Smart Energy Grids and Cyber Security

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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 may result in similar consequences and pose a substantial threat

Is this a "real" concern?

Motivation

Getting quite real…

- First **known** hacker-caused outage
  - Dec 23rd, 2015
- Malware infected 3 regional operators in Ukraine
- Substations were disconnected, resulting in blackouts
- Malware "BlackEnergy" with "KillDisk" component

Ars Technica has arrived in Europe. **Check it out!**

RISK ASSESSMENT / SECURITY & HACKTIVISM

First known hacker-caused power outage signals troubling escalation

Highly destructive malware creates "destructive events" at 3 Ukrainian substations.

by **Dan Goodin** - Jan 4, 2016 9:36pm CET

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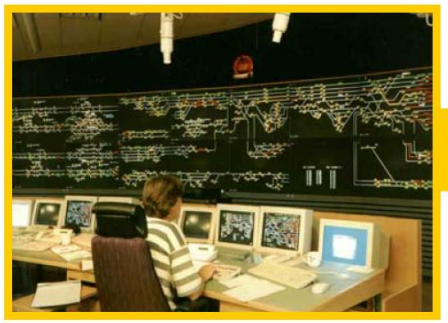
Krzysztof Lasoń

Highly destructive malware that infected at least three regional power authorities in Ukraine led to a power failure that left hundreds of thousands of homes without electricity last week, researchers said.

http://arstechnica.com/security/2016/01/first-known-hacker-caused-power-outage-signals-troubling-escalation/

From cybersecurity vulnerabilities to societal costs

Attack



SCADA system

Power network

Societal cost

Security issues

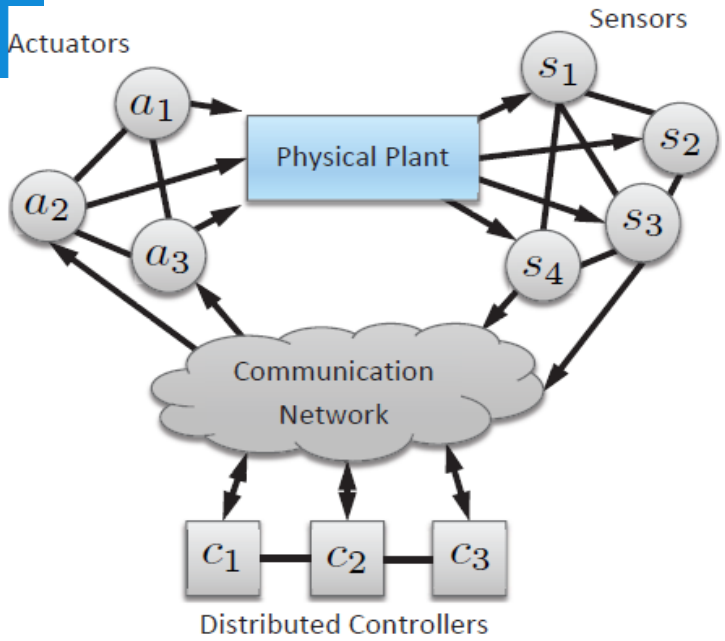
Power system: susceptible to operational errors and external attacks

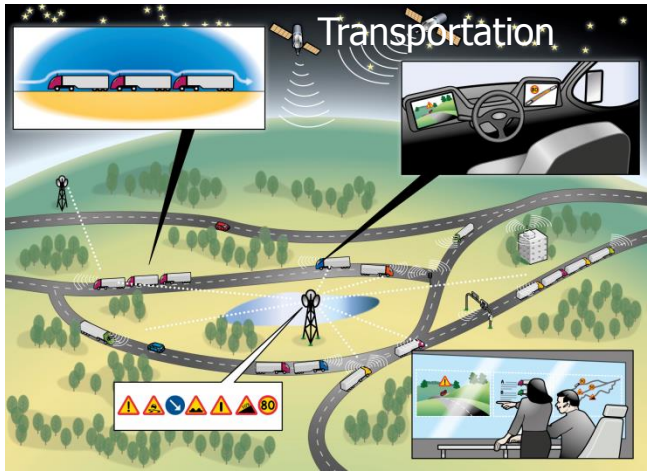
Smart grid technology makes the system even more vulnerable

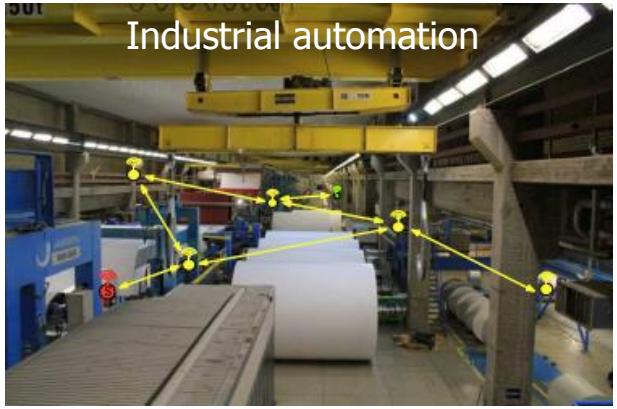
André Teixeira – Research Background

- 2009: Electrical engineer from the University of Porto, Portugal
- 2014: Ph.D. in Automatic Control at KTH Royal Institute of Technology, Stockholm, Sweden
  - "Cyber-Secure and Resilient Networked Control Systems".
  - **Networked Control System:** use digital data (exchanged through ICT infrastructures) to steer and monitor the behavior of physical processes
    - E.g.: autonomous cars, power plants, *power distribution systems*, *flood management systems…*
  - Cybersecurity concerns:
    - What if the **digital data is corrupted**/hacked? How can it be detected?
    - How does the **control algorithm react**? How is the **physical process affected**? How can it be **detected** and **mitigated**?
  - For more details: see my personal web page
- Oct. 2015: Assistant Prof. at TPM in the field of Cybersecurity of Critical Infrastructures

Networked Control Systems





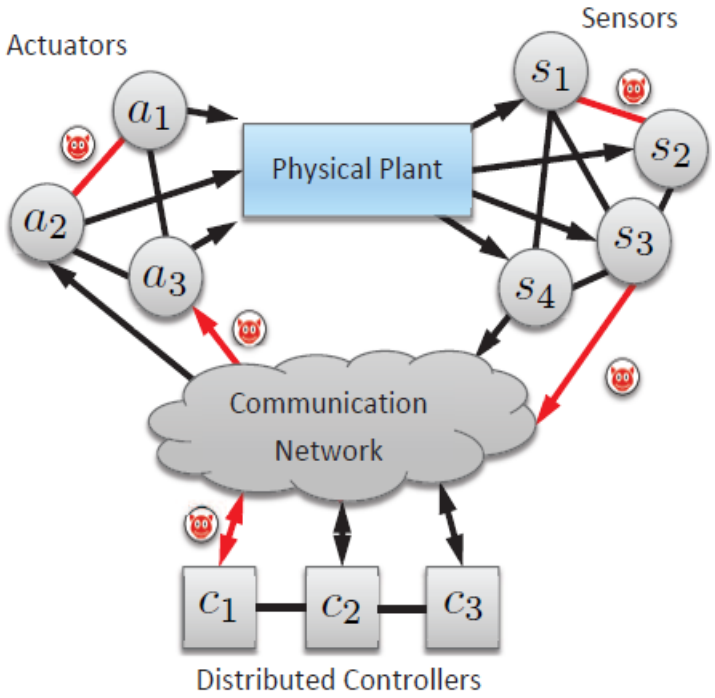


Cyber-Secure and Resilient Networked Control Systems

Networked control systems are to a growing extent based on **open communication and software technology**

- **E.g.: Legacy Energy Systems → Smart Energy Systems**

- Leads to **increased vulnerability** to cyber-threats with many potential points of attacks
- Cyber-attacks can have dramatic physical impact



- How to model adversaries and attacks?
- How to measure vulnerability?
- How to compute consequences?
- How to design protection and detection mechanisms?

