Distributed Agent-Based Intrusion Detection for the Smart Grid

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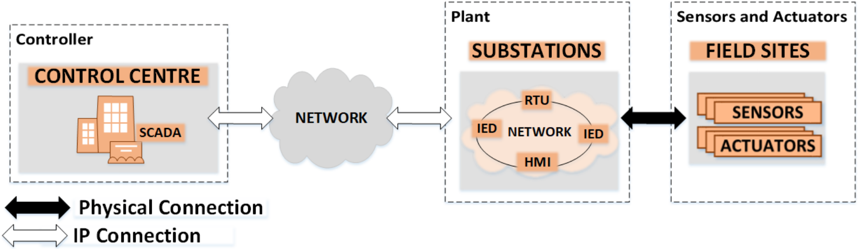
Introduction

- The smart-grid can be viewed as a Large-Scale Networked Control System (LSNCS).
- LSNCS components such as controllers, plants, sensors and actuators are connected through communication links.
- Typically the computational and physical infrastructure operate side by side in a highly integrated manner.



- The next generation power system is envisioned to integrate advanced control,communication and computational technology improving resilience, reliability and efficiency.

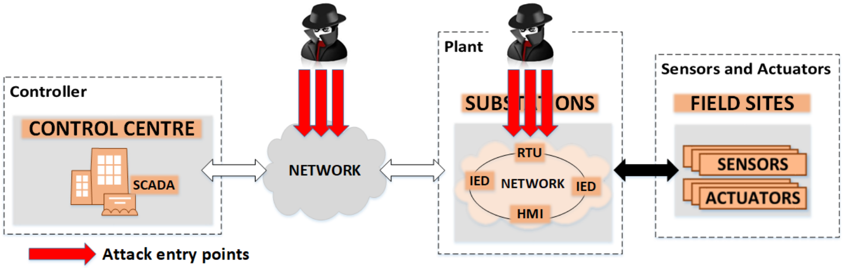
Motivation

- Control of LSNCS is mostly centralized.
- Challenges associated with centralized management:
  - Computational burden
  - Reliance on telemetered data
  - Sensitivity to failure and modeling errors
  - Dynamic topology, configuration not always known
- Distributed operations, monitoring and control architectures solve some problems associated with centralized management.
- Computational advancements support such distributed algorithms.
- Multi-agent systems and robust control algorithms such as consensus are some desirable distributed paradigms.
  - Consensus algorithms are robust and scalable
  - Agents are autonomous,reactive, sociable and proactive.
- Facilitate distributed intrusion detection and mitigation in a time-bound and computationally efficient manner.

Our approach

- Study the impact of cyber attacks on the power grid control system
  - False data injection attacks (FDIA)
- Adapt well studied control systems algorithms to address cyber related problems.
  - Multi-agent systems
  - State Estimation algorithms
  - Consensus algorithms
- We propose a multi-agent system comprising multiple interacting autonomous agents that can:
  - Breakdown a complex power system into smaller logical partitions
  - Poll RTUs and IEDs for measurement data
  - Process data in parallel
  - Exchange data and state information in a time-bound fashion.
- RTU and IED data collected can be used by agents for state estimation, intrusion detection and resilient control.
- Consensus algorithms can be used by agents to rapidly and interactively share information to coordinate results.

Overview-False data injection attacks



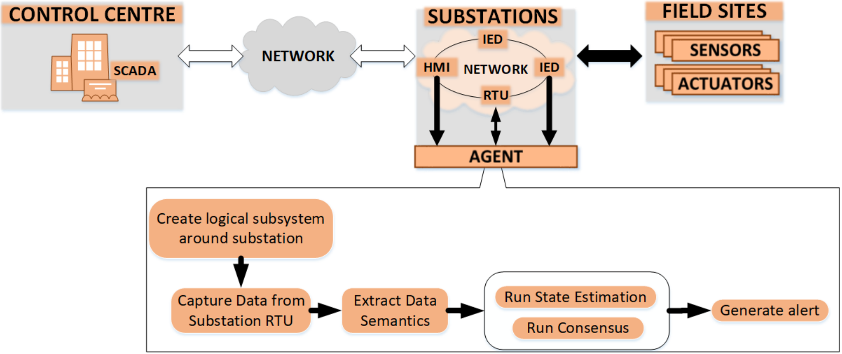
- False data injection attacks affect:
  - Control commands originating from the control center.
  - Measurement data sent to the control center from remote field devices.
- Attacks on control commands alter the topology of the power grid.
- Attacks on measurement data affect state estimation

