Cyber-Security of Networked Control Systems

Karl Henrik Johansson
ACCESS Linnaeus Center
Royal Institute of Technology, Sweden

Joint work with Henrik Sandberg, André Teixeira, Kin C. Sou

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ACCESS Linnaeus Center

- ACCESS was established at KTH from an Excellence Grant from the Swedish Research Council
- Developed into **one of Europe's largest university research centers** in networked systems
  - 36 faculty, 20 postdocs, >100 PhD students
  - Basic funding from VR on 1.3 MEUR per year
  - Total research budget 2010 over 12 MEUR
- Graduate school with **>40 graduated PhD's**
- **Faculty renewal** and mobility programs
- Extensive international and industrial collaborations
- External communication and dissemination

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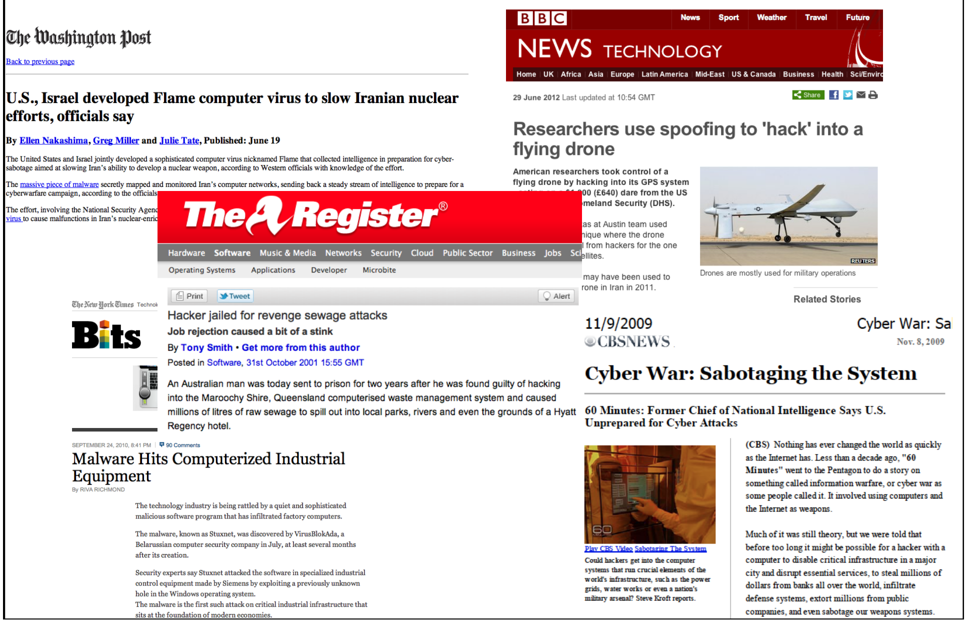
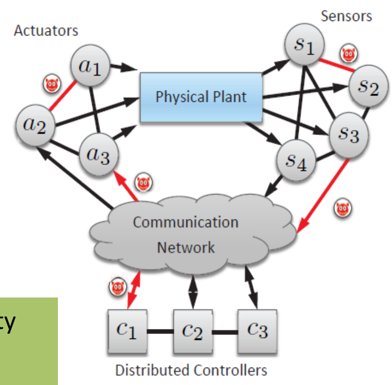
Recent Cyber-Attacks on Control Systems



Cyber-Security of Networked Control Systems

- Networked control systems are to a growing extent based on **open communication and software technology**
- Leads to **increased vulnerability** to cyber-threats with many potential points of attacks



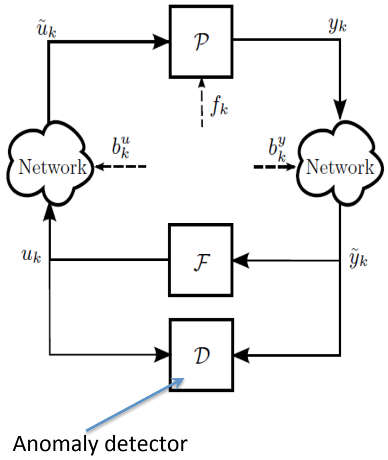
- How to model attacks?
- How to measure vulnerability?
- How to compute consequences?
- How to design secure control systems

- Traditional computer and information security do not provide answers these questions
- Need for a theory for secure control systems

