UPPSALA UNIVERSITET

Uppsala Secure Learning and Control Lab

Security Allocation in Networked Control Systems

Anh Tung Nguyen

Dissertation for the degree of Licentiate

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Stiftelsen för Strategisk Forskning

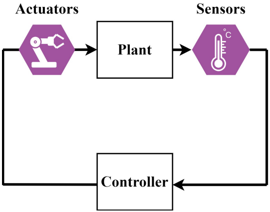
Swedish Research Council

Outline

1. Introduction
2. Security in Networked Control Systems
3. Problem Formulation
4. Contributions
   - Paper I
   - Paper II
   - Paper III
   - Paper IV
5. Conclusion and Future Work

Critical Infrastructure

Control of Critical Infrastructure



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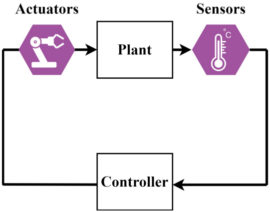

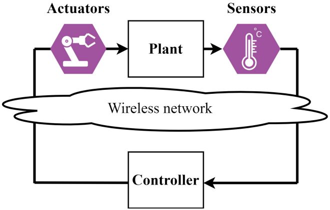

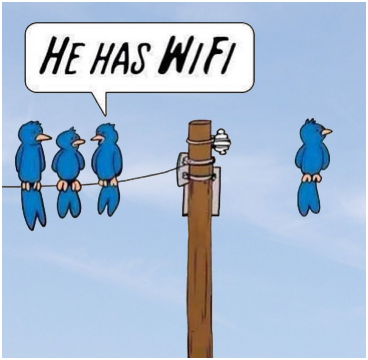

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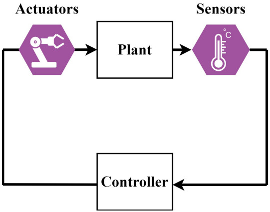
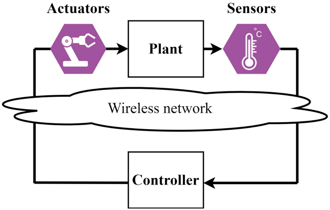
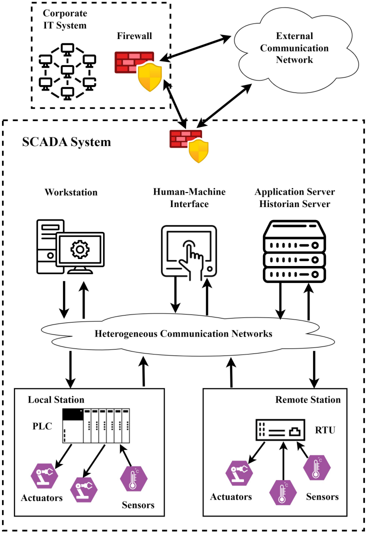
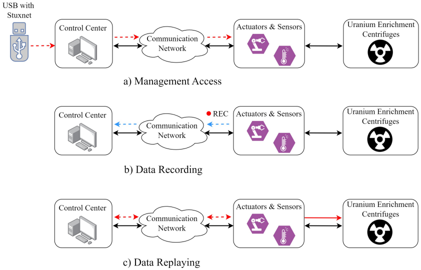




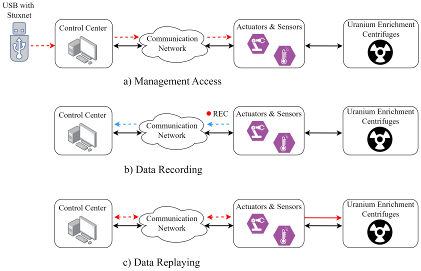


Vulnerabilities in Critical Infrastructure



Stuxnet

Vulnerabilities in Critical Infrastructure



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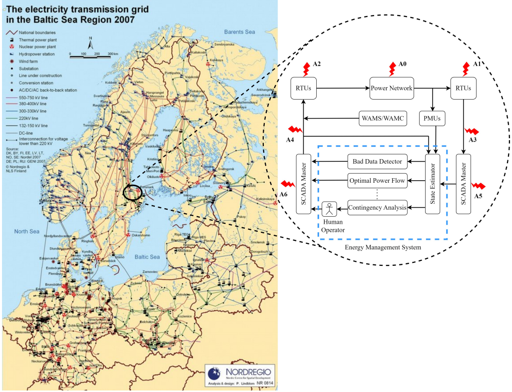