- Related to:
  - **Modeling frameworks**
  - **Risk Management**
  - **Anomaly detection**

Outline

- Motivation and Research Background
- **The Concept of Risk**
  - **Impact metrics for Energy Systems**
  - Likelihood Metrics for Energy Systems
- Scenarios and Risk metrics for Smart Grids
  - Scenario 1: False-Data injection on Transmission Grids
  - Scenario 2: Voltage control under adversarial actions
- Summary
- Future Challenges and Opportunities
- References

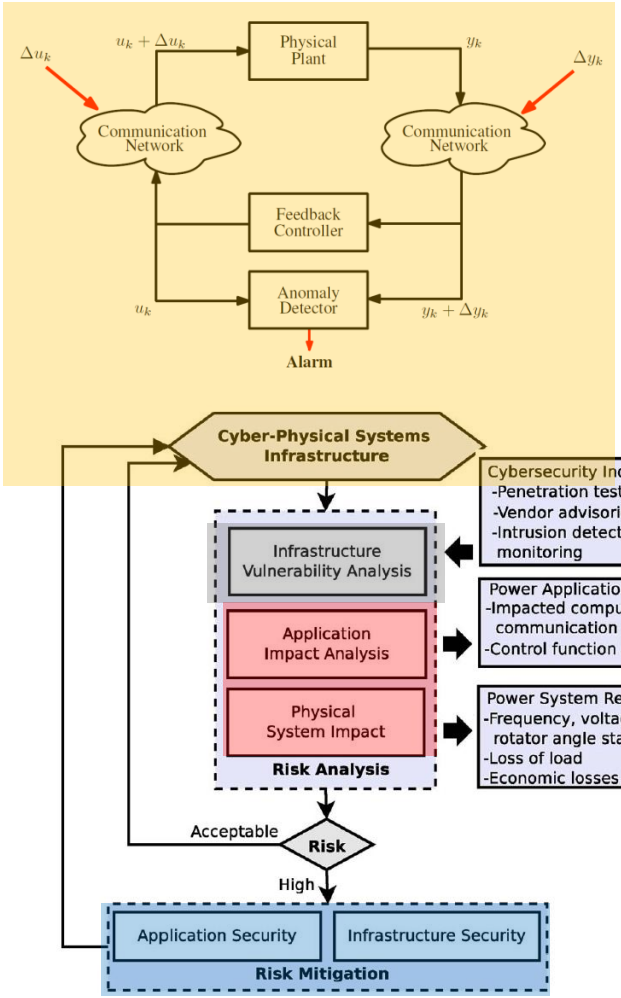
The Concept of Risk

- [Kaplan & Garrick, 1981] **Risk** is a set of tuples:
  - Attack **Scenario**
  - **Impact** of the attack
  - **Likelihood** of the attack

- How to model adversaries and attacks?
  - *Describe the system*
  - *Characterize the attack **scenario***

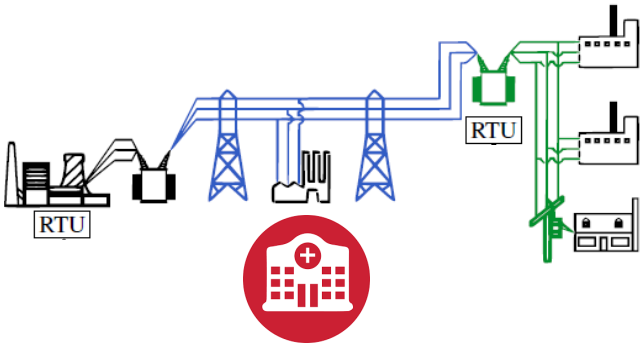
- How to measure vulnerability?
  - *Assess **likelihood** of attack (or a proxy)*
    - *Attack effort*
    - *Amount of resources (knowledge, corrupted channels)*

- How to compute consequences?
  - *Assess **impact** on performance objectives*
    - *Loss of performance*
    - *Loss of stability*
    - *Loss of desired properties*
    - *Violation of safety constraints*



[Sridhar *et al.*, Proc. IEEE, 2012]

Impact Metrics for Energy Systems



- **Operation Goals:**
- No blackouts (ideal)
- No blackouts in **critical loads**
- Efficiency
- Quality of power supply
  - Voltage @ 230V
  - Frequency @ 50Hz

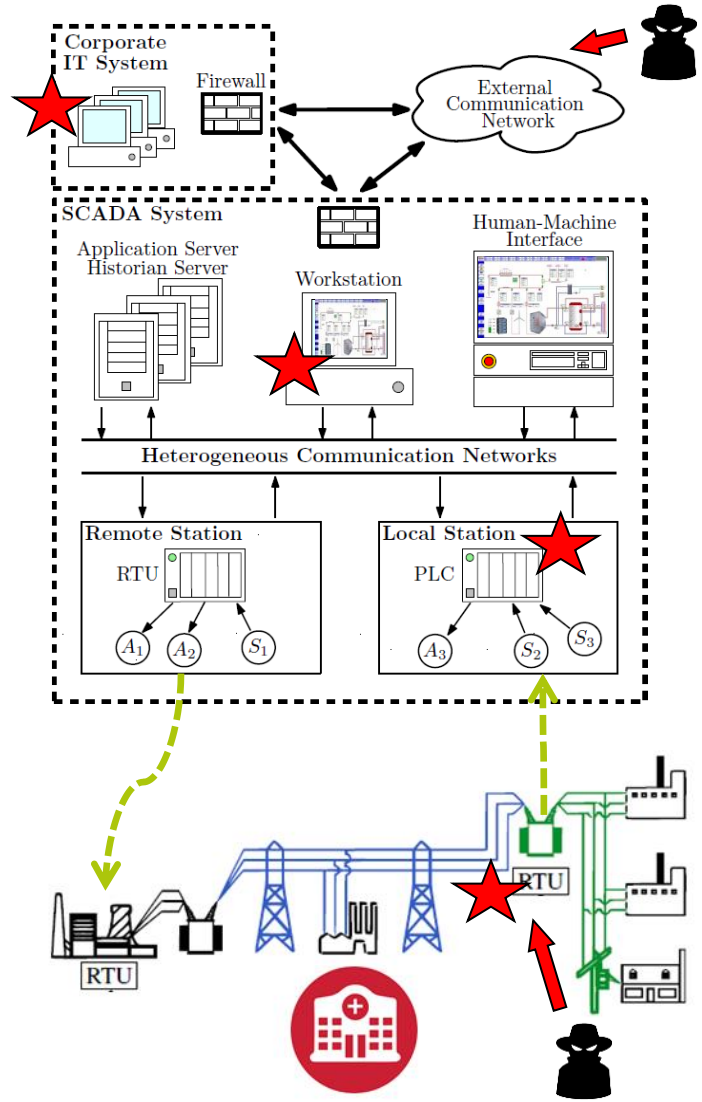
- **Impact Metrics:**
- Loss of load
- Loss of **critical load**
- Increase of costs
- Reduced quality of power supply
  - Maximum voltage variation
  - Maximum frequency variation
- Loss of stability / desired properties

Likelihood Metrics for Energy Systems

- Likelihood depends on ICT infrastructure

- **Successful attack:**
  - Successful initial infection
  - Sucessful dissemination of malware
  - **Sucessful infection of target devices**
  - **Sucessful control of target devices**

- **Likelihood metric:** probability of successful attack
  - Hard to compute – lack of historical data
  - Alternative: use proxy metrics that assess the attack effort
  - E.g.: number of infected target devices



