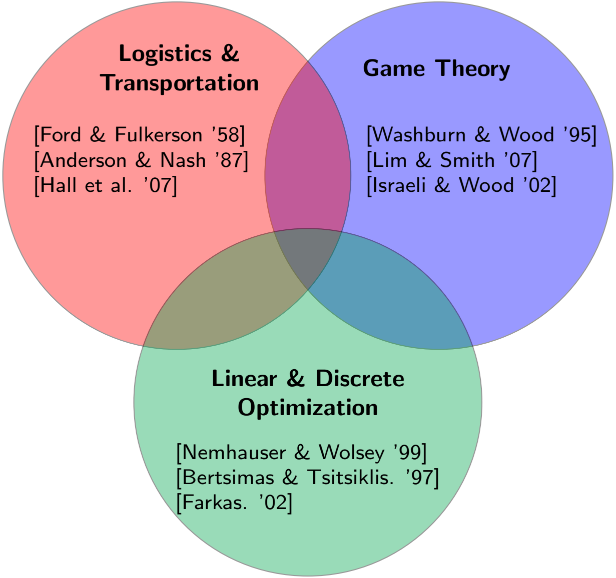
- **Agenda:**

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

Related Work



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- **Goal:**
  1. **Leader:** Interdict edges to maximize the commodity delivery costs between all OD pairs
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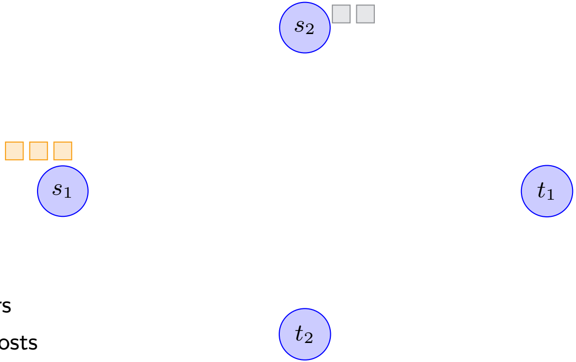

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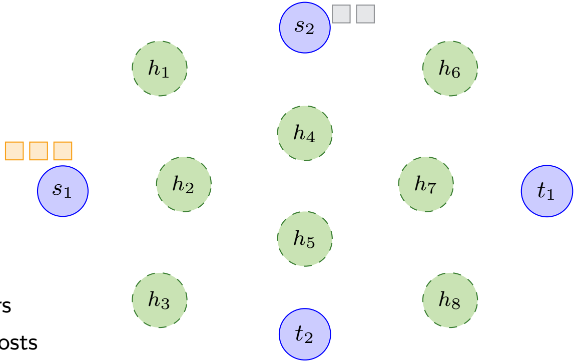

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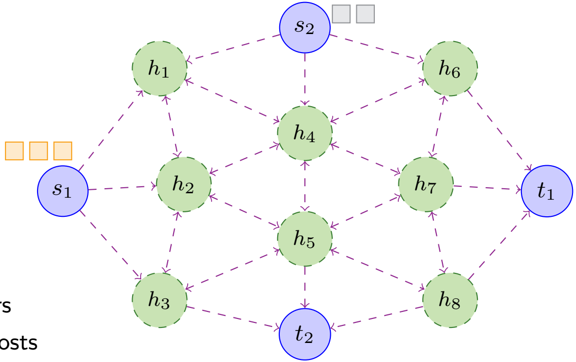

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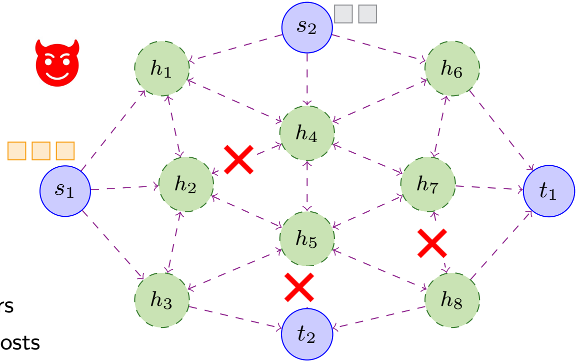