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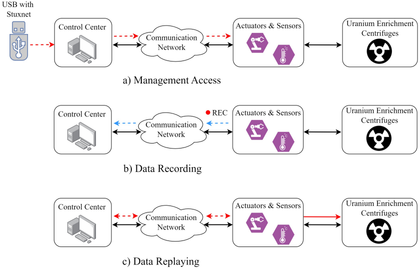

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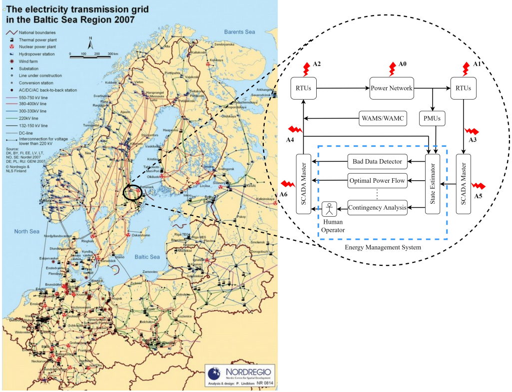

Motivation

Critical Infrastructure should be protected actively

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Security Triad and Threats

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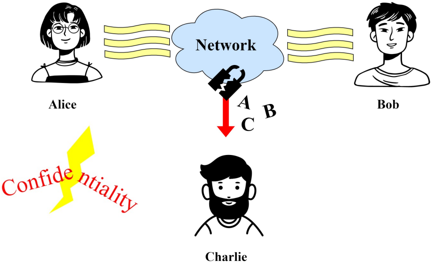

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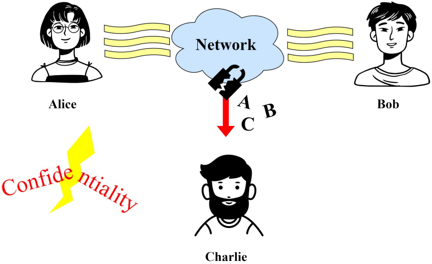

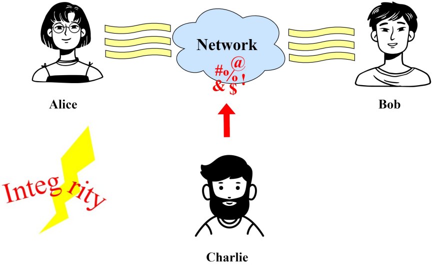

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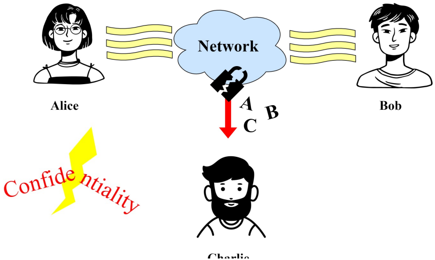

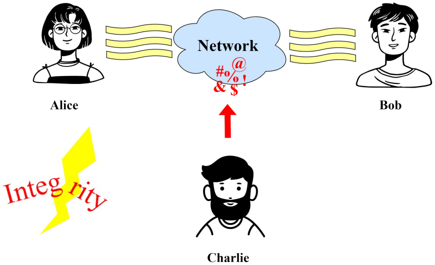

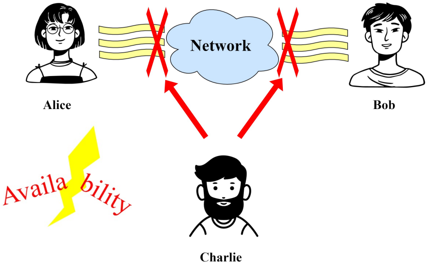

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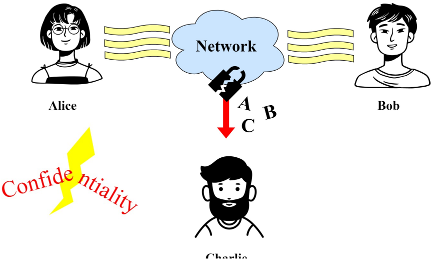