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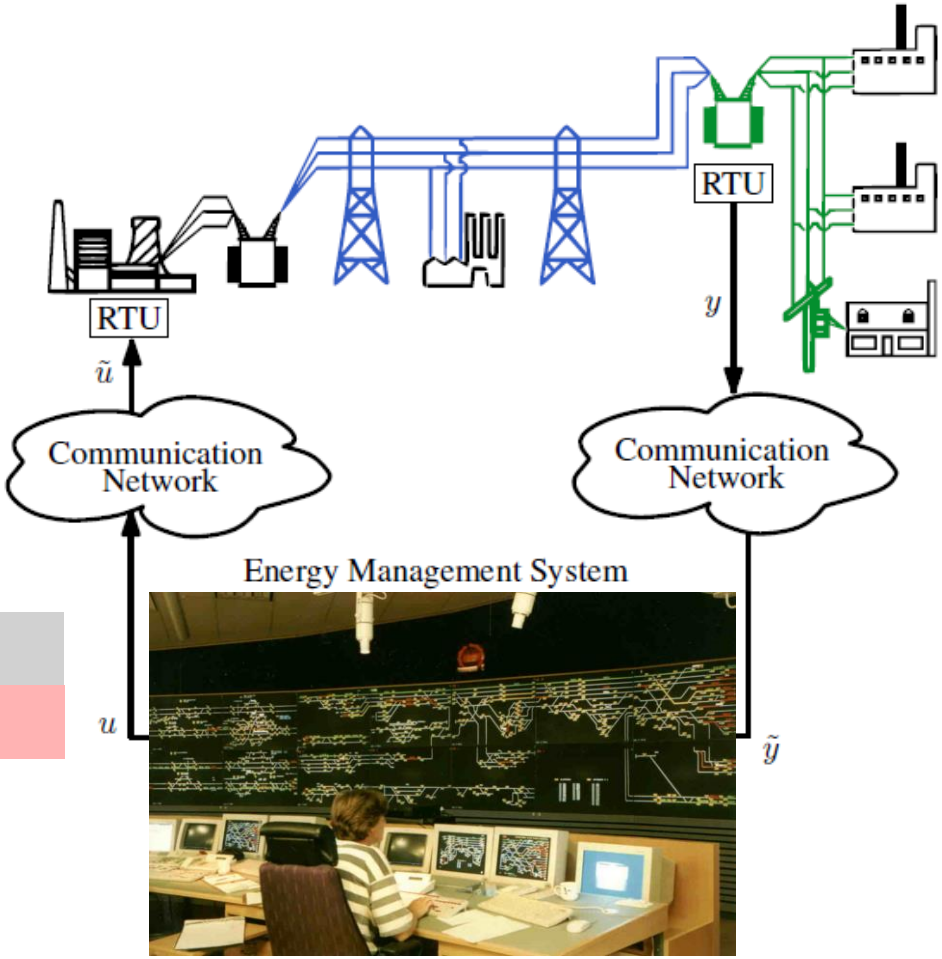
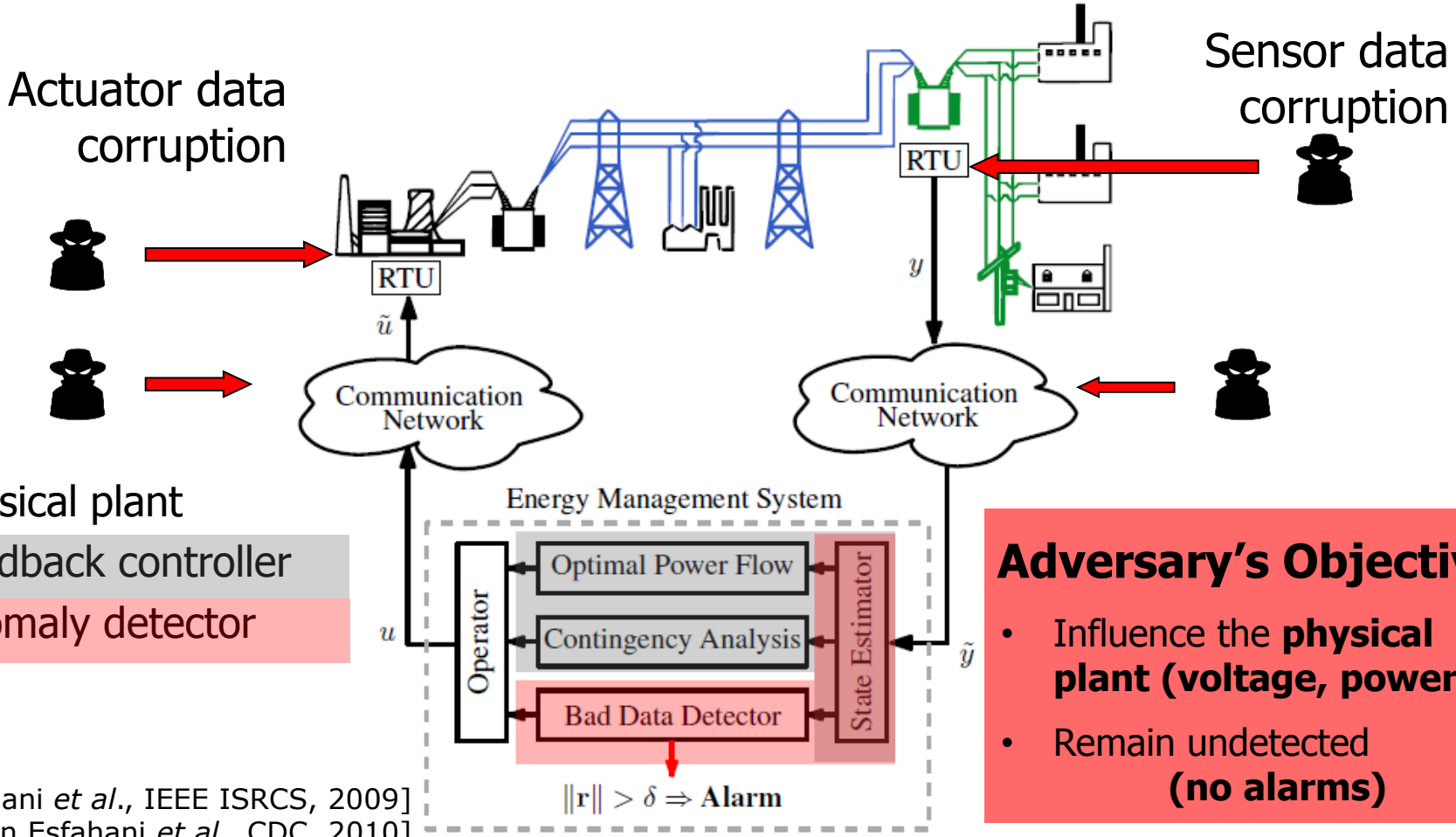
Control of Power Networks



- Physical plant
- Feedback controller
- Anomaly detector

Scenario: Closing the loop over corrupted data



- Physical plant
- Feedback controller
- Anomaly detector

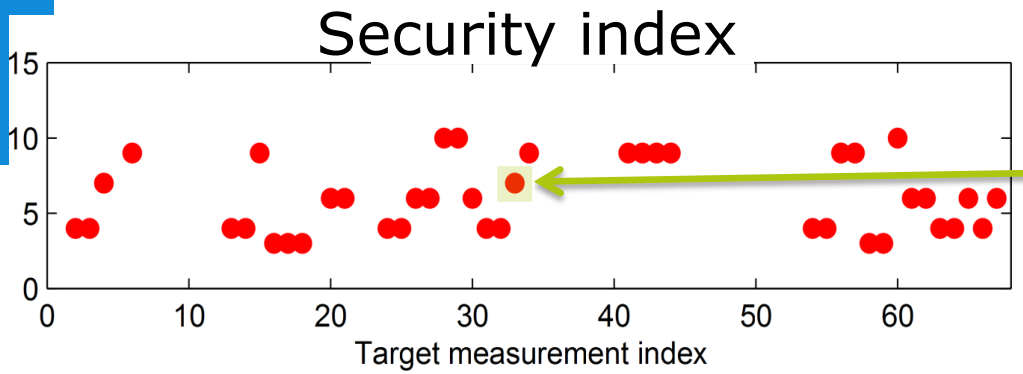
Adversary's Objective

- Influence the **physical plant (voltage, power)**
- Remain undetected **(no alarms)**

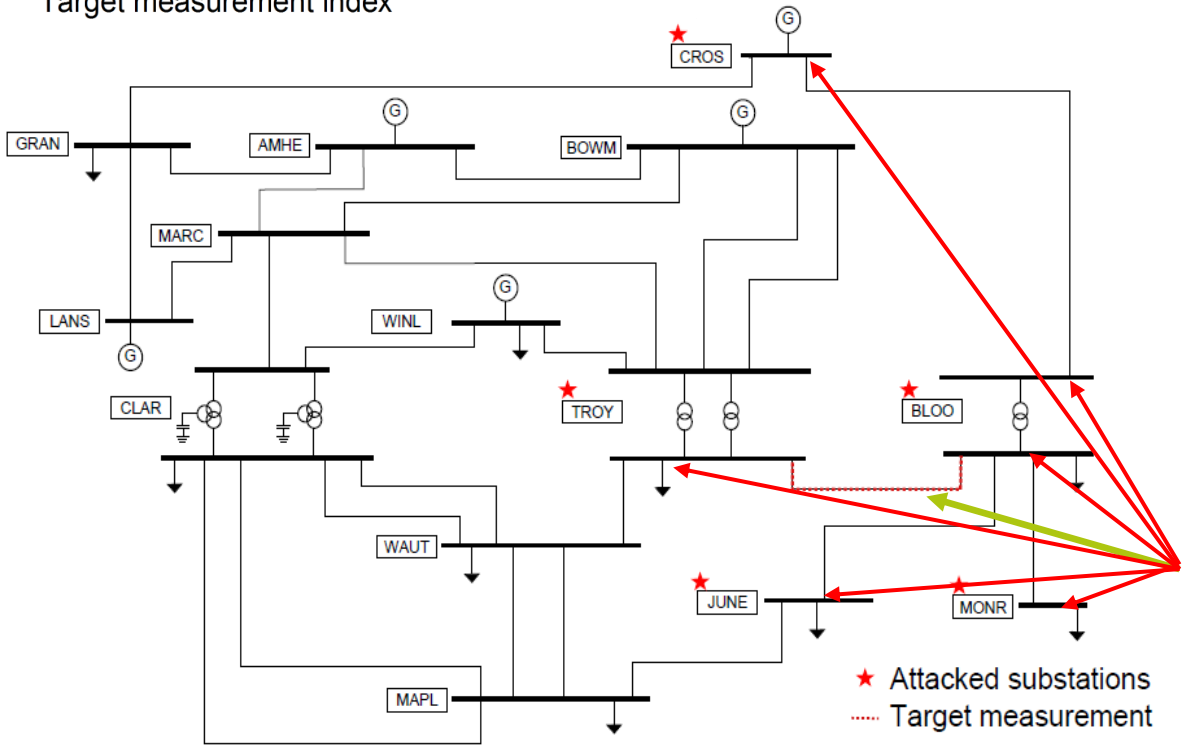
[Giani *et al.*, IEEE ISRCS, 2009]
[Mohajerin Esfahani *et al.*, CDC, 2010]

(Proxy for) **Likelihood**: Security Indices

- *How many measurements* must be corrupted to *remain undetected*?