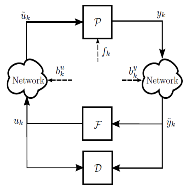
Outline

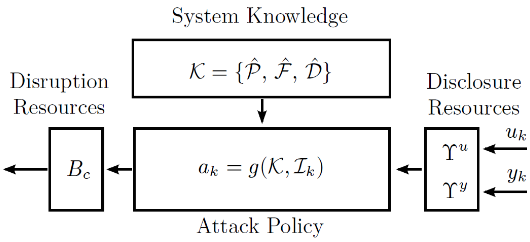
- Introduction
- Attack model for control systems
- Attack on power network state estimator
- Stealthy minimum-effort attacks
- Security index
- Conclusions
- Biography

Networked Control System under Attack



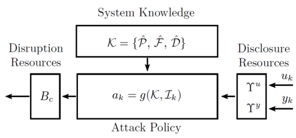
Adversary Model

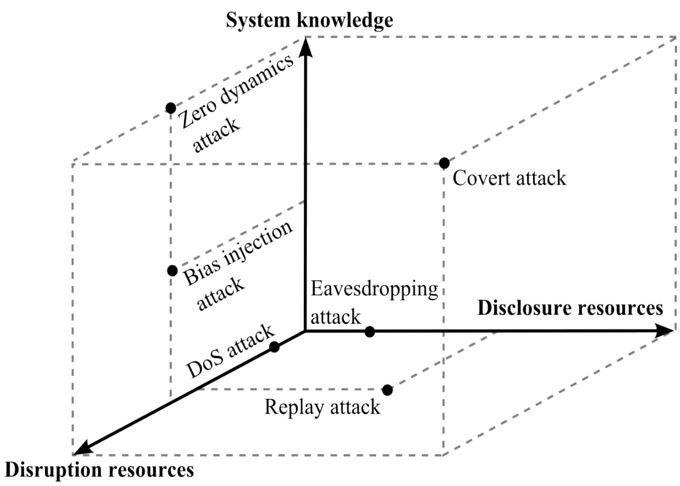




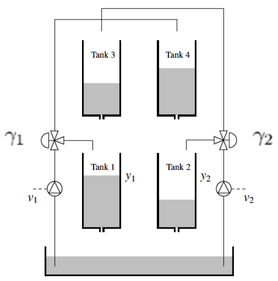
- Adversary constrained by limited resources
- Attack policy depends on adversary goals and constraints

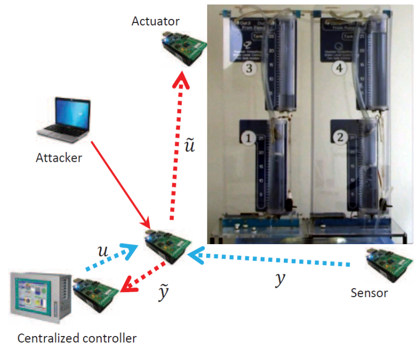
Attack Space





Experimental Set-Up





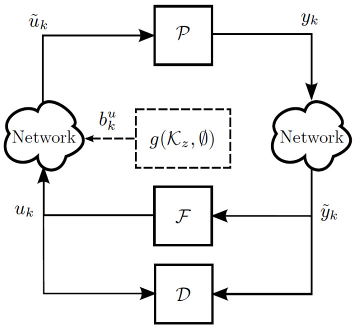
$$\frac{dx}{dt} = \begin{bmatrix} -\frac{1}{T_1} & 0 & \frac{A_3}{A_1 T_3} & 0 \\ 0 & -\frac{1}{T_2} & 0 & \frac{A_4}{A_2 T_4} \\ 0 & 0 & -\frac{1}{T_3} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_4} \end{bmatrix} x + \begin{bmatrix} \frac{\gamma_1 k_1}{A_1} & 0 \\ 0 & \frac{\gamma_2 k_2}{A_2} \\ 0 & \frac{(1-\gamma_2)k_2}{A_3} \\ \frac{(1-\gamma_1)k_1}{A_4} & 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} k_c & 0 & 0 & 0 \\ 0 & k_c & 0 & 0 \end{bmatrix} x$$

Quadruple-tank process has non-minimum-phase zero if $0 < \gamma_1 + \gamma_2 < 1$

[J, 2000]

Zero Dynamics Attack



- Zero dynamics are characterized by:

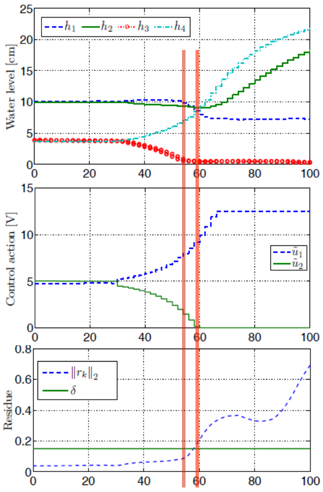
$$\begin{bmatrix} \nu I - A & -B \\ C & 0 \end{bmatrix} \begin{bmatrix} x_0 \\ g \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

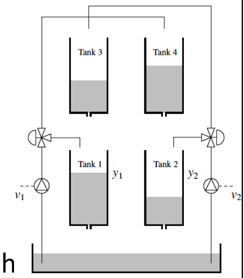
- Suggests attack on actuators with policy:

$$a_k = g\nu^k$$

- If the zero is unstable, then the plant state can be moved by this attack without detection
- Requires system knowledge (zero dynamics) but no disclosure resources

Experimental Validation





- **Attack goal:** Empty Tank 3
- Zero dynamics attack on both actuators starts at t=30s
- Tank 3 becomes empty at t=55s
- The attack is detected at t=58s
- Actuator 2 saturates at t=60s

Teixeira et al, HiCoNS, 2012

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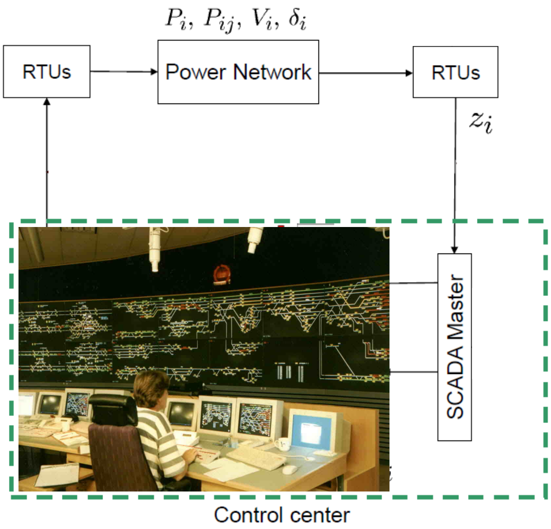
Motivation

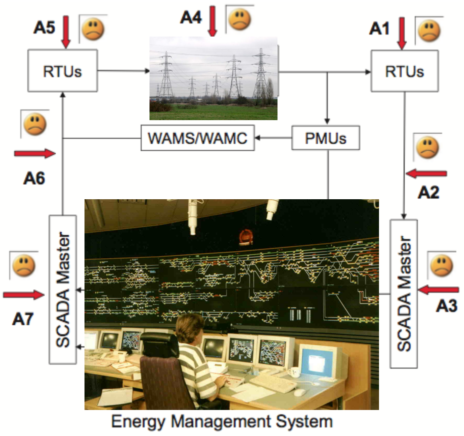
- Northeast blackout Aug 14, 2003: 55 million people affected
- Software bug in energy management system **stalled alarms in state estimator for over an hour**
- Cyber-attacks against the power network control systems with similar consequences pose a substantial threat

SCADA/EMS Systems



(SCADA/EMS = Supervisory Control and Data Acquisition/Energy Management Systems)

Attacks on Power Systems

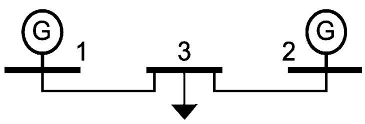


- Many attack opportunities
  - Sensor and actuators
  - Communication systems
  - Software systems (e.g., control)
  - Human operators
  - Physical infrastructure
- How strengthen the systems against cyber-attacks?

SCADA = Supervisory Control and Data Acquisition **EMS** = Energy Management System **WAMS** = Wide Area Monitoring System
RTUs = Remote Terminal Units (Sensors/Actuators) **PMUs** = Phasor Measurement Units (Sensors)

(Static) Power Network Model

- Local states at bus i:
  - θ_i – phase angle
  - V_i – voltage magnitude



- Active and reactive power injections:

$$\begin{aligned} P_i &= V_i \sum_{j\in N_i} V_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \\ Q_i &= V_i \sum_{j\in N_i} V_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right) \end{aligned}$$