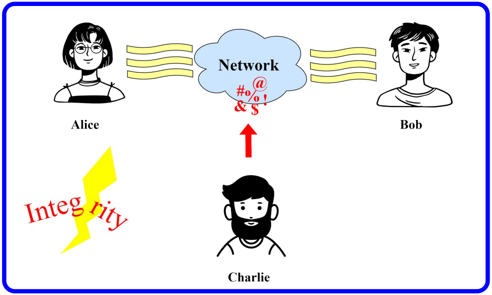

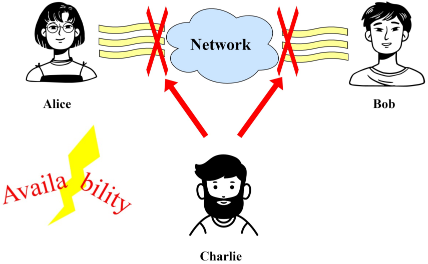

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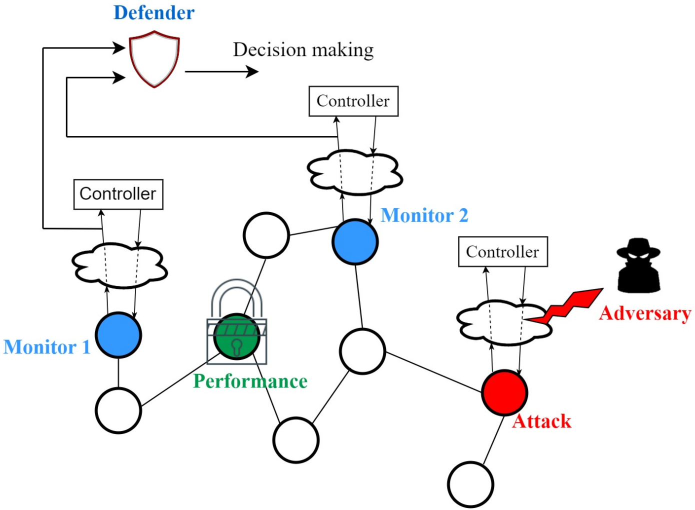
Problem description



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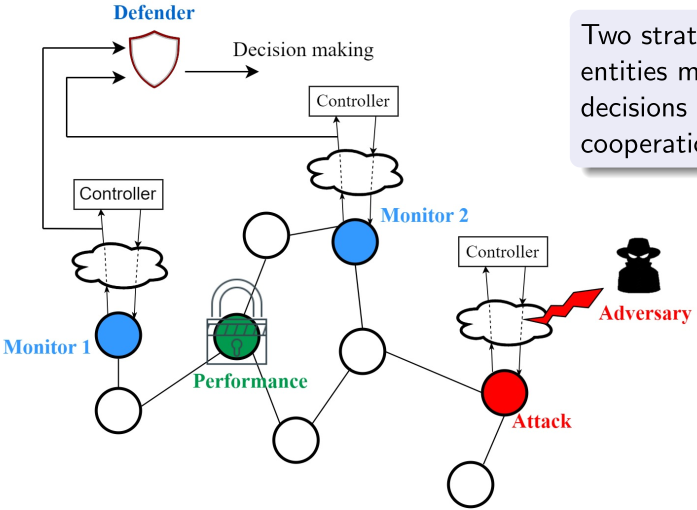

Two strategic entities make decisions without cooperation

Problem analysis

- Purpose: protect the system

- Purpose: attack the system

Problem analysis

- Purpose: protect the system
- Action: monitor what?

- Purpose: attack the system
- Action: attack what?

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Action order:

1) Make decisions simultaneously

2) The defender goes first

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Non-cooperative two-player game

Problem analysis

- Purpose: protect the system
- Action: monitor what?

- Purpose: attack the system
- Action: attack what?

Action order:

1) Make decisions simultaneously

2) The defender goes first

Problem variations

▷ System models
▷ Resources & knowledge
▷ Action order

Problem variations


Defender


Adversary


Performance ρ

Paper I
- Certain LFO
- Performance ρ is fixed
- Def./Adv. chooses one
- Take actions simultaneously

Paper II
- Uncertain LFO
- Performance ρ is fixed
- Def./Adv. chooses one
- Take actions simultaneously

Paper III
- Certain LSO
- Performance ρ is fixed
- Def./Adv. chooses one
- Take actions simultaneously

Paper IV
- Certain LFO
- Performance ρ is uncertain
- Adv. chooses one, Def. chooses several
- Def. takes action firstly

Problem variations


Defender


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Problem formulation

- Undirected connected graph $\mathcal{G}$ with N nodes

$$\begin{aligned} \dot{x}_i(t) =& A_i x_i(t) + b\tilde{u}_i(t), \\ y_i(t) =& c^\top x_i(t). \end{aligned}$$