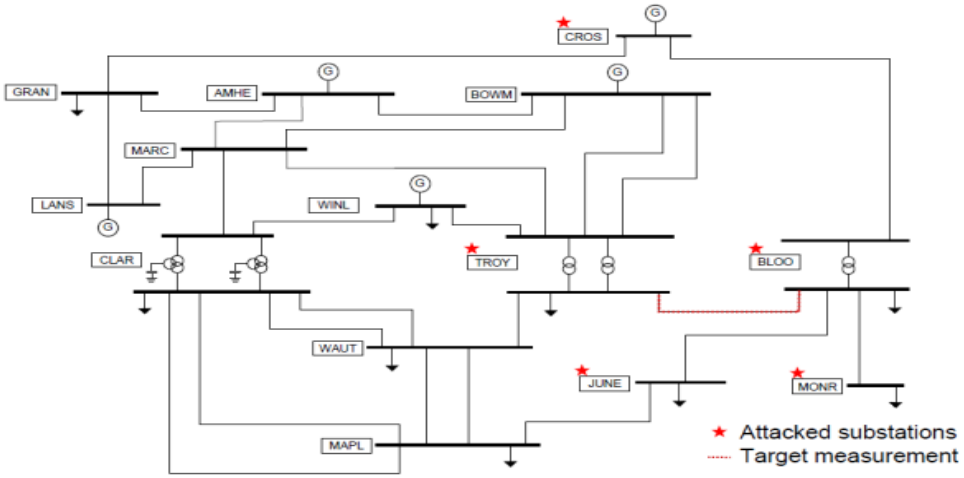


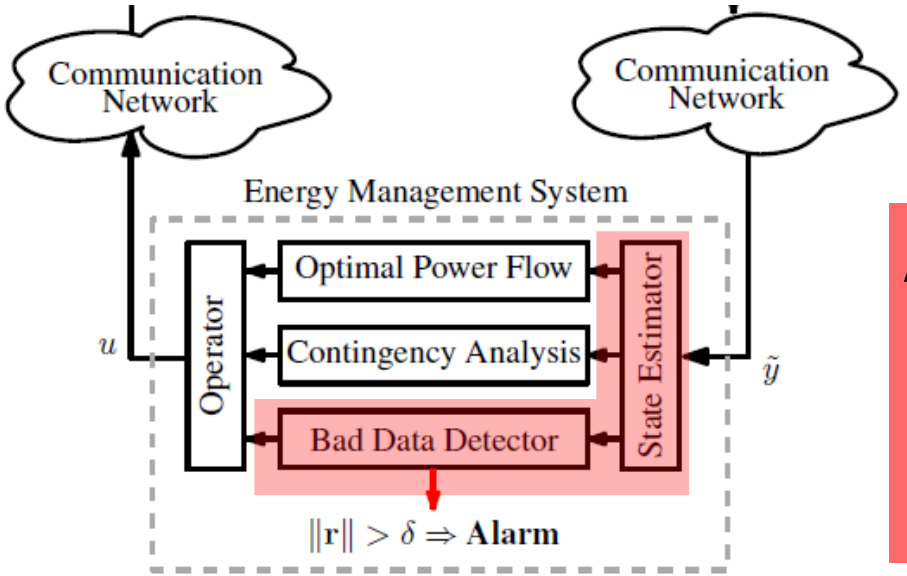
At least 7 measurements involved in a stealth attack against measurement 33



Attack 33
(7 measurements)

Experiments on SCADA/EMS Testbed





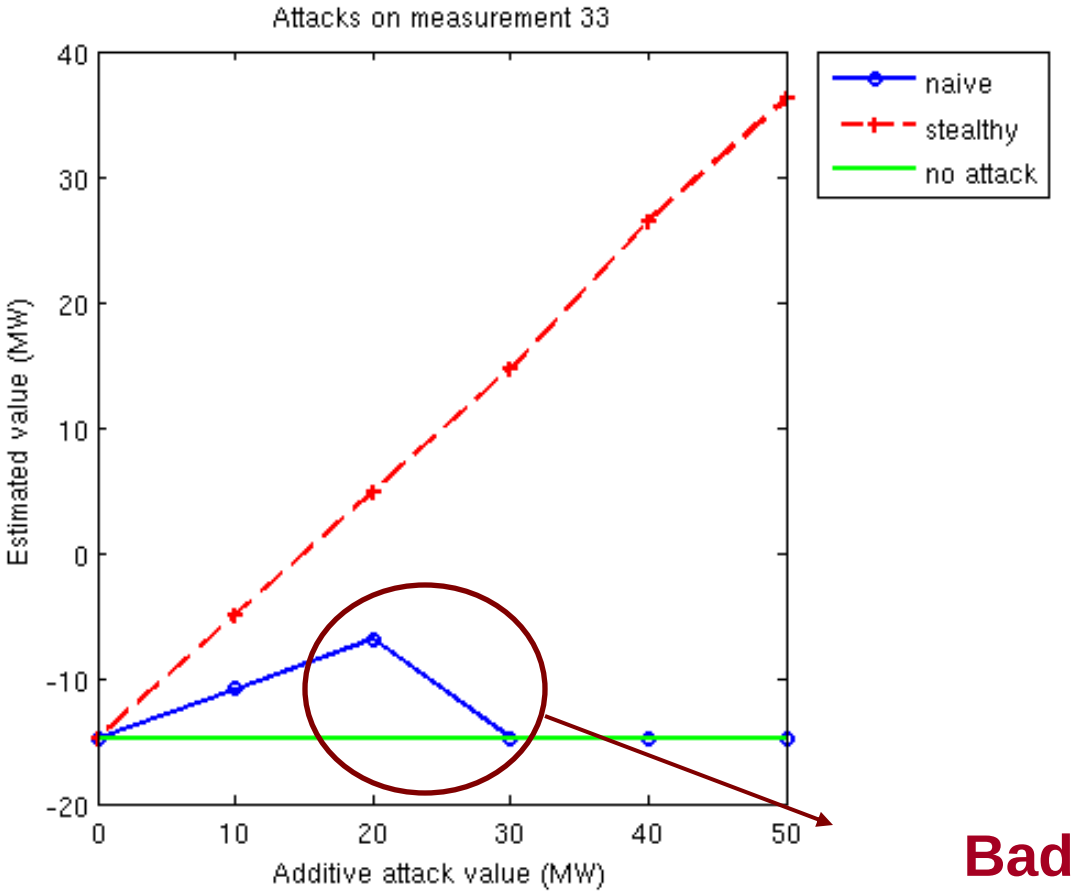
Sensor data corruption

Adversary's Objective

- Remain undetected **(no alarms)**

[Teixeira *et al.*, 2011]