- Active and reactive power flows:

$$\begin{aligned} P_{ij} &= V_i^2(g_{si}+g_{ij}) - V_iV_j\left(g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij}\right) \\ Q_{ij} &= -V_i^2(b_{si}+b_{ij}) - V_iV_j\left(g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij}\right) \end{aligned}$$

where

$$\theta_{ij} = \theta_i - \theta_j$$

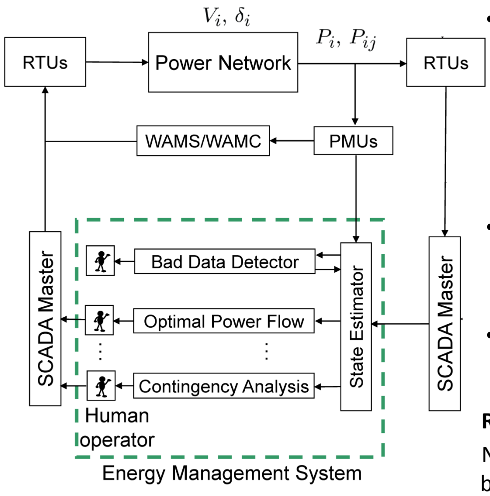
- Measurement model:

$$z = h(x) + \epsilon$$

  - $x \in \mathbb{R}^n$: network states
  - $z \in \mathbb{R}^m$: power flow measurements
  - ϵ : measurement noise

Static model because the power grid time constant ~10 ms is beyond existing measurement technology. Typical sampling time ~1 s.

Energy Management System for Power Networks



- SCADA-EMS provides power network state information to
  - Identify faulty equipment
  - Optimize power flows
  - Analyze reliability (contingency)
  - Etc
- Large system with slow sampling
  - 100-1 000's of RTUs sampled in sec's
  - 10K-40K measurements
- Decisions taken by human operators

Remark

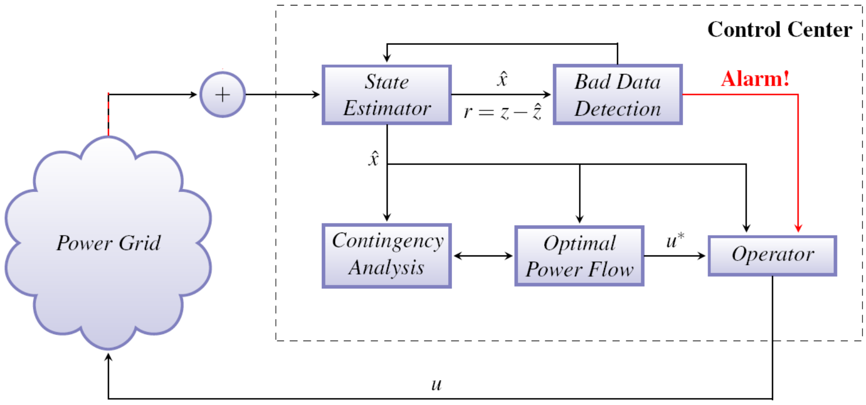
New WAMCs based on high-rate PMUs are better protected but constitute only a small portion of the overall network

WAMC = Wide Area Monitoring and Control System

RTUs = Remote Terminal Units (Sensors/Actuators)

PMUs = Phasor Measurement Units (Sensors)

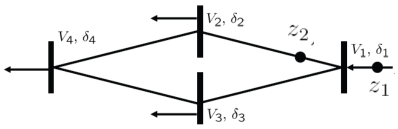
Energy Management System



- The **state estimator** has a crucial role in the EMS
- If the **bad data detector** identifies a faulty sensor, the corresponding measurement is removed from the state estimator
- Bad data detection is typically done under the assumption of **uncorrelated faults**, which does not hold for intelligent attacks

State Estimator

- Steady-state models:



$$\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \frac{V_1V_2}{X_{12}} \sin(\delta_1 - \delta_2) + \frac{V_1V_3}{X_{13}} \sin(\delta_1 - \delta_3) \\ \frac{V_1V_2}{X_{12}} \sin(\delta_1 - \delta_2) \end{pmatrix} + \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} = h(x) + e \in \mathbb{R}^m$$