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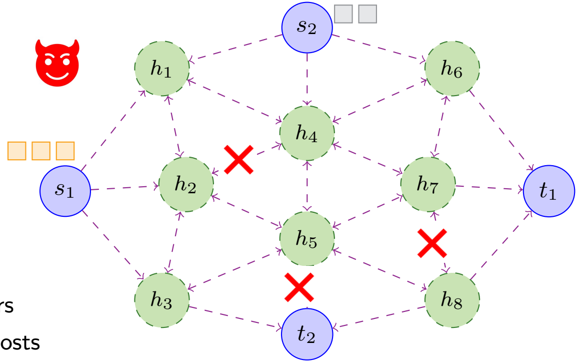

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  - $x_{i,j} \in \{0, 1\}$: Arc (i, j) is interdicted .

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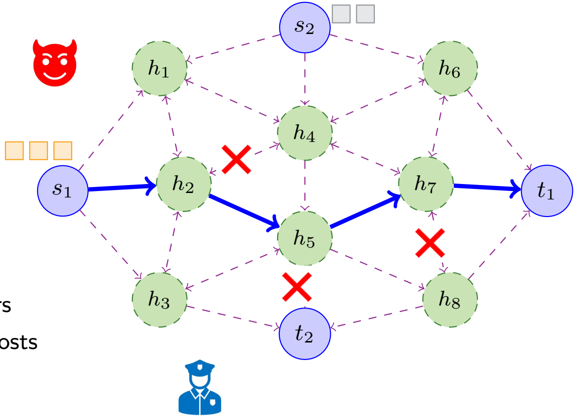

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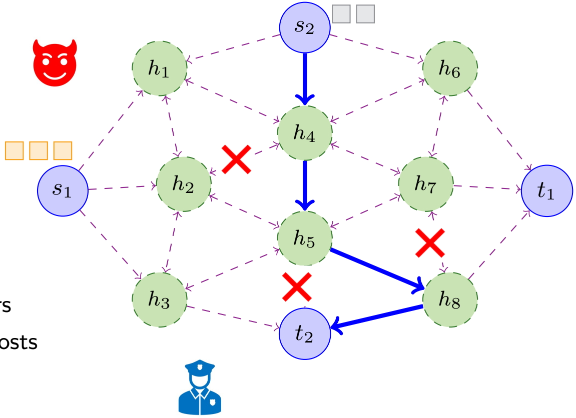

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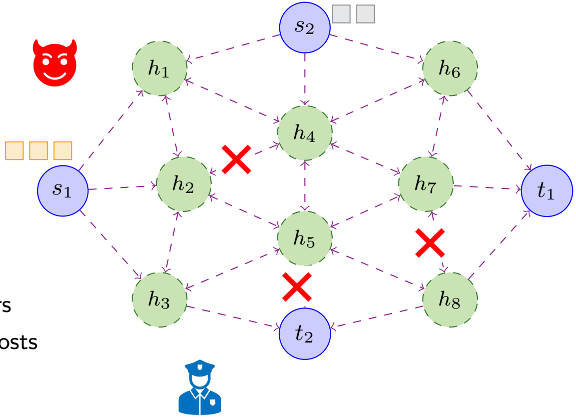

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  - $x_{i,j}$ 2 f$0, 1$g: Arc (i, j) is interdicted .
  - $f^{p}_{i,j}$ 2 $\mathbb{R}_{\geq 0}$: Commodity flow on arc (i, j) for O-D pair p.

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

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subject to:

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subject to:

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

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

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Bi-level program

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Dual of the inner problem $\longrightarrow$

Single-level mixed integer program

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

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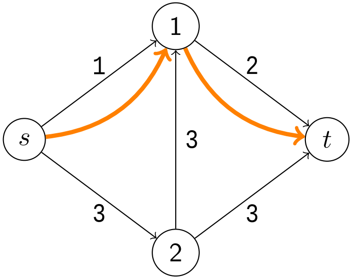
Large # variables: Problem size reduction required

