On the Security of Distributed Power System State Estimation under Targeted Attacks

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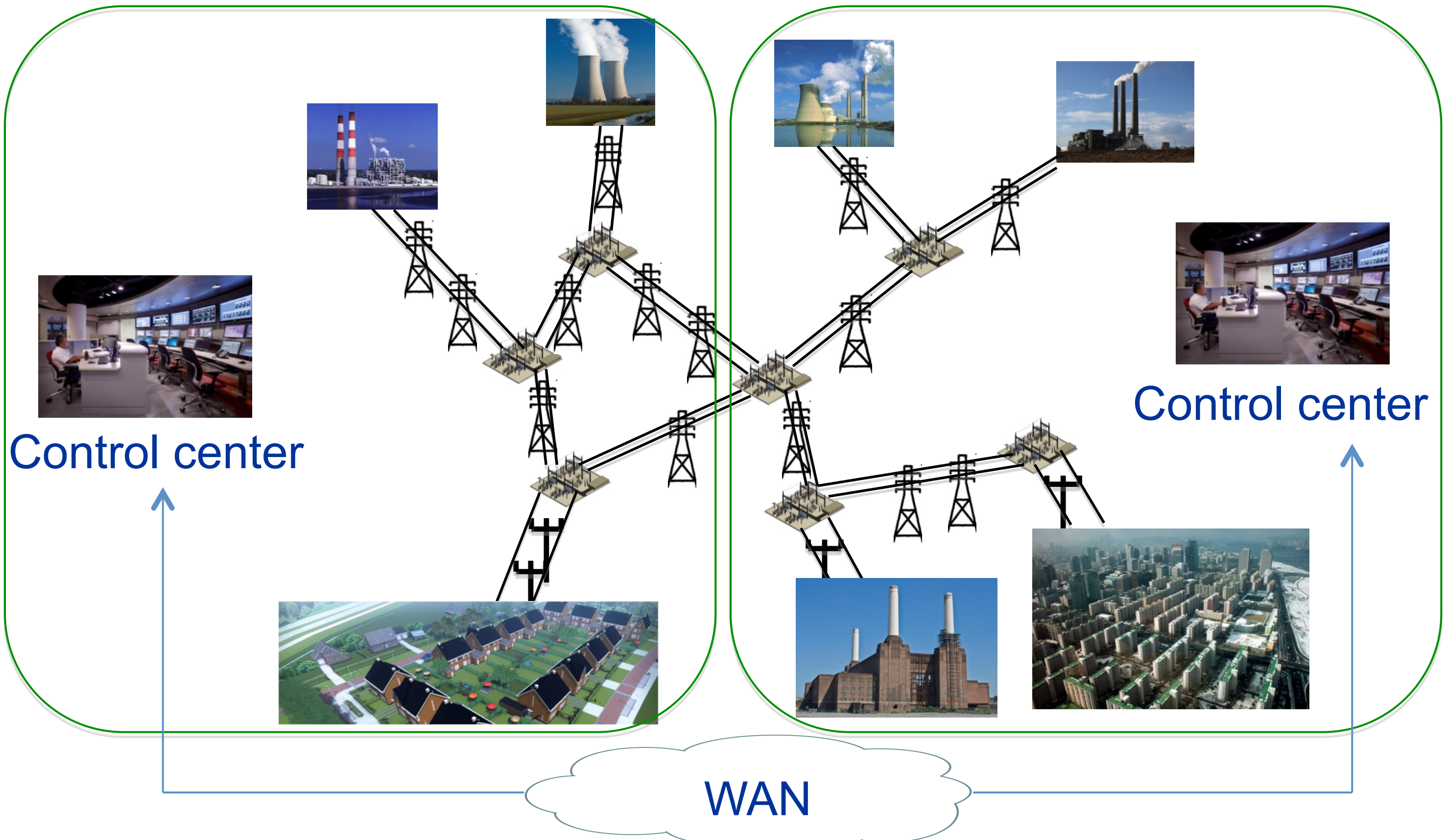
Power System Supervision and Control

- Supervisory Control and Data Acquisition (SCADA)
- Energy Management System (EMS)
  - State Estimation (SE) – a core EMS component
- Distributed Supervision and Control
  - Cooperation between operators; ICCP