Attack Model

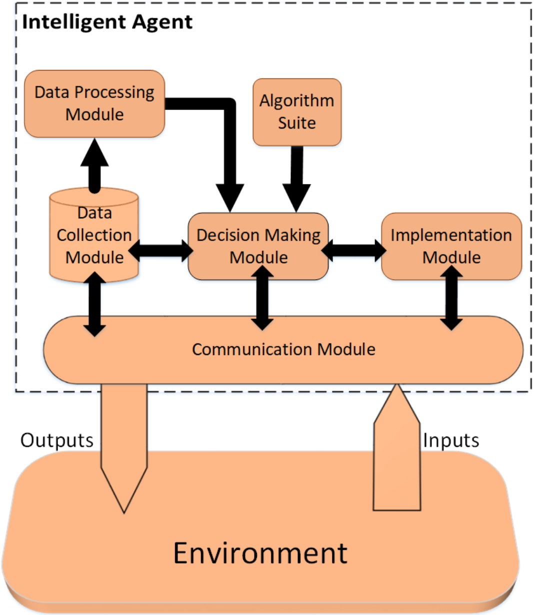
- Adversaries can gain access to control traffic by penetrating the control center's local area network (LAN).
- Within the substations, IEDs can be penetrated by attackers.
- We assume that the only data that can be trusted is data obtained directly from sensors and actuators within substations.

Proposed approach-Distributed agent-based framework

- Deploying software-based agents at substations.
- We assume there's some form communication among adjacent substations (Specified under the IEEE substation automation standards).
- Agents leverage this communication infrastructure to interact with adjacent agents and substation IEDs.



Software agent architecture



- Inputs:
  - Data from the RTU and PMUs
  - Data from other agents
- Outputs:
  - State Estimates
  - Measurements
  - Intrusion Detection results
- Algorithm suite (Knowledge base)
  - Attack detection
  - State estimation
  - Consensus

Using MAS to detect FDIA

FDIA against state estimation

- Consider a power network with n substations and n agents each deployed at a substation.
- For substation i, the corresponding agent determines the measurement vector z_i and corresponding state x_i from

$$z_i = H_i x_i + e \tag{1}$$

- For an FDIA vector a, to evade detection the attack must satisfy the condition

$$a_i = H_i c_i \tag{2}$$

- The attack is detected if for any agent i the conditon (2) is not satisfied
- The condition is not satisfied if $a_i \in image(H_i)$. For a subsystem created around a substation, H_i is sufficiently small.

Using MAS to detect FDIA

FDIA against control commands

- Let x_i be the correct state estimate and z_i be the vector of measurements for subsystem i.

$$\mathbf{x_i} = (\mathbf{H_i^T R_i H_i})^{-1} \mathbf{H_i^T R_i z_i} \tag{3}$$

- For a command with semantics s_i, agents can simulate the impact of s_i by computing

$$\mathbf{\hat{x}_i} = (\mathbf{H_i^T R_i H_i})^{-1} \mathbf{H_i^T R_i (z_i + s_i)} \tag{4}$$

- The resulting power flows can then be simulated by computing

$$\mathbf{z_{s_i}} = \mathbf{H_i \hat{x}_i} \tag{5}$$

Consensus algorithm to coordinated detection results

The Consensus problem

- Agents converge to desired state values using local information and that from neighboring agents
- Let the undirected graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ represent the multi-agent system where the nodes $\mathcal{V} = (1, 2, \ldots, n)$ represent agents and edges $\mathcal{E} \subset \mathcal{V} \times \mathcal{V} = (\mathcal{V}, \mathcal{E})$ represent communication links between agents

Information Sharing

- Agent i uses state information from its neighbors to update its state according to the law

$$\psi_i(k+1) = -\sum_{j=1}^{n} a_{ij}(\psi_i(k) - \psi_j(k)) \quad (6)$$

- The information at each agent asymptotically converges to

$$\psi_i := lim_{k\to\infty}(k) = \frac{1}{n}\sum_{j=1}^{n} \psi_i(0) \quad (7)$$