Problem formulation

- Undirected connected graph $\mathcal{G}$ with N nodes

$$\begin{aligned}\dot{x}_i(t) =& A_i x_i(t) + b\tilde{u}_i(t),\\ y_i(t) =& c^\top x_i(t).\end{aligned}$$

- Local performance: $\|y_\rho\|^2_{\mathcal{L}_2[0,T]} = \frac{1}{T}\int_0^T |y_\rho(t)|^2 \, \mathrm{d}t$

Problem formulation

- Undirected connected graph $\mathcal{G}$ with N nodes

$$\dot{x}_i(t) = A_i x_i(t) + b\tilde{u}_i(t),$$
$$y_i(t) = c^\top x_i(t).$$

Adversary chooses node a

- Local performance: $\|y_\rho\|^2_{\mathcal{L}_2[0,T]} = \frac{1}{T}\int_0^T |y_\rho(t)|^2 \, \mathrm{d}t$

- Healthy/attacked local controller

$$\tilde{u}_i(t) = \underbrace{\sum_{j \in \mathcal{N}_i} \phi_{ij}(x_i, x_j)}_{\text{healthy}} + \begin{cases} 0, & \text{if } i \neq a \\ \zeta(t), & \text{if } i \equiv a \end{cases}$$

$\Rightarrow$ Closed-loop system: $\dot{x}(t) = Ax(t) + b \otimes e_a \zeta(t)$

Problem formulation (Cont.)

- Closed-loop system:

$$\dot{x}(t) = Ax(t) + b \otimes e_a \zeta(t), \quad x(0) = 0$$

Problem formulation (Cont.)

- Closed-loop system:

$$\dot{x}(t) = Ax(t) + b \otimes e_a \zeta(t), \quad x(0) = 0$$

- The defender can choose several nodes $\mathcal{M} = \{m_1, m_2, \dots, m_{|\mathcal{M}|}\}$

$$y_{m_1}(t) = e_{m_1}^\top x(t), \quad y_{m_2}(t) = e_{m_2}^\top x(t), \quad \dots \quad y_{|\mathcal{M}|}(t) = e_{|\mathcal{M}|}^\top x(t).$$

- Monitor outputs such that at least

$$\|y_{m_k}\|_{\mathcal{L}_2}^2 = \frac{1}{T}\int_0^T |y_{m_k}(t)|^2 \, \mathrm{d}t > \delta_{m_k} \quad \Rightarrow \quad \text{Attack is detected!!!}$$

Problem formulation (Cont.)

- Closed-loop system:

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- Adversary's purpose: stay stealthy

$$\|y_{m_k}\|_{\mathcal{L}_2}^2 = \frac{1}{T}\int_0^T |y_{m_k}(t)|^2 \, \mathrm{d}t \leq \delta_{m_k} \quad \forall m_k \in \mathcal{M}$$

$\Rightarrow$ Stealthy False Data Injection Attacks (Stealthy FDI Attacks)

Challenges

Attack, Monitor, Performance

$$J_\rho(a, \mathcal{M}) \triangleq \sup_{\zeta \in \mathcal{L}_{2e},\ \text{zero init. state}} \|y_\rho\|^2_{\mathcal{L}_2} \tag{1}$$

$$\text{s.t.} \quad \|y_{m_k}\|^2_{\mathcal{L}_2} \leq \delta_{m_k},\ \forall m_k \in \mathcal{M}$$

Challenges

Attack → a, Monitor → $\mathcal{M}$, Performance → ρ

$$J_{\rho}(a, \mathcal{M}) \triangleq \sup_{\zeta \in \mathcal{L}_{2e},\ \text{zero init. state}} \|y_{\rho}\|^2_{\mathcal{L}_2} \qquad (1)$$

$$\text{s.t.} \quad \|y_{m_k}\|^2_{\mathcal{L}_2} \leq \delta_{m_k}, \ \forall m_k \in \mathcal{M}$$

The defender minimizes $J_{\rho}(a, \mathcal{M})$

The adversary maximizes $J_{\rho}(a, \mathcal{M})$

Challenges

Attack, Monitor, Performance

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Combinatorial optimization problem

Challenges

Attack → a, Monitor → $\mathcal{M}$, Performance → ρ

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Combinatorial optimization problem ⇒ Computational burden

Challenges

Attack, Monitor, Performance

$$J_\rho(a, \mathcal{M}) \triangleq \sup_{\zeta \in \mathcal{L}_{2e},\ \text{zero init. state}} \|y_\rho\|^2_{\mathcal{L}_2} \quad \text{s.t.} \quad \|y_{m_k}\|^2_{\mathcal{L}_2} \leq \delta_{m_k},\ \forall m_k \in \mathcal{M} \tag{1}$$