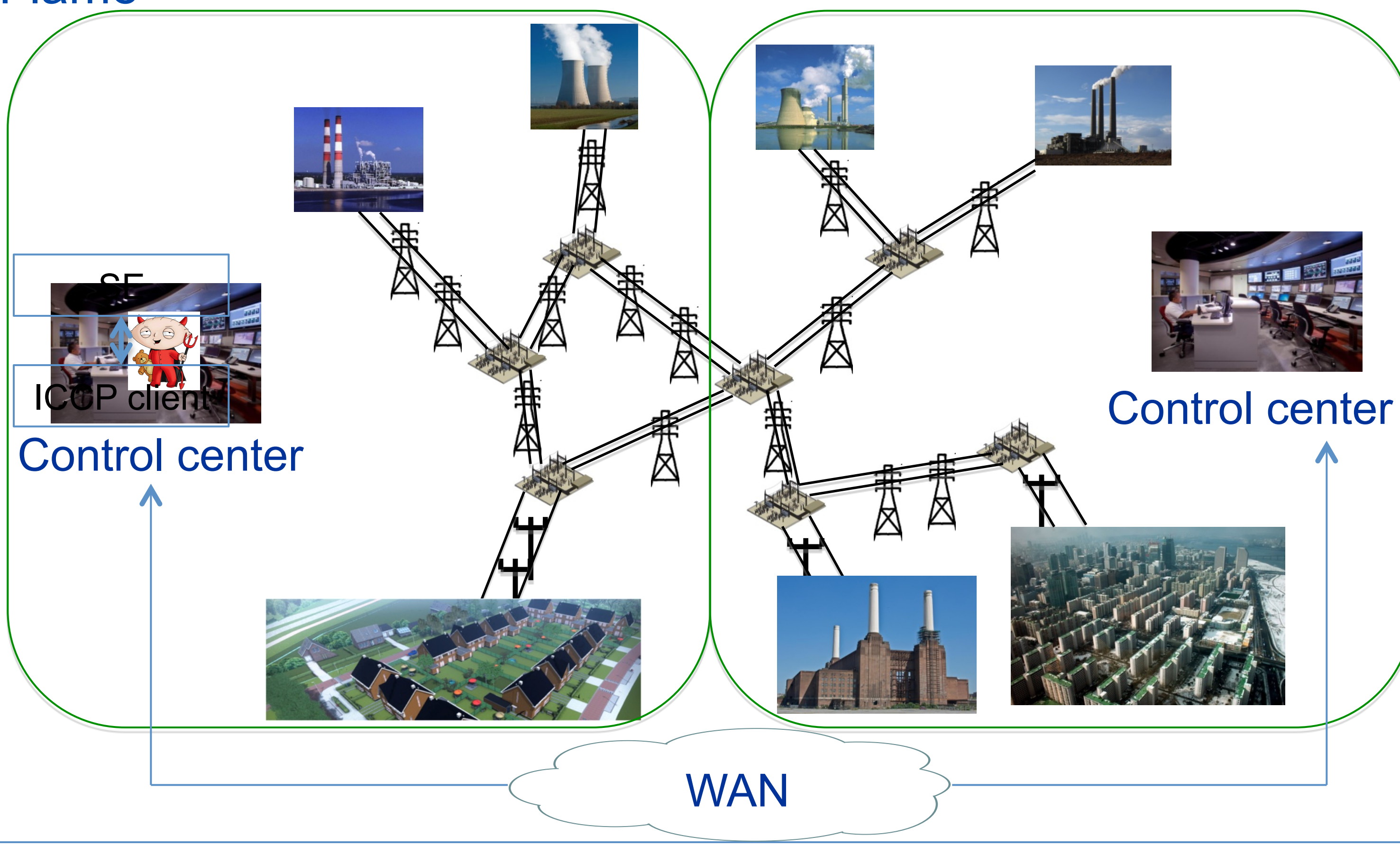
Distributed State Estimation (DSE)

- State Estimate of the Entire Interconnected System
  - Local state estimation + synchronization
- Security of Distributed State Estimation
  - Violation of the integrity of exchanged data
  - Stuxnet, Flame

Can the attack affect the DSE?

Detection?

Mitigation?