Bad Data Detection Alarms

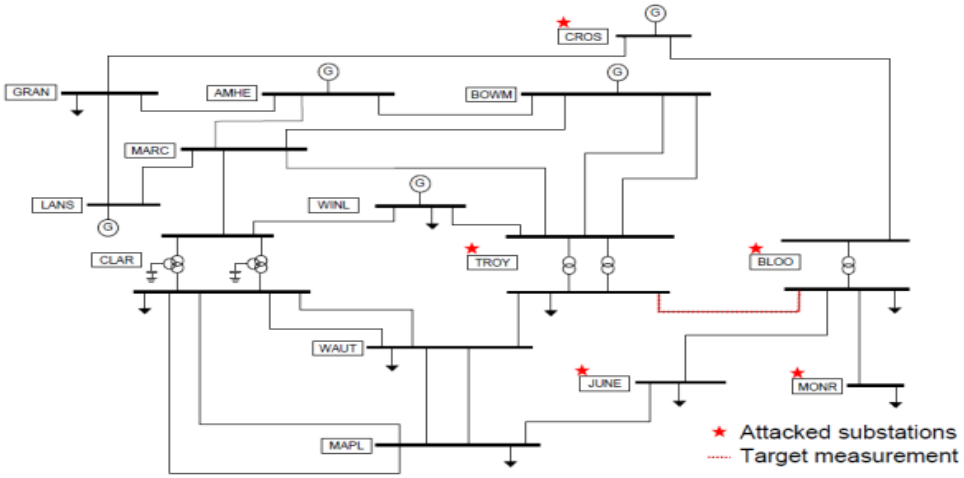


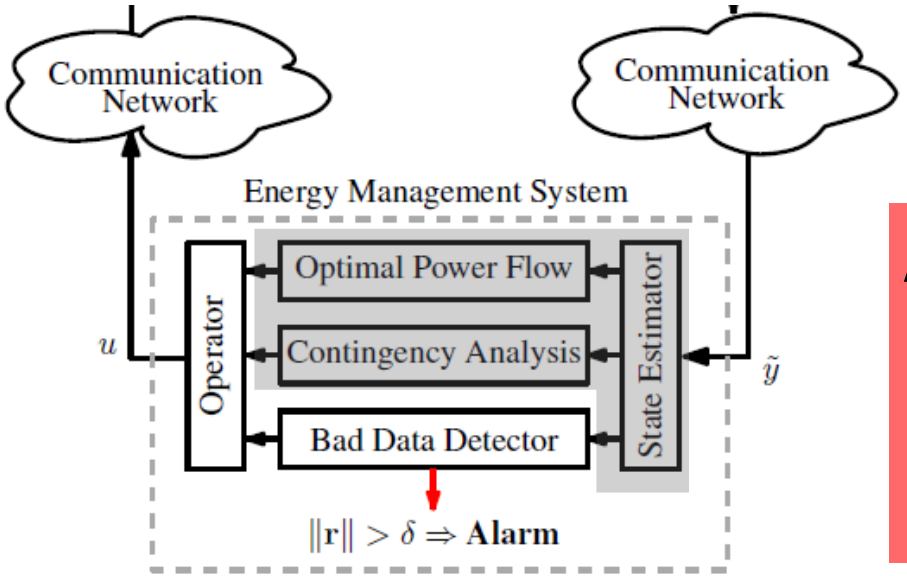
False value (MW)	Estimated value (MW)	# BDD Alarms
-14.8	-14.8	0
35.2	36.2	0
85.2	86.7	0
135.2	137.5	0
185.2	Non convergent	-

Bad Data Detected & Removed

- Attacks of 150 MW (55% of nominal value) pass undetected in a real system!

Experiments on SCADA/EMS Testbed





Sensor data corruption

Adversary's Objective

- Influence the **physical plant (voltage, power)**
- Remain undetected **(no alarms)**

[Teixeira *et al.*, 2011]

Contingency Alarms

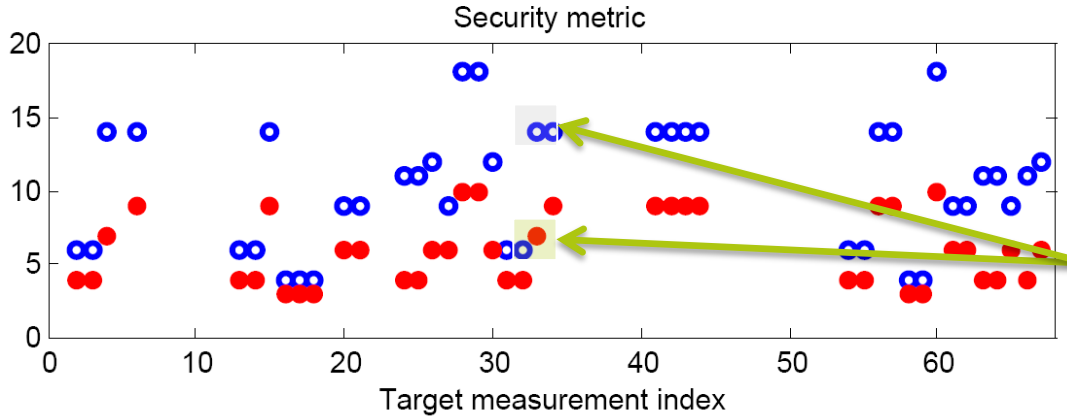
Target bias, a_{33}	False value (MW), z^a_{33}	Estimate (MW), $\hat{z}^a_{33}$	#BDD Alarms	#CA Alarms
0	-14.8	-14.8	0	2
50	35.2	36.2	0	2
100	85.2	86.7	0	10
150	135.2	137.5	0	27
200	185.2	-	-	-

- 25 new CA alarms and no BDD alarms!
- What is the reaction in the control room?
  - The human operator may think the system is in a seriously bad state, but in reality the system is in the same state as before the attack

Protection Strategies

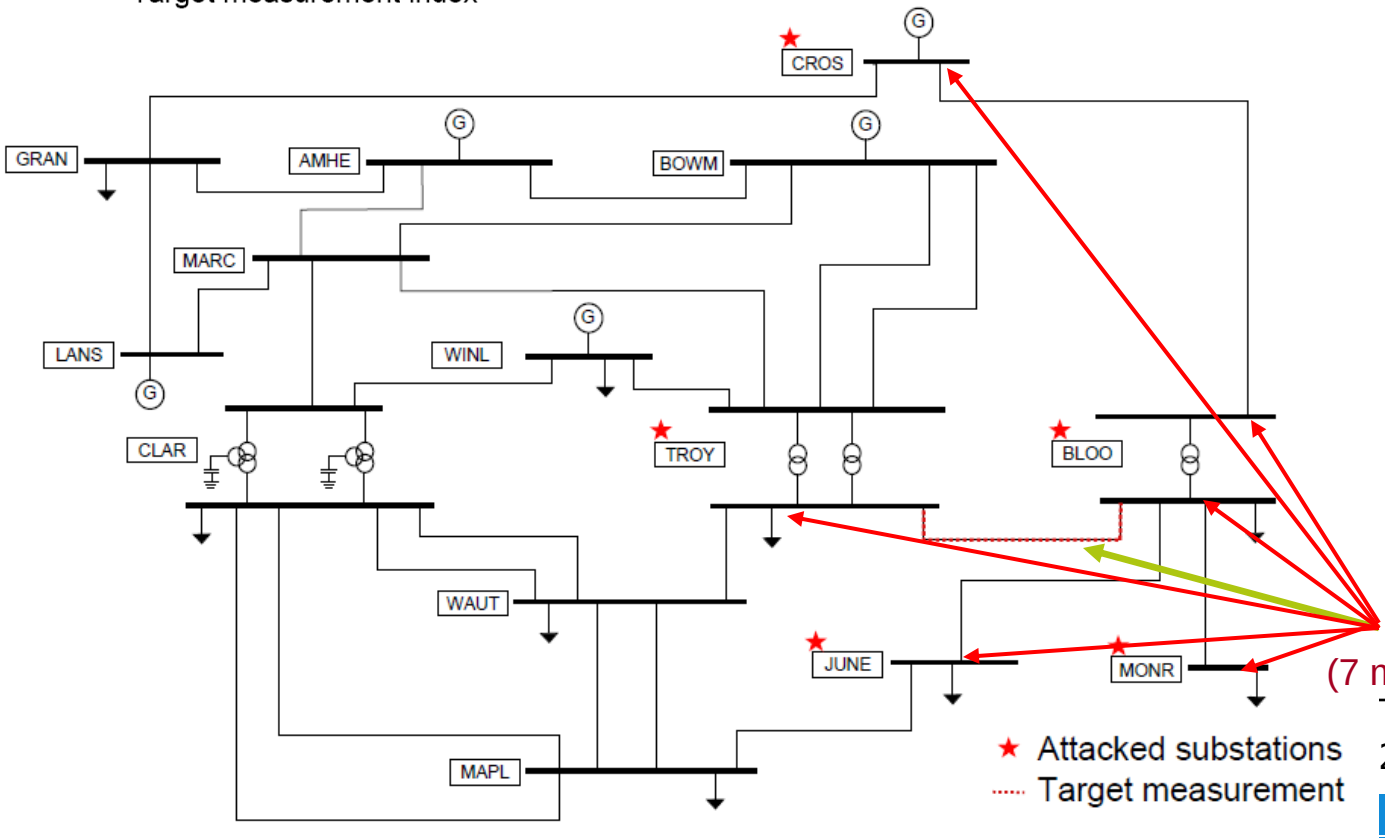
- Introduce encryption and re-route communication
  - Use security metric to identify critical measurements
  - Possibly weight metric based on expected impact, using optimal power flow [Vukovic *et al.*, 2012], [Teixeira *et al.*, 2012]
- Augment bad-data detection with cross-checking with historical data of operation [Kosut *et al.*, 2010]
- Improve available bad-data detection algorithms
  - Discover model mismatch between active/reactive power flow measurements [Sou *et al.*, 2012]

1. Use Metric to Assign Protection



• = Current measurement config.
o = Upgraded measurement config.