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Combinatorial optimization problem $\Rightarrow$ Computational burden

Shrink defender action space $\mathcal{M} \subset \mathbb{D} \subset \mathcal{V}$

Challenges

Attack → a, Monitor → $\mathcal{M}$, Performance → ρ

$$J_\rho(a,\mathcal{M}) \triangleq \sup_{\zeta\in\mathcal{L}_{2e},\ \text{zero init. state}} \|y_\rho\|^2_{\mathcal{L}_2} \tag{1}$$

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Combinatorial optimization problem ⇒ Computational burden

Shrink defender action space $\mathcal{M}\subset\mathbb{D}\subset\mathcal{V}$ ⇒ Efficiently allocate defense resources

Challenges

Attack ↘ Monitor ↙

$$J_{\rho}(a, \mathcal{M}) \triangleq \sup_{\zeta \in \mathcal{L}_{2e},\ \text{zero init. state}} \|y_{\rho}\|_{\mathcal{L}_2}^2 \quad (1)$$

↗ Performance

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Combinatorial optimization problem ⇒ Computational burden

Shrink defender action space $\mathcal{M} \subset \mathbb{D} \subset \mathcal{V}$ ⇒ Efficiently allocate defense resources

⇑

$\mathbb{D}$ guarantees the boundedness of (1)

Challenges

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Main contributions

Characterize $\mathbb{D}$

Preliminary results

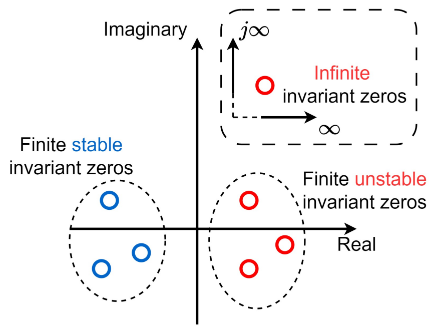
Boundedness of the worst-case impact of stealthy FDI attacks

$\Leftrightarrow$ Invariant zeros

Preliminary results

Boundedness of the worst-case impact of stealthy FDI attacks

⇔ Invariant zeros

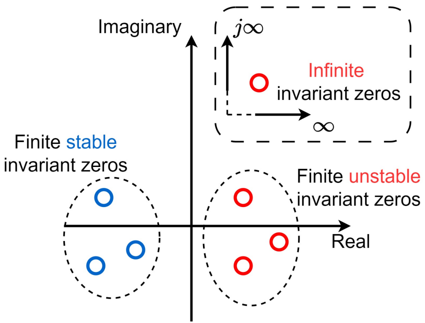


Preliminary results

Boundedness of the worst-case impact of stealthy FDI attacks

$\Leftrightarrow$ Invariant zeros

$$\dot{x}(t) = Ax(t) + b \otimes e_a \zeta(t),$$
$$y_\rho(t) = e_\rho^\top x(t),$$
$$y_{m_k}(t) = e_{m_k}^\top x(t), \ \forall m_k \in \mathcal{M}$$



- Systems $\Sigma_\rho = \big(A, b \otimes e_a, e_\rho^\top, 0\big)$ and $\Sigma_{m_k} = \big(A, b \otimes e_a, e_{m_k}^\top, 0\big)$

$$J_\rho(a, \mathcal{M}) \triangleq \sup_{\zeta \in \mathcal{L}_{2e},\ \text{zero init. state}} \|y_\rho\|_{\mathcal{L}_2}^2$$
$$\text{s.t.} \quad \|y_{m_k}\|_{\mathcal{L}_2}^2 \leq \delta_{m_k}, \ \forall m_k \in \mathcal{M}$$

Preliminary results

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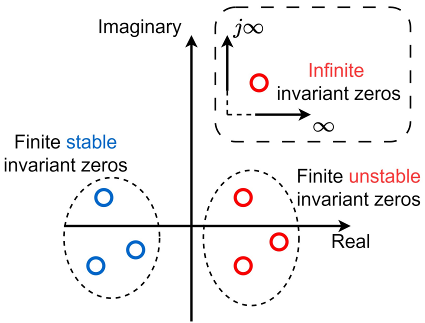

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$$\text{s.t.} \quad \|y_{m_k}\|_{\mathcal{L}_2}^2 \leq \delta_{m_k}, \ \forall m_k \in \mathcal{M}$$