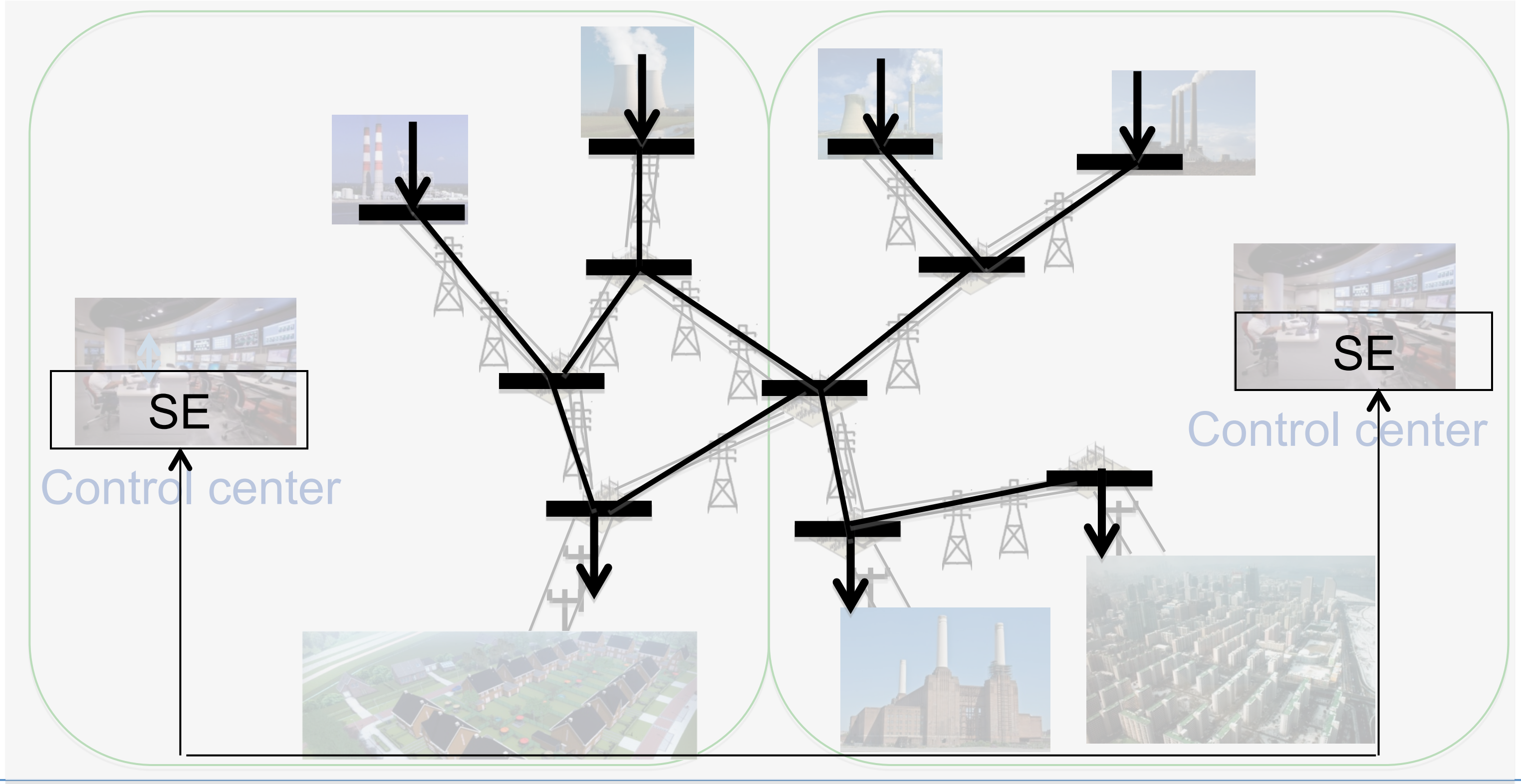


Outline

- Motivation
- System Model
- Attack Model and Strategies
- Attack Impact
- Detection and Mitigation
- Conclusion