- WLS estimates of bus phase angles δ_i (in vector $\widehat{x}$):

$$\hat{x}^{k+1} = \hat{x}^k + (H_k^T R^{-1} H_k)^{-1} H_k^T R^{-1}(z - h(\hat{x}^k))$$

$$H_k := \frac{\partial h}{\partial x}(\hat{x}_k) \qquad R := \mathbf{E} ee^T$$

- Linear DC approximation (≈ ML estimate):

$$\hat{x} = (H^T R^{-1} H)^{-1} H^T R^{-1} z \qquad \boldsymbol{H} := \left.\frac{\partial \boldsymbol{h(x)}}{\partial \boldsymbol{x}}\right|_{\boldsymbol{x}=0}$$

E.g., [Schweppe and Wildes, 1970; Abur and Exposito, 2004]

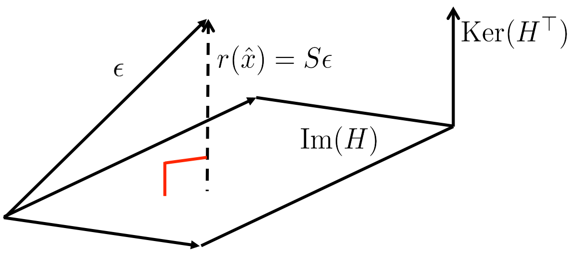
Bad Data Detector

$$H = \left.\frac{\partial h(x)}{\partial x}\right|_{x=\hat{x}}$$

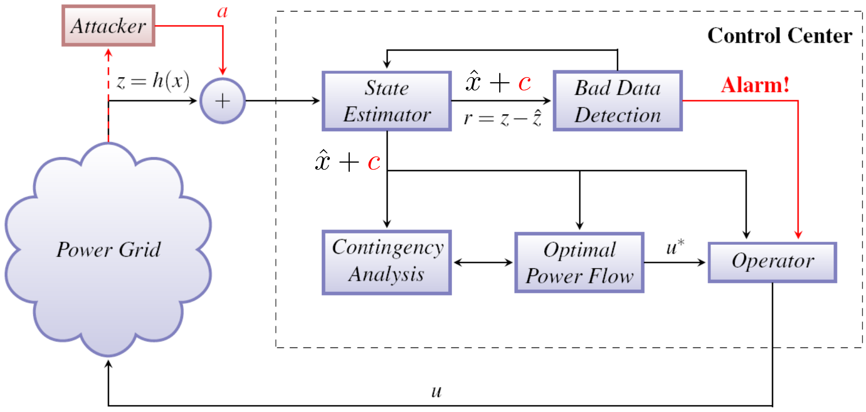
- Today's BDD is based on measurement residual $r(\hat{x}) = z - h(\hat{x})$

$$\|Wr(\hat{x})\|_p \underset{H_1}{\overset{H_0}{\lessgtr}} \tau$$

- For the Gauss-Newton method: $r(\hat{x}) \approx (I - H(H^\top H)^{-1} H^\top)\epsilon = S\epsilon$
- Note that $S = \mathbf{P}_{\mathrm{Ker}(H^\top)}$ is the orthogonal projection onto $\mathrm{Ker}(H^\top)$
- Can be exploited by an attacker



Attack Model



- **Scenario:** Attacker injects **malicious data** a to corrupt analog measurements in the power grid, in order to change state estimates without generating bad data detection alarm
- How characterize the set of **undetectable** malicious data a?

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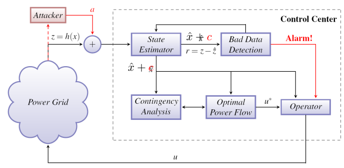
Bad-Data Detection and Stealthy Attacks



- Bad-data detection trigger alarm when residual r is large

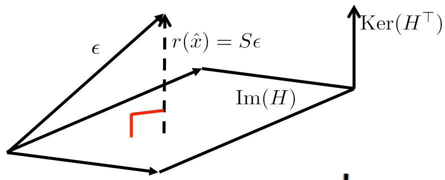
$$r := z - \hat{z} = z - H\hat{x} = z - H(H^T R^{-1} H)^{-1} H^T R^{-1} z$$

- Characterization of undetectable malicious data a

$$z_a := z + a$$

$$a = Hc \in \mathrm{Im}(H)$$

$$r = z - \hat{z} = z_a - \hat{z}_a$$



- The attacker has a lot of freedom in the choice of a!
- Attacker likely to seek sparse solutions a , i.e., manipulate only few measurements

[Liu *et al.*, 2009]