Detection Algorithm

Algorithm 1 Distributed FDIA detection at agent

Require: Sampling time k , Subsystem i, where $i = \{1, \ldots, n\}$,

Initialize $k = 0$, $z_i(0)$, $x_i(0)$, $\psi_i(0)$

Ensure: $z_i(0)$, $x_i(0)$, $\psi_i(0)$, $\psi_j(0)$, A_i, H_i, τ_i

for Each iteration $k \geq 0$ **do**

    $\psi_i(k+1) = \psi_i(k) + \sum_{j=1}^{n} a_{ij}(\psi_j(k) - \psi_i(k))$

    $z_i(k+1) \leftarrow f(\psi_i(k+1), z_i(k))$

    $\hat{x}_i(k+1) = (H_i^T R_i H_i)^{-1} H_i^T R_i(z_i(k+1))$

    $z_{si}(k+1) = H_i \hat{\mathbf{x}}_\mathbf{i}$

  for $z_{si}(k+1) \gtrapprox \tau_i$ **do**

    Generate alert

  end for

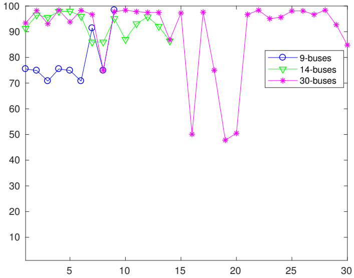
    repeat for $k = k + 1$

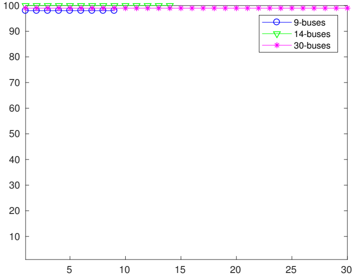
end for

Experimental evaluation

Attacks against measurement data

- MATPOWER is used to simulated power flow for the IEEE 9, IEEE 14 and IEEE 30 bus systems.
- Attack scenario: 1000 random attack vectors are simulated
- Each agent performs a distributed state estimation with a tighter bound on the threshold of bad data
- For the attack cases simulated, probability for a succesfull FDIA against state estimation was ≤ 0.01



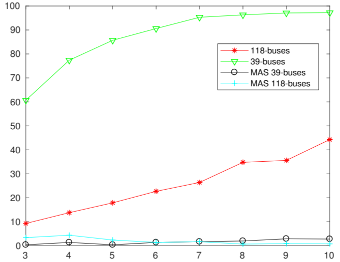


Experimental evaluation on detecting FDIA against commands

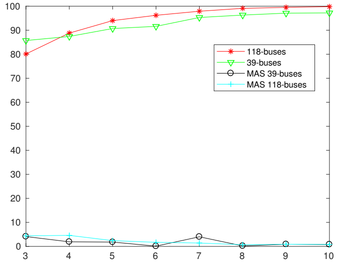
- Using the IEEE 118 and IEEE 38 power systems simulated using MATPOWER
- Agents continuously run state estimation and consensus to update neighbors.
- To demonstrate how agents detect malicious commands, we simulate commands that disconnect transmission lines and vary loads and generation
  - 1000 random attacks
  - 1000 targeted attacks
- The agent based architecture successfully detects random and targeted attacks with a success rate of over 96%

Experimental evaluation on detecting FDIA against commands

Random attacks



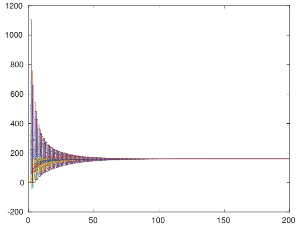
Targeted attacks



Experimental Evaluation on consensus algorithm

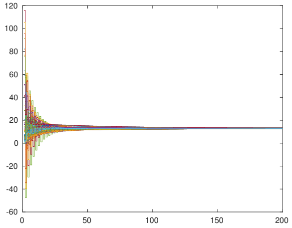
- The consensus algorithm described in (6) enables agents rapidly communicate their results to adjacent neighbors

39-bus



$$Time = \frac{n_i(3n_b)|\psi_i|}{n_t} = 0.001498 \quad (8)$$

118-bus



$$Time = \frac{n_i(3n_b)|\psi_i|}{n_t} = 0.0101952 \quad (9)$$

Conclusion

Recap

- Introduced a distributed false data injection attack framework based on multi-agent systems.
- Demonstrated how agents use a limited amount of information to detect attacks and coordinate detection results by a consensus-based rapid information exchange algorithm.

Future Work

- Evaluate the MAS systems in a realistic power grid environment

Thank you!! Questions??