Edge Interdictions

- **Examples:**



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Edge interdictions: 0

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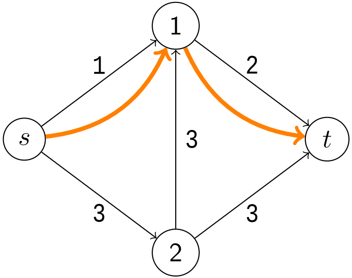

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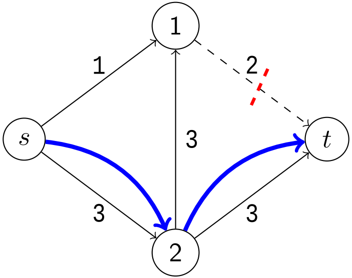

Shortest Path Length: 5
Edge interdictions: 1

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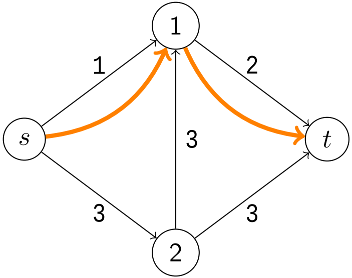

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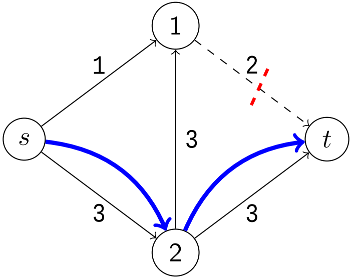

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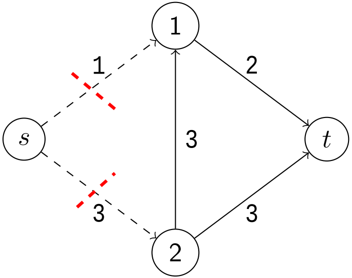
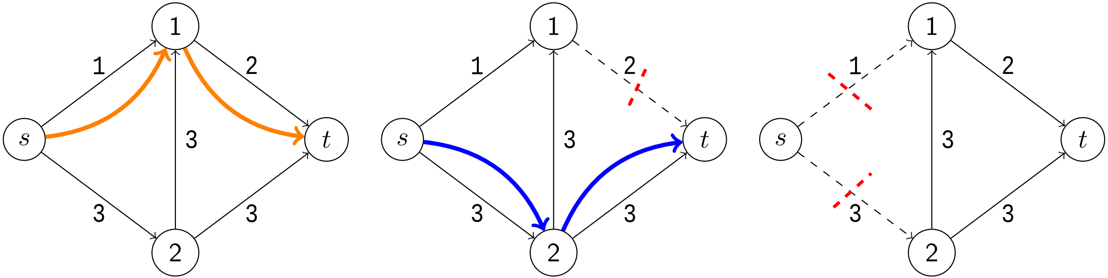


Shortest Path Length: ∞
Edge interdictions: 2

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	$\lvert\mathcal{A}\rvert$	$\lvert\mathcal{A}'\rvert$
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