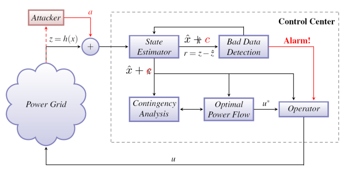
Stealthy Minimum-Effort Attack

- Attack single measurement z_k

$$\min_a \|a\|_2$$

$$\text{s.t. } a \in \mathcal{U} \cap \mathcal{G}_k \cap \mathcal{C}$$

- $\mathcal{U} = \mathrm{Im}(H)$
- $\mathcal{G}_k = \{a \in \mathbb{R}^m : a_k = 1\}$
- $\mathcal{C} = \mathbb{R}^m$



- Optimal attack

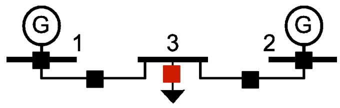
$$a^* = K_{kk}^{-1} K e_k$$

$$K = HH^\dagger$$

- a^* is typically not sparse, so many sensors need to be corrupted
- Consider **0-norm instead of 2-norm**

Stealthy Minimum-Effort Attack

$$\min_{a} \|a\|_0$$
$$\text{s.t. } a \in \mathcal{U} \cap \mathcal{G}_k \cap \mathcal{C}$$



- P_3 is the target measurement
- A few possible attacks:
  - ~~$\{P_3\}, \{P_3, \star\}$~~ not stealthy
  - $\{P_1, P_{13}, P_3\}$ minimum effort
  - $\{P_2, P_{23}, P_3\}$
  - $\{P_1, P_{13}, P_3, P_{23}, P_2\}$

Security Index ρ_k

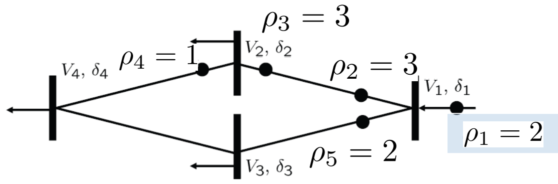
- Security index for measurement k: $\rho_k = \|a^*\|_0$
  - a^* is the optimal solution of

$$\min_{a} \|a\|_0$$
$$\text{s.t. } a \in \mathcal{U} \cap \mathcal{G}_k \cap \mathcal{C}$$

- $\mathcal{U} = \text{Im}(H)$ Stealthy
- $\mathcal{G}_k = \{a \in \mathbb{R}^m : a_k = 1\}$ Corrupted
- $\mathcal{C} = \{a \in \mathbb{R}^m : a_i = 0 \quad \forall i \in \mathcal{P}\}$ Protected

- ρ_k is the minimum number of measurements to manipulate for a successful attack

Example



- Sparse attack corresponding to ρ_k:

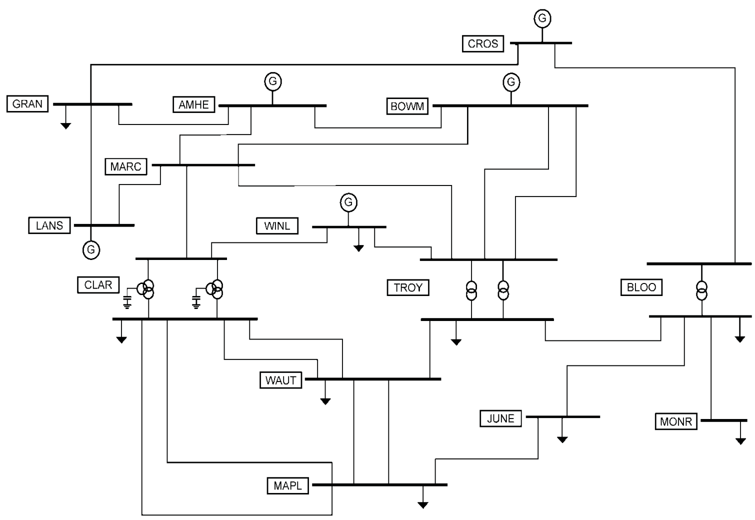
$$\begin{pmatrix} a_1 & a_2 & a_3 & a_4 & a_5 \end{pmatrix} = \begin{pmatrix} 1 & 1 & -1 & 0 & 1 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 \end{pmatrix}$$

- Compare with the "hat matrix":