With few measurements protected, 14 measurements have to be involved in an undetectable attack! (instead of 7)



Attack 33
(7 measurements)

Summary Scenario 1

- Multiple interacting attacked measurements may be undetectable
- Security metric identifies measurements that are relatively "easy" to attack (locates weak spots)
- Experimental validation shows significant possible impact in control center (CA alarms)
- Protection strategies include encryption and re-routing of critical measurements

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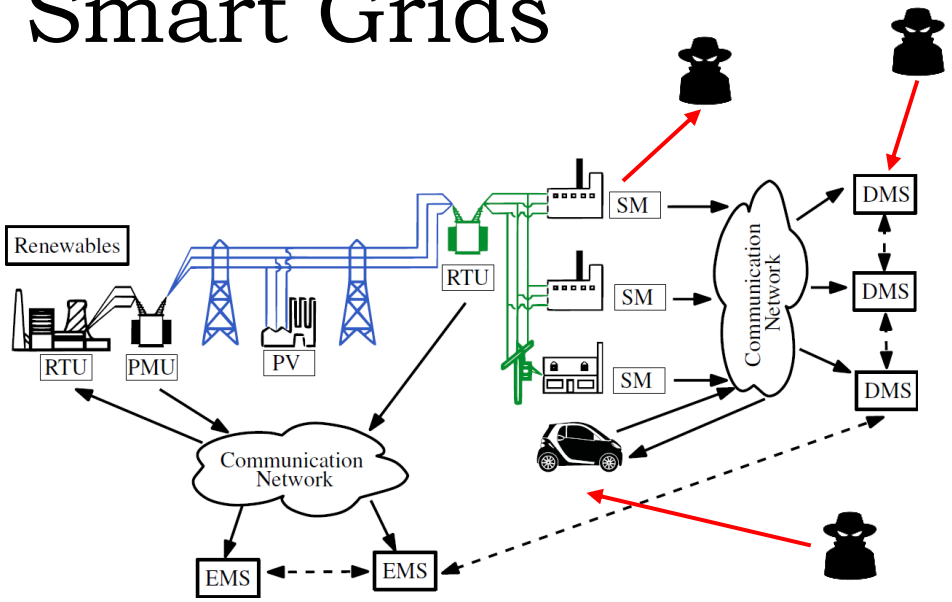
Cyber Security of Smart Grids

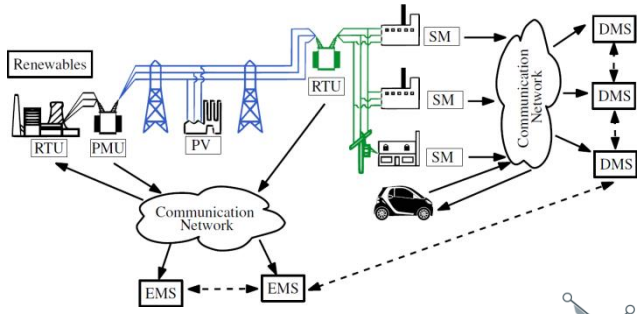
Smart Grids

- More smart devices and control loops
- Large increase in communication and data
- Leads to increasing vulnerability to cyber-physical threats with many potential points of attacks
- The Smart Grid is a cyber-physical system
  - **Power system** and **IT infrastructure** tightly coupled through SCADA and control systems
  - integrated with data analytics environments
  - Multiple stakeholders



SMART GRID PROTECTION AGAINST CYBER ATTACKS

Attack Scenarios for Smart Grids



References with Attack Scenarios

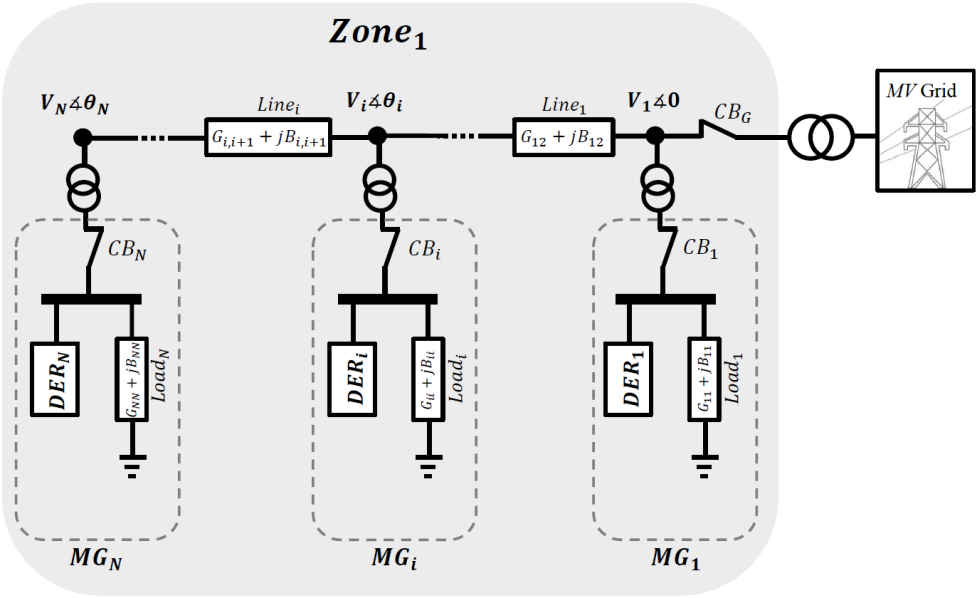
- "*Cyber Security for DER Systems*",
  NESCOR, Electric Power Research Institute, 2013

- "*The Future Of Smart Cities: Cyber-physical Infrastructure Risk*",
  Office of Cyber and Infrastructure Analysis, DHS, August 2015

- *"Electric Sector Failure Scenarios and Impact Analyses"*,
  NESCOR, Electric Power Research Institute, 2014
  - DER.15 Threat Agent Spoofs DER Data Monitored by DER SCADA Systems
  - DGM.6 Spoofed Substation Field Devices Influence Automated Responses

- Chosen scenarios: Voltage control under adversarial actions [Teixeira et al., ETFA, 2015]

Power System Model

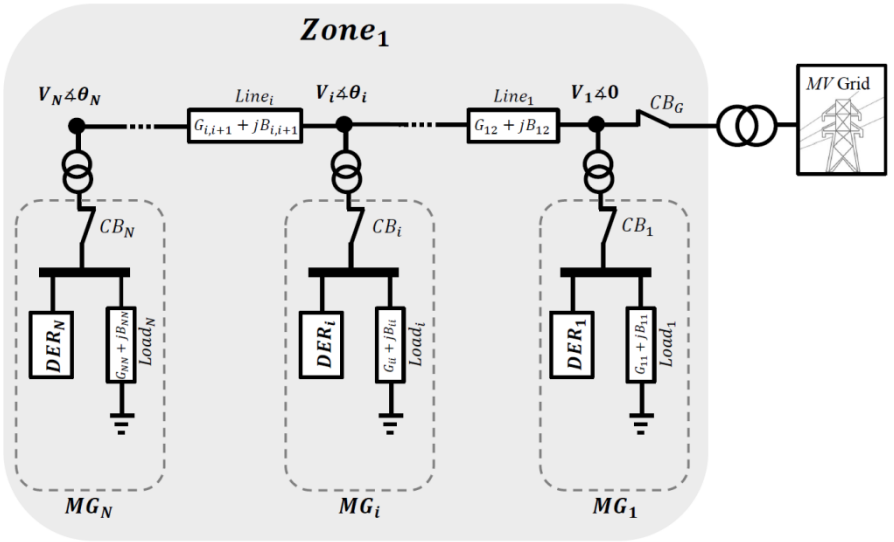


- **Interconnected microgrids**
- Model each microgrids as:
  - Lumped inverter-controlled Distributed Energy Resources (DERs)
  - Lumped loads
- Inductive lines, but with resistive losses

Power System Model

- States of each microgrid
  - Voltage level: V_i (pu)
  - Phase angle: θ_i (rad)
- Microgrid model

$$\tau_i \dot{V}_i(t) = u_{V_i}(t)$$
$$\tau_{\theta_i} \dot{\theta}_i(t) = u_{\theta_i}(t)$$



- Transmission Line: $Y_{ij} = G_{ij} + \mathrm{j}B_{ij}$

Homogeneous line ratio: $\rho = \dfrac{G_{ij}}{B_{ij}}$

- Power injections:

$$P_i = V_i^2 G_i - \sum_{j \in \mathcal{N}_i} V_i V_j \left(G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right),$$

$$Q_i = -V_i^2 B_i - \sum_{j \in \mathcal{N}_i} V_i V_j \left(G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right)$$