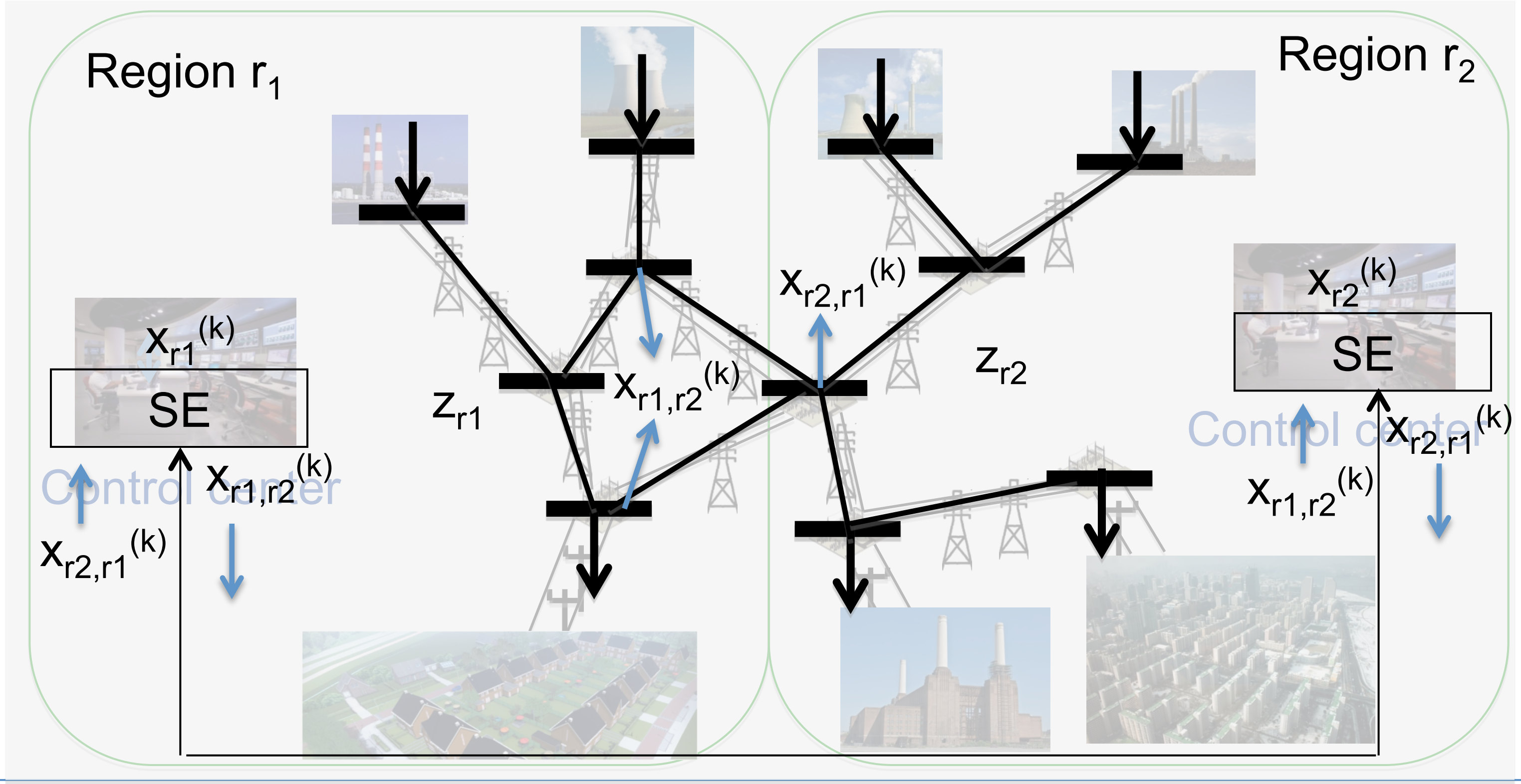
System Model

- Transmission Network: buses and branches
  - *Power injections and power flows* $P = [P_1 , P_2 , \ldots , P_M]^T$
- Measurements: $z = [z_1, z_2, \ldots, z_M]^T$, $z_i = P_i + e_i$
- State Vector x: bus voltage angles and magnitudes
  - $P = f(x^*)$, x^*: actual state of the system



System Model

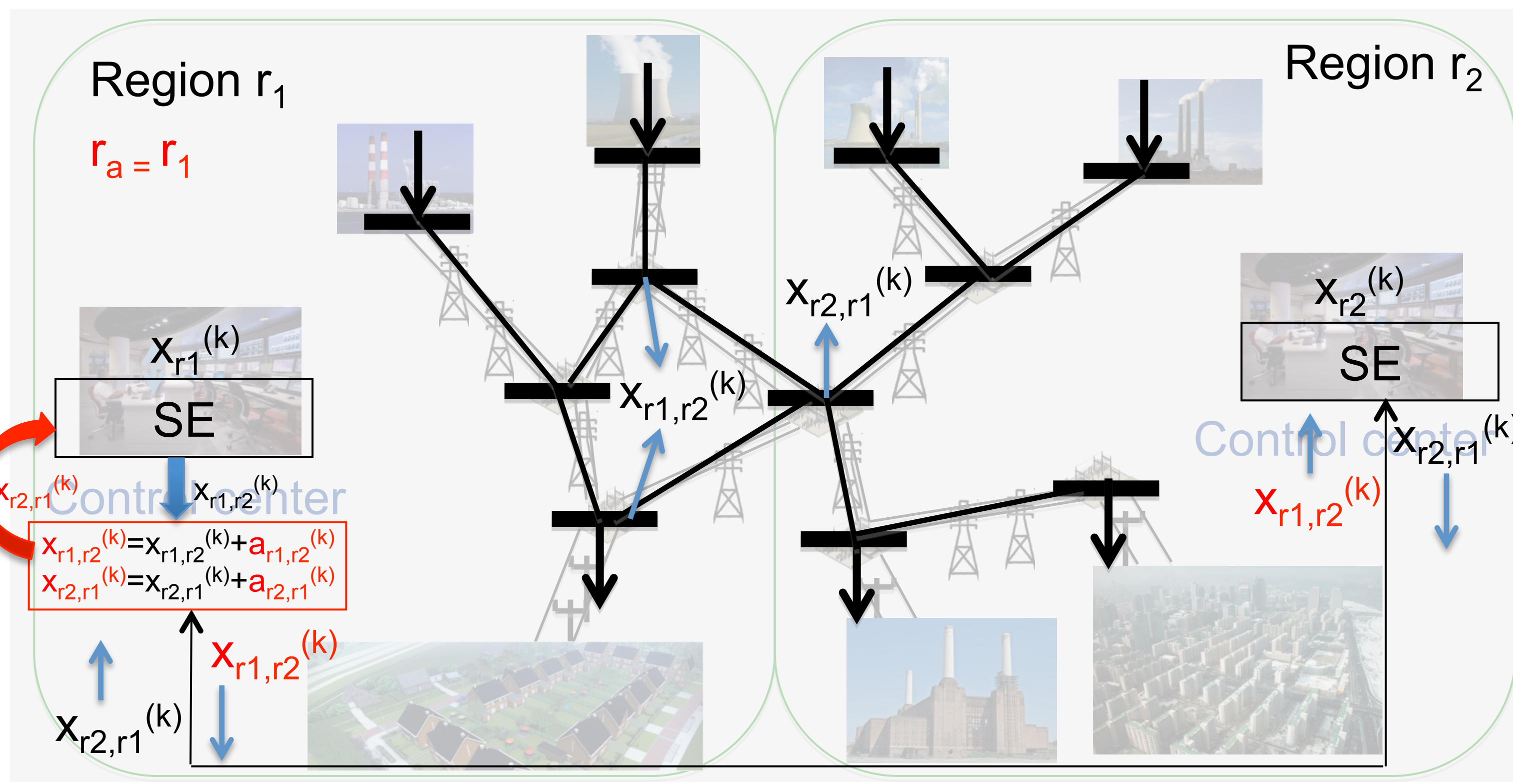
- State Estimation
  - Find x^*; Weighted Least Square estimation
  - Gauss-Newton algorithm: $x^{(k+1)} = x^{(k)} + \underbrace{[H^{(k)T} W^{-1} H^{(k)}]^{-1} H^{(k)T} W^{-1} [z - f(x^{(k)})]}_{\Delta x^{(k)}}$
- Distributed State Estimation
  - Local measurements z_r ; find x_r^*; send $x_{r,r'}^{(k)}$, use $x_{r',r}^{(k)}$ ($x_{b,r'}^{(k)}$) in k+1