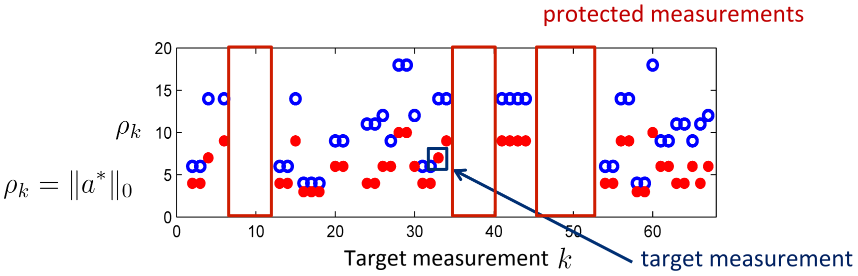
$$\begin{pmatrix} \hat{z}_1 \\ \hat{z}_2 \\ \hat{z}_3 \\ \hat{z}_4 \\ \hat{z}_5 \end{pmatrix} = \underbrace{\begin{pmatrix} 0.60 & 0.20 & -0.20 & 0 & 0.40 \\ 0.20 & 0.40 & -0.40 & 0 & -0.20 \\ -0.20 & -0.40 & 0.40 & 0 & 0.20 \\ 0 & 0 & 0 & 1.00 & 0 \\ 0.40 & -0.20 & 0.20 & 0 & 0.60 \end{pmatrix}}_{=H(H^T R^{-1} H)^{-1} H R^{-1}} \begin{pmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \end{pmatrix}$$

- Hat matrix misleading for judging sparsity of attacks!

VIKING 40-bus Benchmark



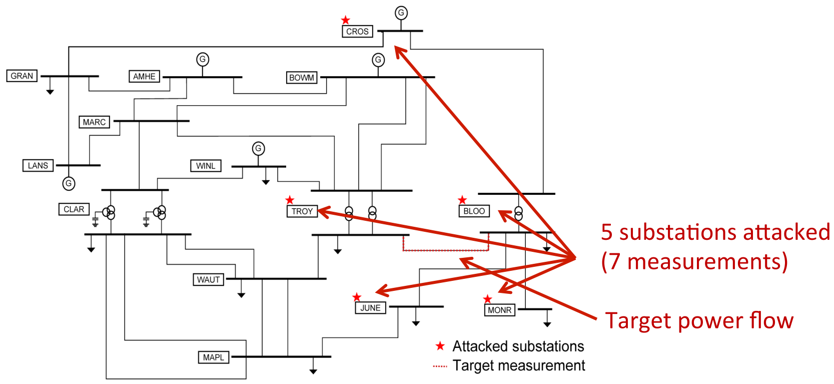
VIKING Benchmark: Security Index



Existing measurement configuration

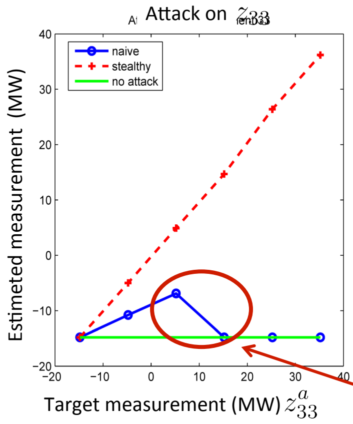
Extended measurements configuration

VIKING Benchmark: Experimental Results



- Target measurement: flow between TROY and BLOO, z_{33}
- Nonlinear models are used by the state estimator and bad data detector
- Attacker knows the linear DC model accurately

VIKING Benchmark: Experimental Results



$$z^a = z + a$$

Table 1: Results from the stealthy attack for large bias

Target bias, a_{33}	False value (MW), z_{33}^a	Estimate (MW), $\hat{z}_{33}^a$	#BDD Alarms
0	-14.8	-14.8	0
50	35.2	36.2	0
100	85.2	86.7	0
150	135.2	137.5	0
200	185.2	-	-

- 150 MW was not detected (56% of nominal value)
- State estimator did not converge for 200 MW

Bad data detected and removed

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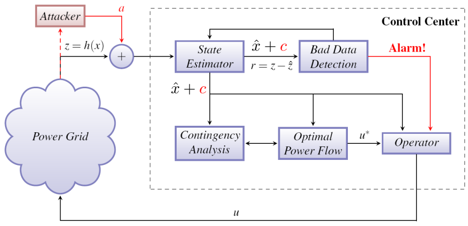
Conclusions

- **Cyber-attack models** for networked control systems
- Undetectable false-data attack against power systems state estimator possible, both in theory and practice
- New **security index** ρ_k to estimate vulnerabilities
- Suggests locations of counter measures
- Many open problems in secure networked control theory



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