Power System Model: Voltage Dynamics

- Microgrid model: $\tau_i \dot{V}_i(t) = u_{V_i}(t)$

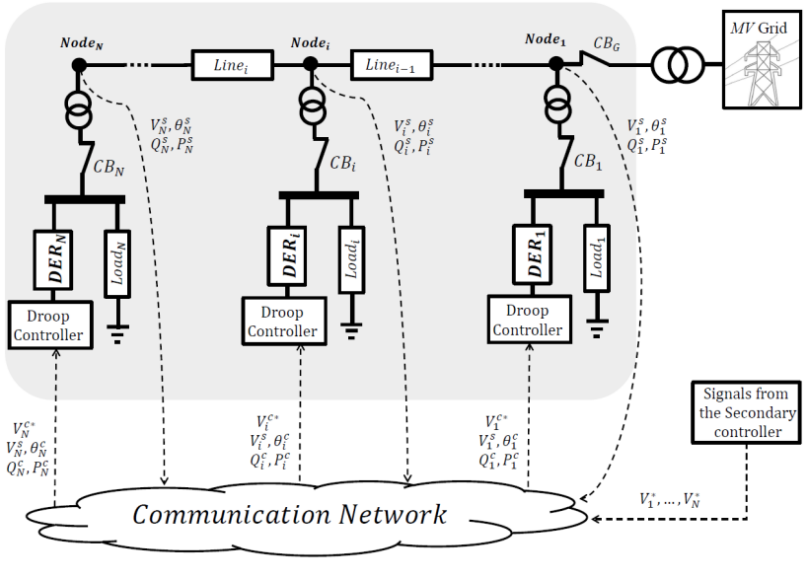
  Assume constant phase-angles

- Voltage droop controller:

$$u_{V_i}(t) = -\kappa_i V_i^c(t)\left(V_i^c(t) - V_i^{c\star}(t)\right) - Q_i^c(t)$$

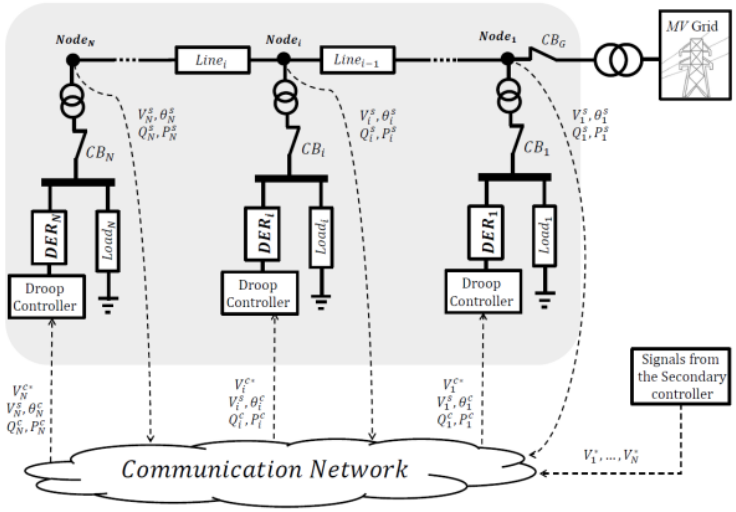
κ_i Controller gain
$V_i^{c\star}$ Received voltage reference
V_i^c Received voltage measurement
Q_i^c Received power injection measurement

[Simpson-Porco et. al, TAC, 2015]



- Under nominal operation: $\tau_i \dot{V}_i = -\kappa_i V_i\left(V_i - V_i^\star\right) - Q_i$

Voltage Dynamics

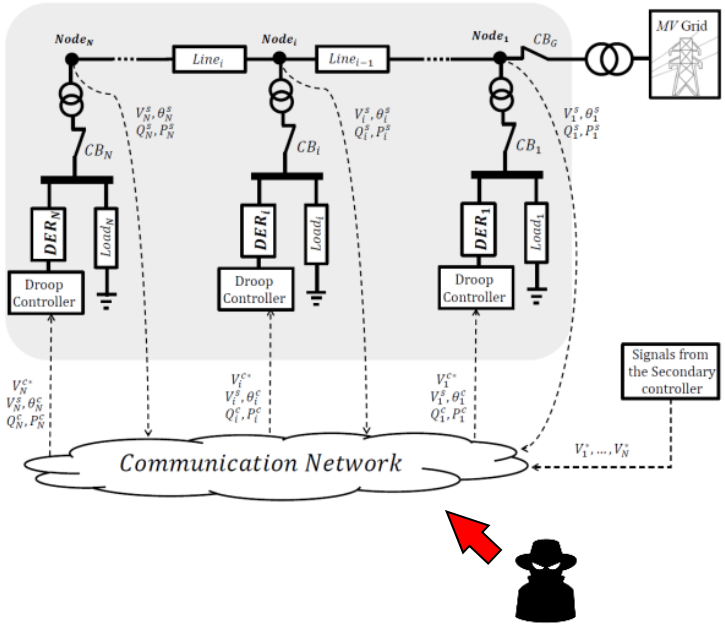


- Nominal operation: $\tau_i \dot{V}_i = -\kappa_i V_i \left(V_i - V_i^\star\right) - Q_i$

- Desired system properties
  - Stability - ensured for large control gains: $\kappa_i \geq \sum_{j \in \mathcal{N}_i} (\sqrt{\rho^2 + 1} - 1)|B_{ij}|$
  - Positivity - ensured for small phase-angle differences: $|\tan(\theta_i - \theta_j)| \leq \rho^{-1}$
    - Positivity ensures desirable properties, e.g.,
      - an **increase in reference** results in a **voltage increase** throughout the system

Risk of Adversarial Actions

- Attack Scenarios:
  - Voltage Reference Attack
  - Voltage Measurement Routing Attack
- Possible Impact Metrics:
  - Maximum Voltage Variation
  - Loss of Positivity
  - Loss of Stability
- Possible Likelihood Metrics:
  - Number of corrupted reference signals
  - Number to re-routed measurement signals
- Risk Assessment: mathematical analysis of attack scenarios
  - Study the impact metrics by analyzing models
  - Use results to guide simulation-based analysis

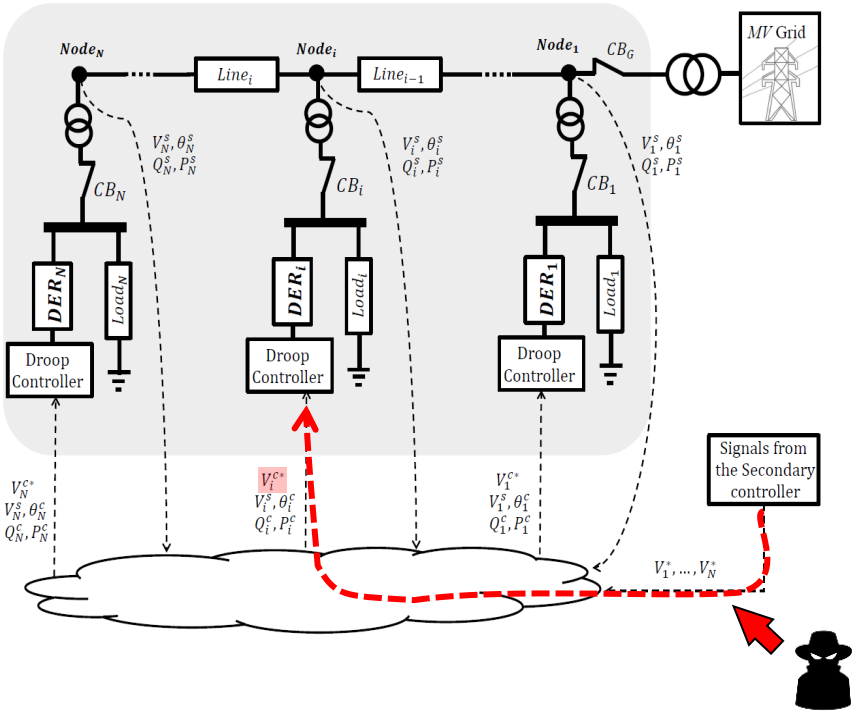


Voltage Reference Attack

- Demonstration reported in Kang et al. ”Investigating Cyber-Physical Attacks against IEC 61850 Photovoltaic Inverter Installations”, ETFA 2015
- Voltage reference of MG-i is compromised

$$u_{V_i}(t) = -\kappa_i V_i^c(t)\,(V_i^c(t) - u^a(t)) - Q_i^c(t)$$

- Theoretical results:
  - **Computation of maximum voltage increase**
  - **Increase in reference** leads to **increased voltages**
  - Voltage increase **decays with distance** to attacked microgrid (for line topologies)