- At least Σ_{m_k}, its λ_{m_k} (Re$[\lambda_{m_k}] > 0$) is also invariant zero of Σ_ρ,

if, and only if, $J_\rho(a, \mathcal{M}) < \infty$

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Paper I - Problem variation


Defender


Adversary


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Challenges

- Unweighted graph $\mathcal{G}$ with N vertices, certain Laplacian matrix L

$$\dot{x}(t) = -Lx(t) + e_a\zeta(t),$$
$$y_\rho(t) = e_\rho^\top x(t),$$
$$y_m(t) = e_m^\top x(t) \quad (\mathcal{M} = \{m\}).$$

- Worst-case impact of stealthy FDI attacks

$$J_\rho(a, m) \triangleq \sup_{\zeta \in \mathcal{L}_{2e},\ \text{zero init. state}} \|y_\rho\|_{\mathcal{L}_2}^2$$
$$\text{s.t.} \quad \|y_m\|_{\mathcal{L}_2}^2 \leq \delta_m$$

Challenges

- Unweighted graph $\mathcal{G}$ with N vertices, certain Laplacian matrix L

$$\dot{x}(t) = -Lx(t) + e_a\zeta(t),$$
$$y_\rho(t) = e_\rho^\top x(t),$$
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- Worst-case impact of stealthy FDI attacks

$$J_\rho(a, m) \triangleq \sup_{\zeta \in \mathcal{L}_{2e},\ \text{zero init. state}} \|y_\rho\|_{\mathcal{L}_2}^2$$
$$\text{s.t.} \quad \|y_m\|_{\mathcal{L}_2}^2 \leq \delta_m$$

No finite unstable invariant zeros[1]

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Infinite invariant zeros

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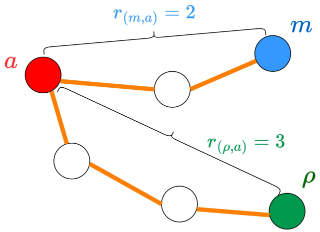
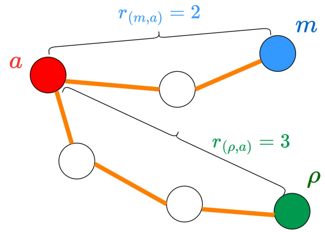


Main results

Σ_m: output at m, relative degree $r_{(m,a)}$
Σ_ρ: output at ρ, relative degree $r_{(\rho,a)}$



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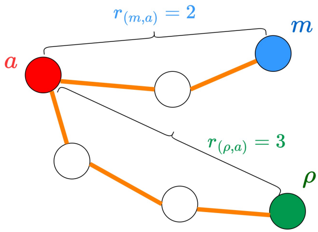

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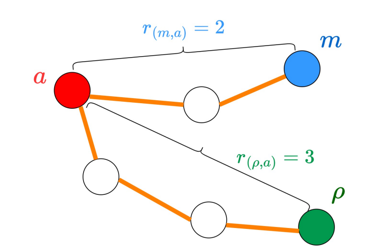

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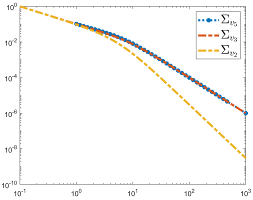

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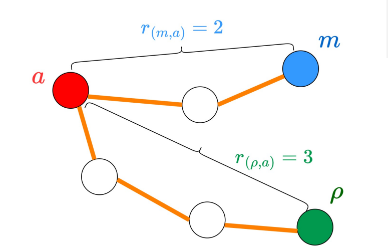

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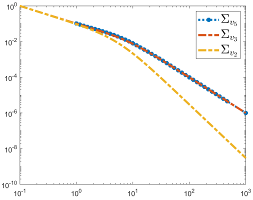

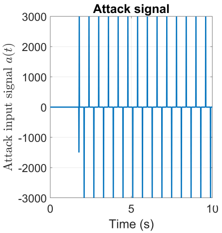

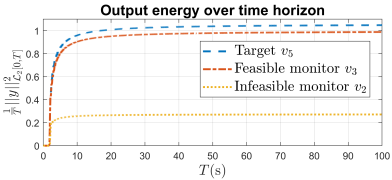

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1. Introduction
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4. Contributions
   - Paper I
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Paper II - Problem variation