Attack Model

- Attacked region r_a ; attack vector $a_{r,r_a}^{(k)}$ $(a_{b,r_a}^{(k)})$, attack size $\left\| a_{b,r_a}^{(k)} \right\|_2$
- Iterations under attack: $x_r^{(k+1)} = x_r^{(k)} + \Delta\tilde{x}_r^{(k)} \neq x_r^{(k)} + \Delta x_r^{(k)}$
- Attacker's objective: $\max\limits_{a_{r,r_a}^{(k)},\, k=1,\ldots} c \quad \text{s.t.} \left\| a_{r,r_a}^{(k)} \right\|_2 < \beta$

$$\boxed{\max_{a_{r,r_a}^{(k)},\, k=1,\ldots} \left\| \Delta\tilde{x}_r^{(k)} \right\|_2 \quad \text{s.t.} \left\| a_{r,r_a}^{(k)} \right\|_2 < \beta}$$



Attack Strategies

$$\max_{a_{r,r_a}^{(k)},\ k=1,\dots} \left\| \Delta\tilde{x}_r^{(k)} \right\|_2 \quad \text{s.t. } \left\| a_{r,r_a}^{(k)} \right\|_2 < \beta$$

First Singular Vector (FSV)

$$\Delta\tilde{x}_r^{(k)} = \Delta x_r^{(k)} - \underbrace{[H^{(k)T}W^{-1}H^{(k)}]^{-1}H^{(k)T}W^{-1}H_b^{(k)}}_{A} a_{r,r_a}^{(k)}$$

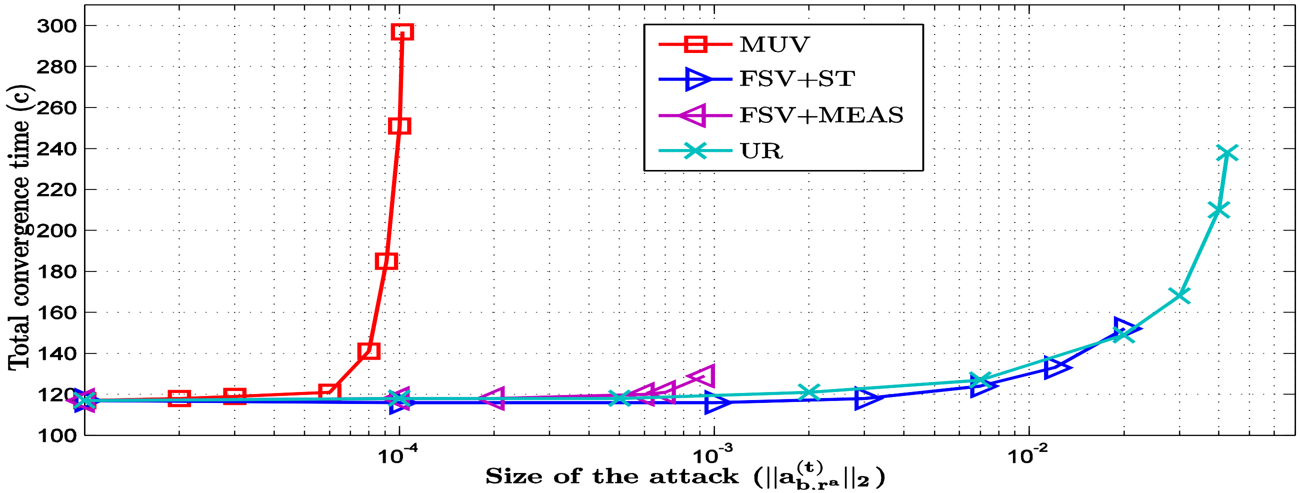
$a_{r,r_a}^{(k)} = u_1$, first singular vector of the matrix A

- Required knowledge of the system model (matrix *H*)
- Required knowledge of power flows/injections (sign($a_{r,ra}^{(k)}$))