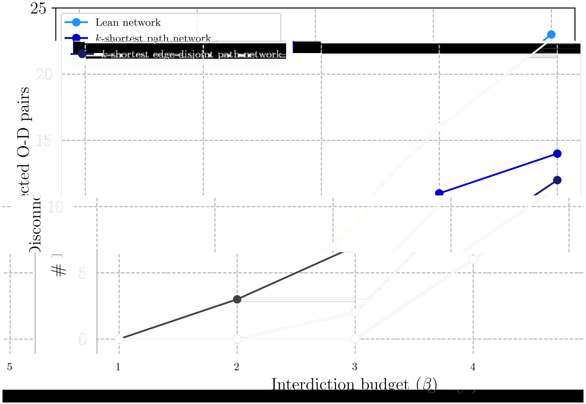
Computational Performance

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

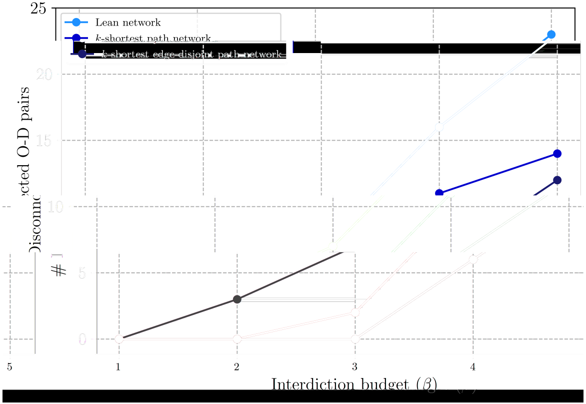
Computational Performance

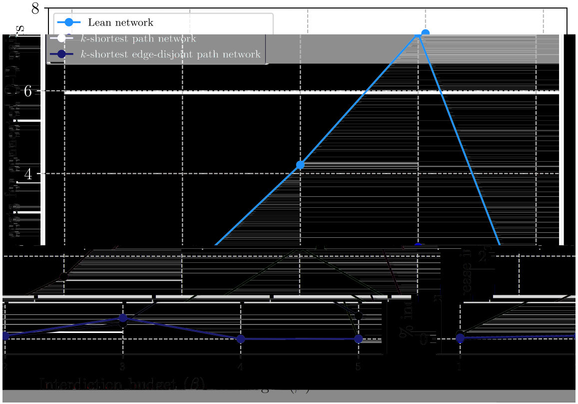
Method	# Hubs	$\lvert\mathcal{A}\rvert$	$\lvert\mathcal{A}'\rvert$	# Variables	# Constraints	Total Time (sec)	Optimality Gap (%)
Pre-processing + Gurobi	60	1005	586	3137	4288	54	0
	70	1074	656	3227	4571	59	0
	80	1344	767	3312	4836	62	0
	90	1429	817	3403	5912	82	0
Gurobi	60	1005	-	18207	150,976	time limit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

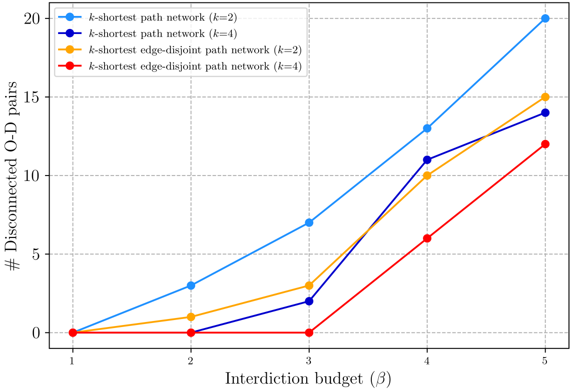


Resilience Analysis of Networks

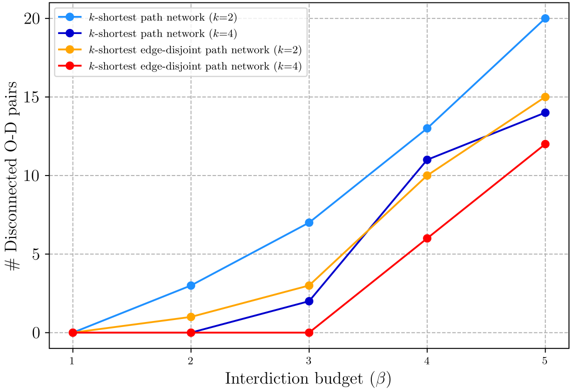


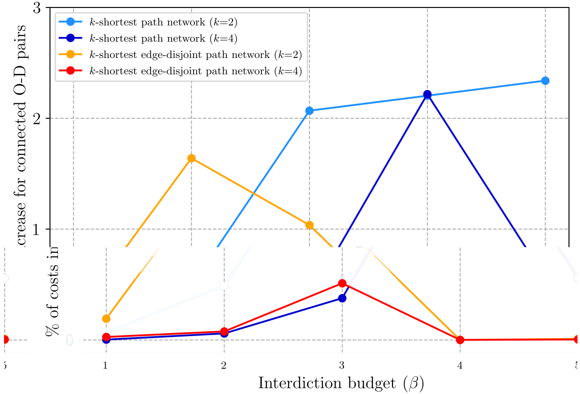


Resilience Analysis of Networks



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!

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