Defender

Adversary

Performance ρ

Paper I	Paper II
• Certain LFO • Performance ρ is fixed • Def./Adv. chooses one • Take actions simultaneously	• Uncertain LFO • Performance ρ is fixed • Def./Adv. chooses one • Take actions simultaneously
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• Certain LSO • Performance ρ is fixed • Def./Adv. chooses one • Take actions simultaneously	• Certain LFO • Performance ρ is uncertain • Adv. chooses one, Def. chooses several • Def. takes action first

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- Uncertain weighted graph $\mathcal{G}$ with N vertices, uncertain L^{Δ}

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Value-at-Risk

$$\mathcal{J}_{\rho}(a, m) = \mathsf{VaR}_{\beta,\Omega}\Big[\sup_{\zeta \in \mathcal{L}_{2e}} J_{\rho}(a, m; \Delta, \zeta)\Big]$$

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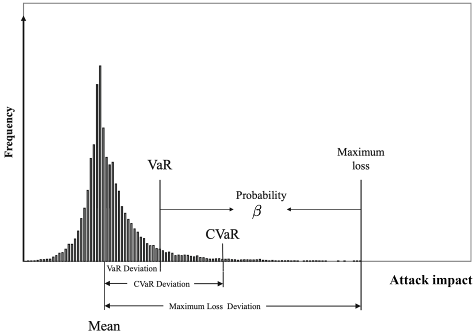

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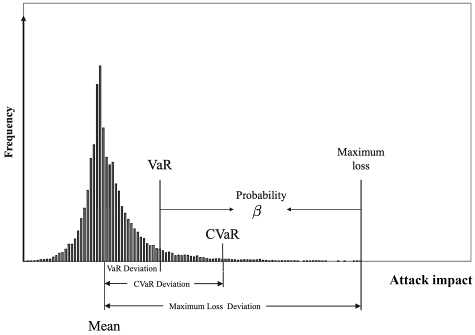

Theorem 1 & Lemma 2

M_1 values from Ω

Evaluate $\lceil M_1(1-\beta_1)\rceil$ values with ϵ accuracy

$M_1 \geq \frac{1}{2\epsilon_1^2}\log\frac{2}{\beta_1}$

E.g., $\epsilon_1 = 0.06$, $\beta_1 = 0.08$, $M_1 \geq 450 \Rightarrow 414$ values

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Challenges

- **Main focus:** Power networks by linearized swing equations

$$m_i\ddot{p}_i(t) + h_i\dot{p}_i(t) = \sum_{j\in\mathcal{N}_i} \ell_{ij}\Big(p_i(t) - p_j(t)\Big) + \tilde{u}_i(t),$$

- Closed-loop system

$$\begin{aligned}\dot{x}(t) &= Ax(t) + e_a\zeta(t),\\ y_i(t) &= C_i x(t), \quad \forall i \in \mathcal{V},\\ y_\rho(t) &= C_\rho x(t),\end{aligned}$$

- Local performance: $\|y_\rho\|^2_{\mathcal{L}_2[0,T]} = \frac{1}{T}\int_0^T |y_\rho(t)|^2 \,\mathrm{d}t$

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Detector

$$\begin{aligned}\dot{\hat{x}}_m(t) &= A\hat{x}_m(t) + K_m\eta_m(t), \quad \hat{x}_m(0) = 0,\\ \eta_m(t) &= y_m(t) - C_m\hat{x}_d(t),\end{aligned}$$

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Finite unstable invariant zeros λ_m of Σ_m can be excluded by proper local control parameters. Then, $J_\rho(a,m) < \infty$.

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$$\mathcal{M}^\star = \arg\min_{\mathcal{M}\subset\mathbb{D}} \text{Defense cost}\big|_{a^\star(\mathcal{M})}$$

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Combinatorial optimization problem $\Rightarrow$ Computational burden

Players' strategies

Defender strategy

$$\mathcal{M}^\star = \arg\min_{\mathcal{M}\subset\mathbb{D}} \text{Defense cost}|_{a^\star(\mathcal{M})}$$

$$a^\star(\mathcal{M}) = \arg\max_{a\in\mathbb{A}} \text{Defense cost}$$

Adversary response

$$a^\star = \arg\max_{a\in\mathbb{A}} \text{Attack impact}|_{\mathcal{M}^\star}$$

Combinatorial optimization problem $\Rightarrow$ Computational burden

Shrink defender action space $\mathcal{M} \subset \mathbb{D} \subset \mathcal{V}$ $\Rightarrow$ Efficiently allocate defense resources