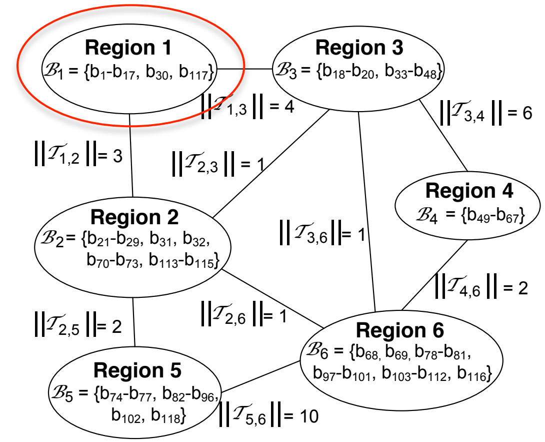
Other Strategies

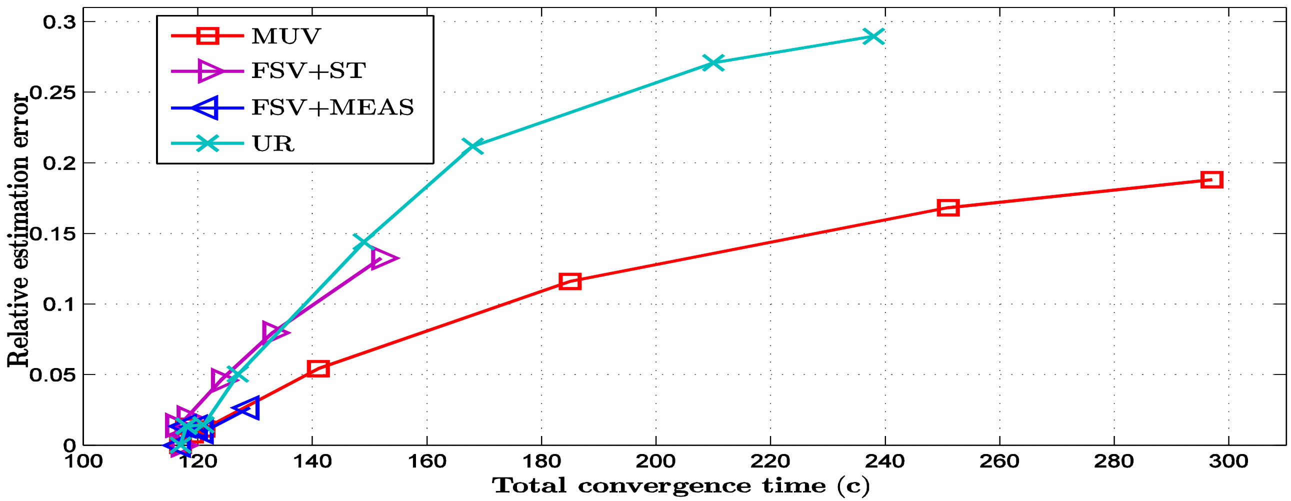
- Maximal Update Vector attack (MUV)
- Uniform Rotation Attack
- A couple more…