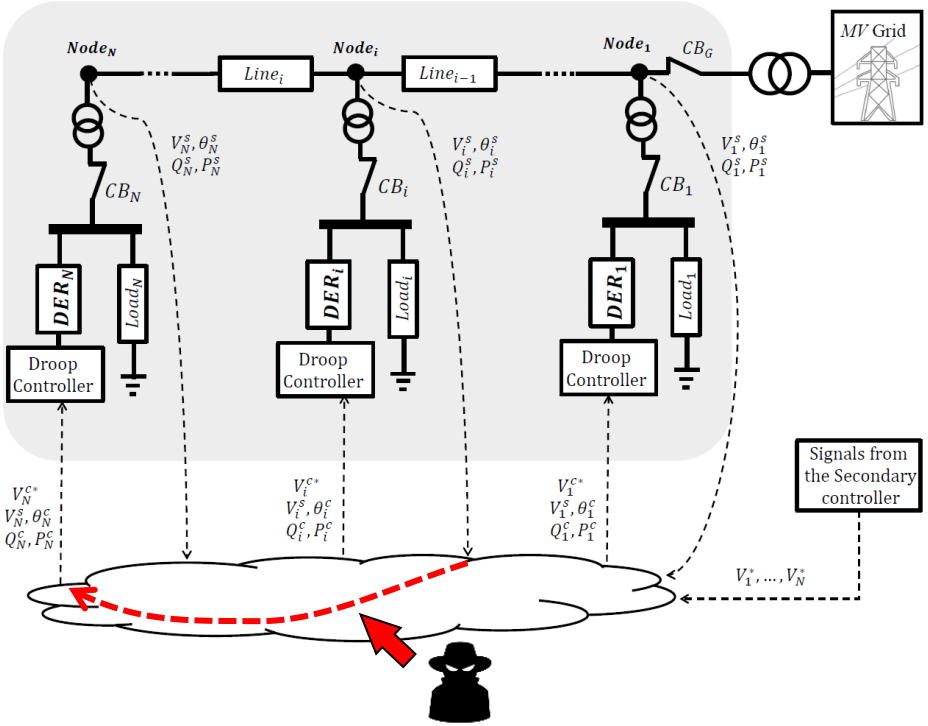


Voltage Measurement Routing Attack

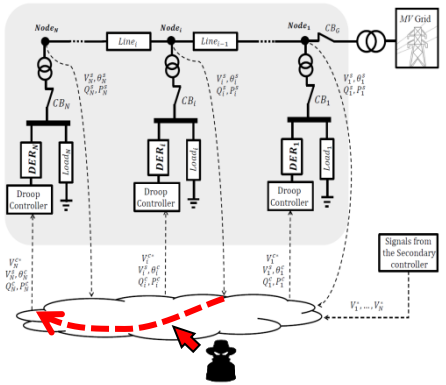
- Voltage measurement of one MG-j redirected to another MG-i

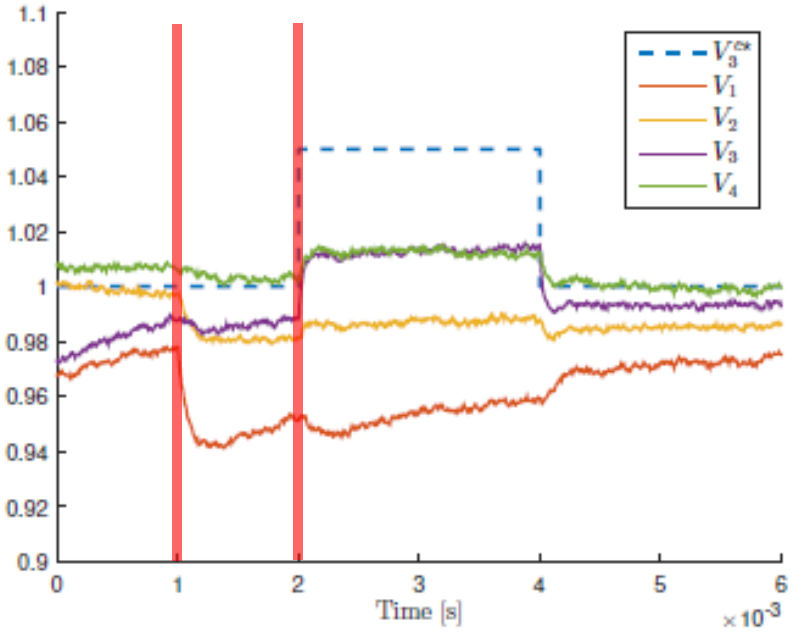
$$u_{V_i}(t) = -\kappa_i V_j^c(t)\left(V_j^c(t) - V_i^{c\star}(t)\right) - Q_i^c(t)$$

- Theoretical results:
  - **Loss of positivity**
  - **Equillibrium change** (depends on pre-attack voltage levels)
  - **Increase in reference** may lead to **decreased voltages**
  - **If** MG-i and MG-j **are not neighbors**, **stability may be lost** for high control gains!



Voltage Measurement Routing Attack: Numerical Results





- Measurement of MG4 redirected to MG1
- Reference of MG3 changed
- Voltage of MG1 **decreases** after attack and after reference change

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- Scenarios and Risk metrics for Smart Grids
  - Scenario 1: False-Data injection on Transmission Grids
  - Scenario 2: Voltage control under adversarial actions
- **Summary**
- **Future Challenges and Opportunities**
- References

Summary

- The concept of Risk: {**Scenario** ; **Impact** ; **Likelihood**}
- The **Scenario** description if the basis for risk assessment
- **Impact** follows from the operational objectives
  - Desired properties (stability)
  - Safety margins
  - Efficiency and performance
- **Likelihood** relates to required resources/effort
  - May be hard to assess, use proxies instead
- Examples of Attack Scenarios:
  - False-data injection
  - Malicious re-routing of measurements

Future Challenges and Opportunities

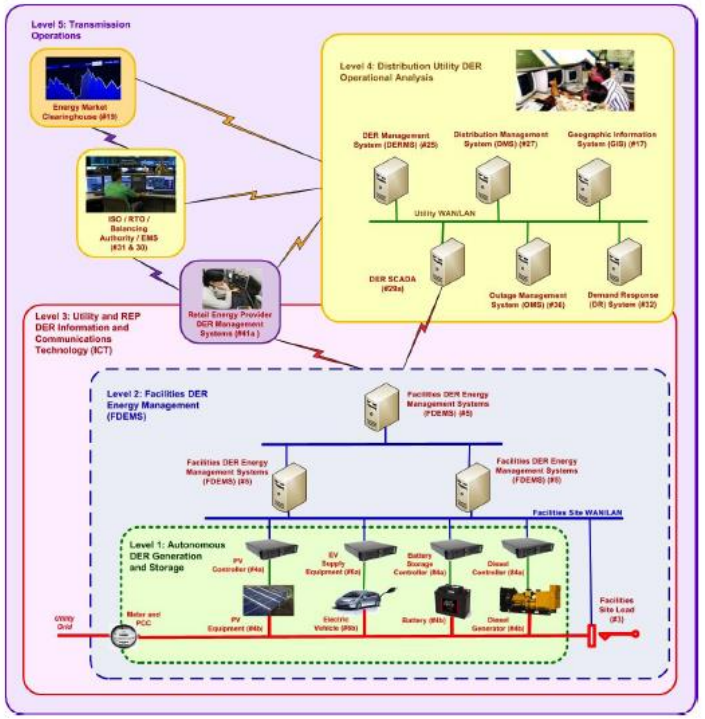
Tackling the diversity of Threat Scenarios for Smart Cities

- *"The Future Of Smart Cities: Cyber-physical Infrastructure Risk",* Office of Cyber and Infrastructure Analysis, DHS, August 2015
  - "Sample Vector 2: A malicious actor intercepts and manipulates **energy price data** in **demand response** systems to cause demand fluctuations and **potential outages**."
  - "Sample Vector 3: **Installation of new** cyber-physical **components** onto legacy components **leads to interoperability problems**, unintended consequences, and smart generation system disruptions."
  - Many other examples in different domains (transportation, water & waste management, energy…)

Future Challenges and Opportunities

Tackling the complexity of Smart Grids (and its security implications)

- *"Cyber Security for DER Systems",* NESCOR, 2013
  - Multiple entities / stakeholders across multiples layers
  - Who "pays the bill" of a cyber attack?
  - Who invests in cyber security and privacy?
  - What are the economics of cyber security and privacy?
- Could *cyber security* be a "show-stopper"?
- New EU data protection regulation
  - 2. Data **processors** will be held responsible for data protection



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Extensions to generic dynamical systems

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