$\Uparrow$

$\mathbb{D}$ s.t. defense cost/attack impact $< \infty$

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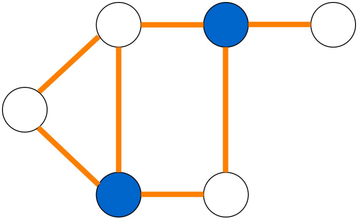
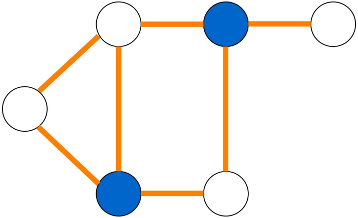
$\mathbb{D}$ s.t. defense cost/attack impact $< \infty$ $\Leftarrow$ **Characterize $\mathbb{D}$**

Main results



Dominating set

Main results



Dominating set

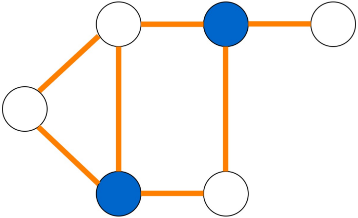
Theorem 2 (necessary and sufficient condition)

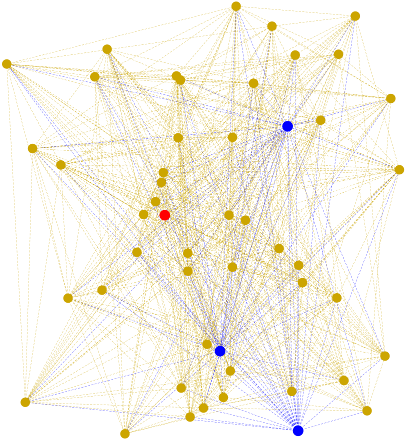
$\mathcal{M}$ is a dominating set

$\Leftrightarrow$ def. cost $R(a, \mathcal{M}) < \infty$

& attack impact $Q(a, \mathcal{M}) < \infty$

Main results





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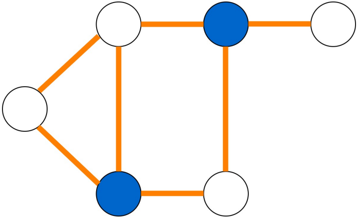

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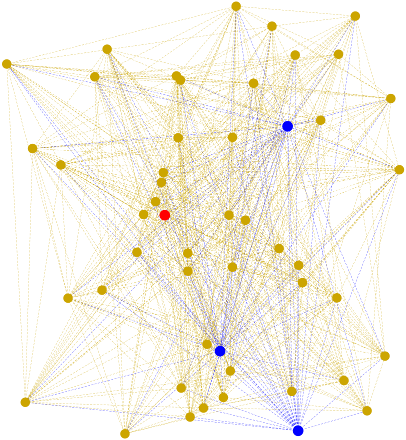

$$R(a, \mathcal{M}) \leq 50.2456$$
$$Q(a, \mathcal{M}) \leq 48.4235$$

Outline

1 Introduction

2 Security in Networked Control Systems

3 Problem Formulation

4 Contributions
- Paper I
- Paper II
- Paper III
- Paper IV

5 Conclusion and Future Work

Conclusion and Future Work

This Licentiate thesis has

1. considered several types of NCSs under attacks
2. intensively investigated the worst-case impact of stealthy FDI attacks
3. found system- and graph-theoretic conditions
4. assisted the defender in allocating defense resources

Conclusion and Future Work

This Licentiate thesis has

1. considered several types of NCSs under attacks
2. intensively investigated the worst-case impact of stealthy FDI attacks
3. found system- and graph-theoretic conditions
4. assisted the defender in allocating defense resources

Toward the PhD thesis, it will be extended to

1. overcome combinatorial optimization problem
2. consider uncompleted information
3. consider multiple adversaries
4. assist the defender in designing detectors
5. ......

Defender

Adversary

Performance ρ

Paper I

- Certain LFO
- Performance ρ is fixed
- Def./Adv. chooses one
- Take actions simultaneously

Paper II

- Uncertain LFO
- Performance ρ is fixed
- Def./Adv. chooses one
- Take actions simultaneously

Paper III

- Certain LSO
- Performance ρ is fixed
- Def./Adv. chooses one
- Take actions simultaneously

Paper IV

- Certain LFO
- Performance ρ is uncertain
- Adv. chooses one, Def. chooses several
- Def. takes action first

Thanks for listening!!!