Attack Impact



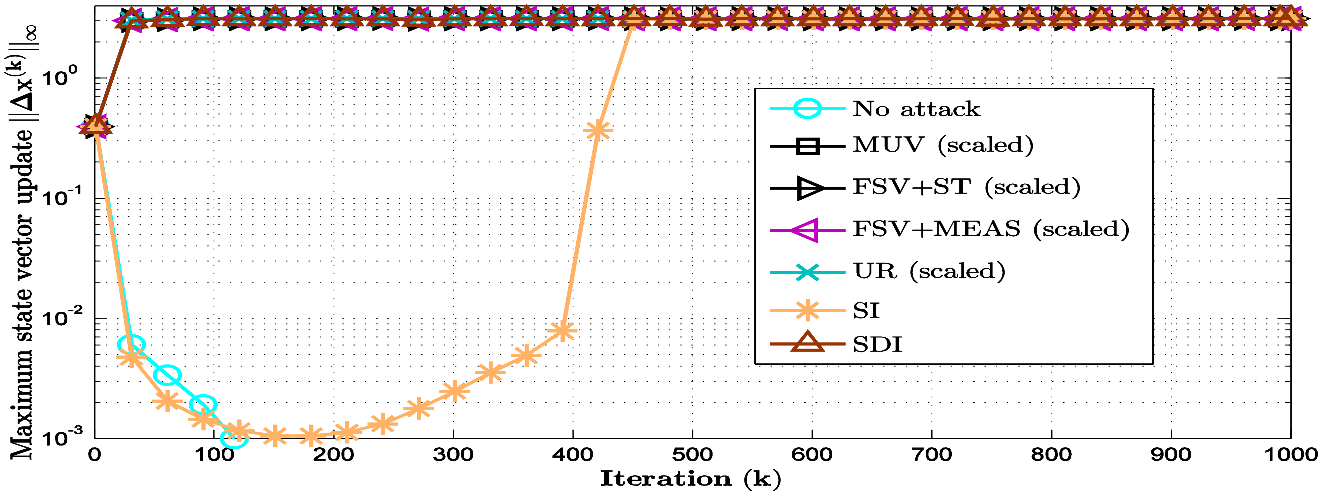
IEEE 118, 6 regions

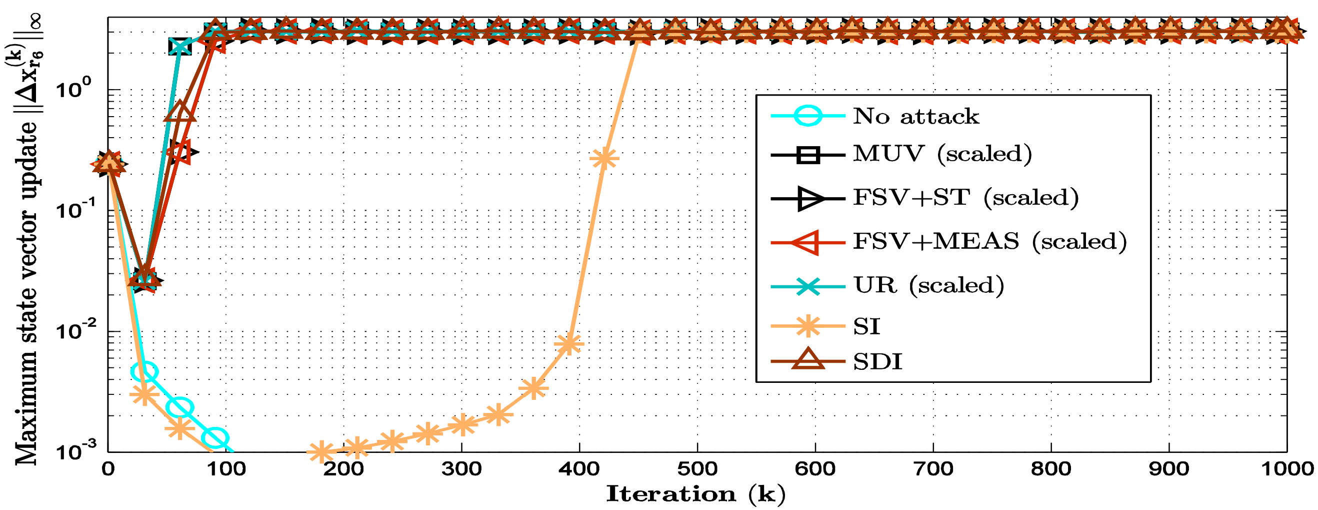




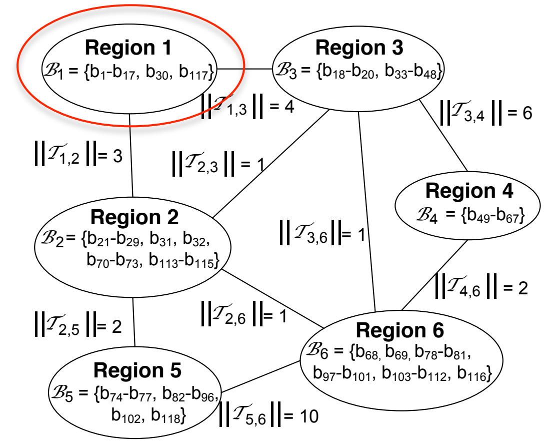
- ❑ Attack may significantly increase *c* and introduce high errors
- ❑ Attacks can prevent the convergence of DSE
- ❑ Protect *z*

Attack Impact





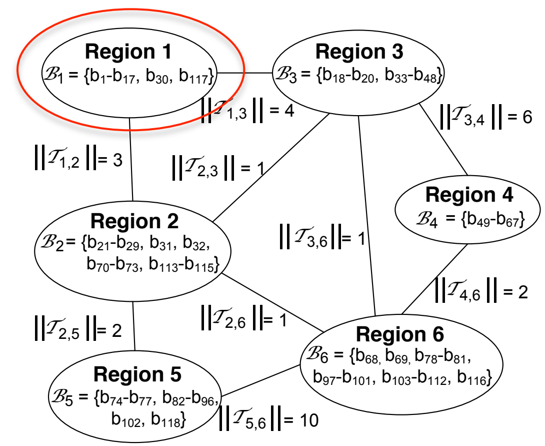
IEEE 118, 6 regions



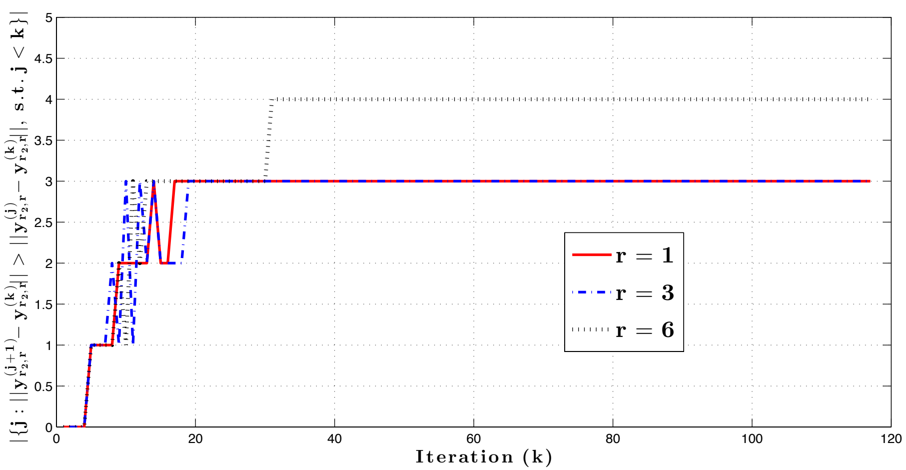
- ❑ All regions affected

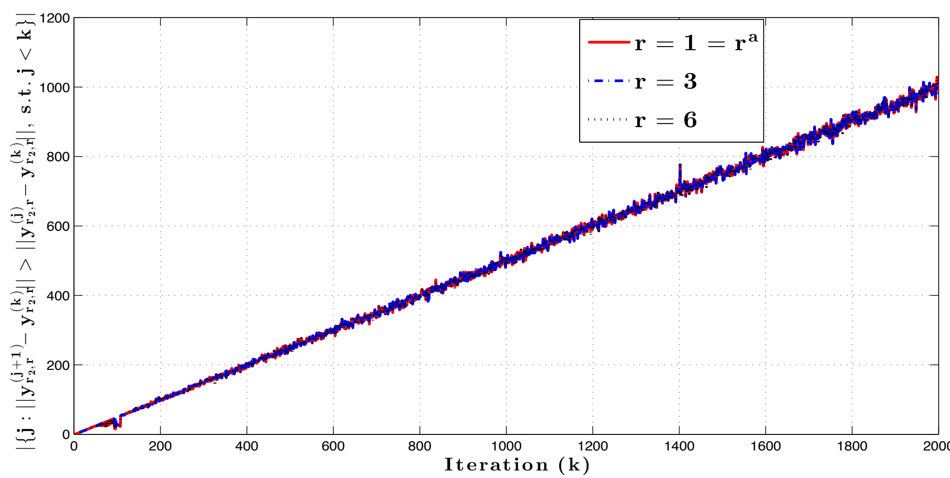
Detection and Mitigation

IEEE 118, 6 regions



- **Evolution of the state vector**
  - $x^{(k+1)} = g(x^{(k)})$, when converged $x^{(k^*+1)} \approx g(x^{(k^*+1)})$
  - If $||g(x)-x^*||_\infty \leq ||x-x^*||_\infty$ $(\forall x, \forall x^*)$, then $x(k)$ -> to a x^*
- **Detection based on the number of outliers**
  - $||x^{(k'+1)}-x^{(k)}||_\infty \leq ||x^{(k')}-x^{(k)}||_\infty$ for large k





- **The attack can be detected**
- **Mitigation: perform independent SE**

Conclusion

- Vulnerability of the DSE to attacks against exchanged data

- Multiple attack strategies
  - Even just one compromised CC can significantly disturb the DSE
  - Important to protect the confidentiality of measurements

- Detection and mitigation
  - Detection possible based on the number of outliers
  - A simple mitigation scheme

- *Localization and an improved mitigation scheme*

ACCESS
the future

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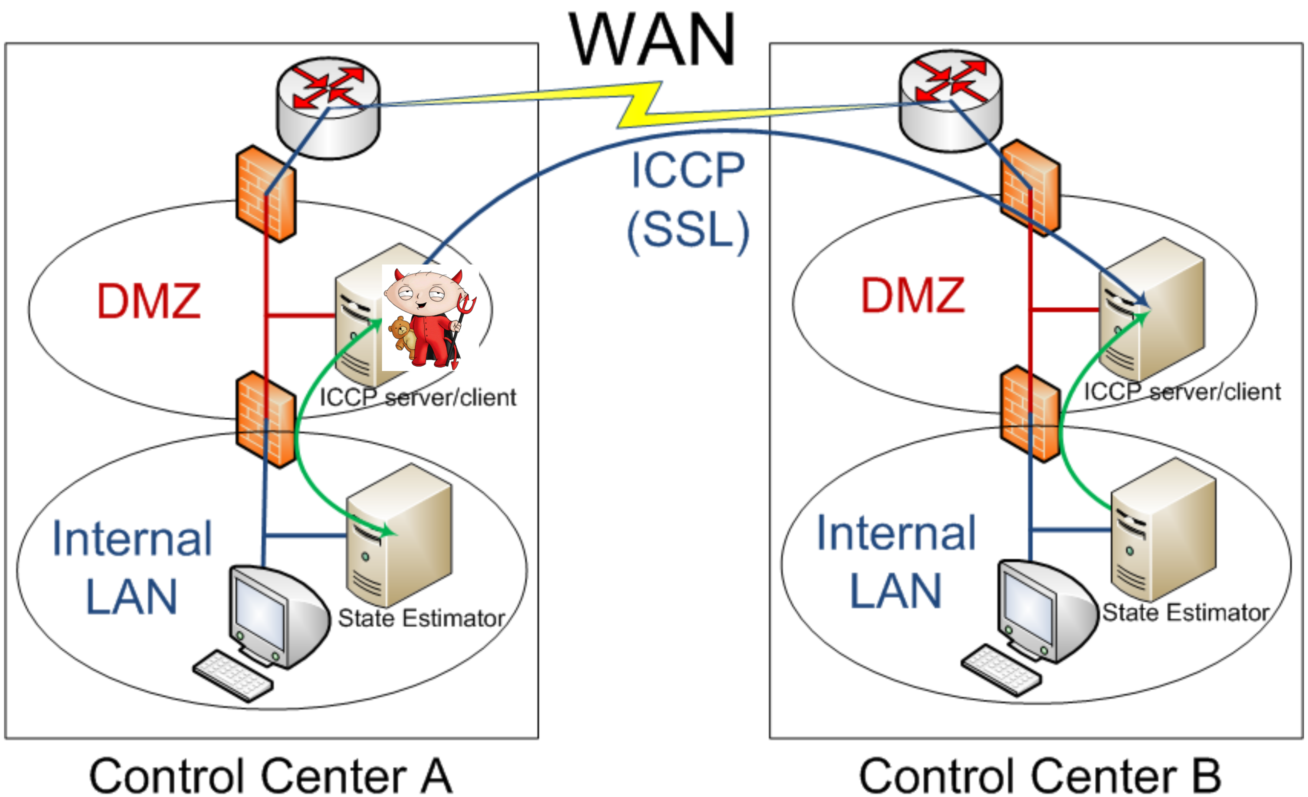
ICCP

- ICCP servers/clients are often in Demilitarized Zones (DMZ)



- Attacker corrupts ICCP server/client to modify the exchanged data