Smart sensing, state estimation and control for enhanced smart grid reliability

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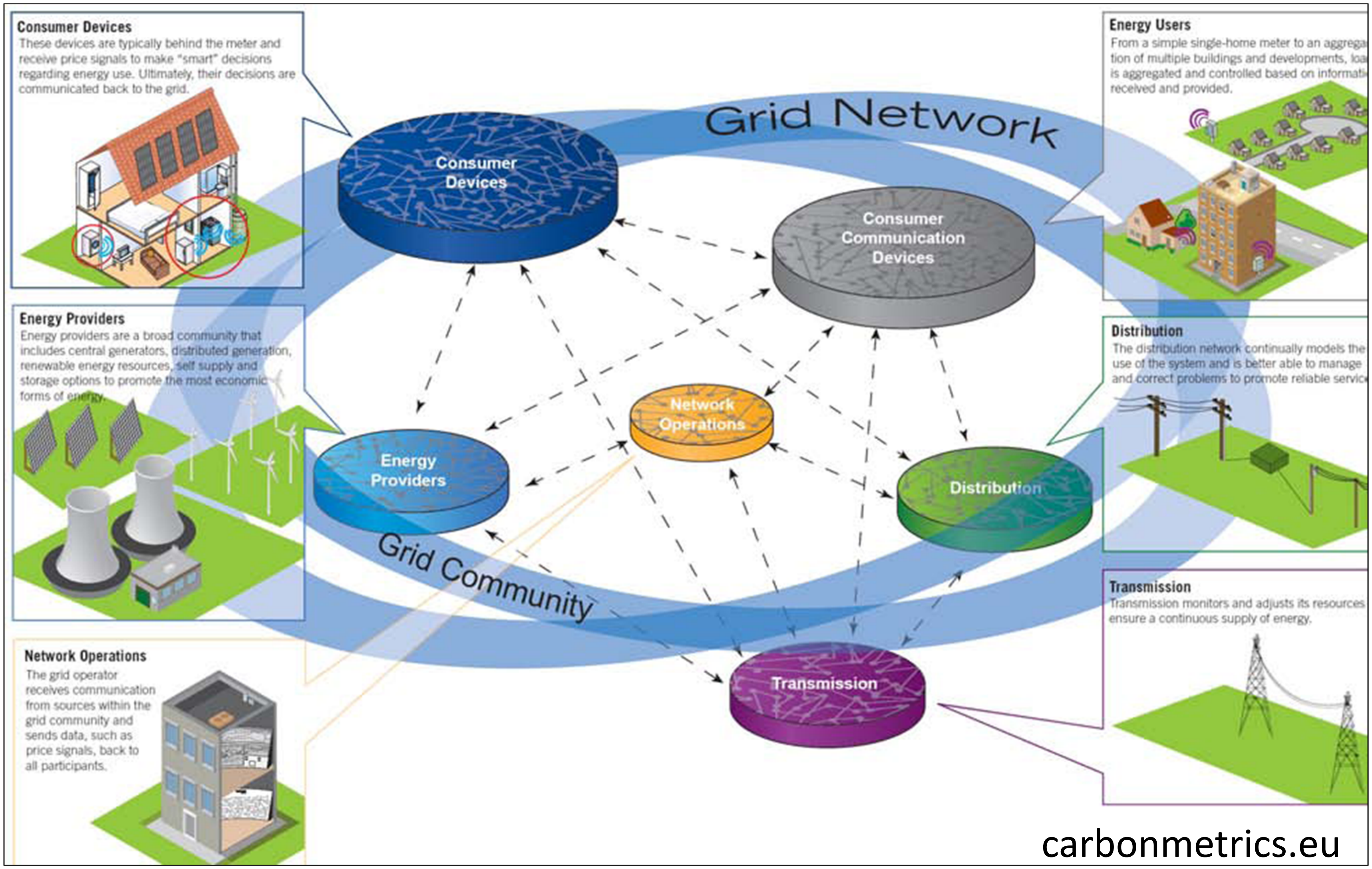
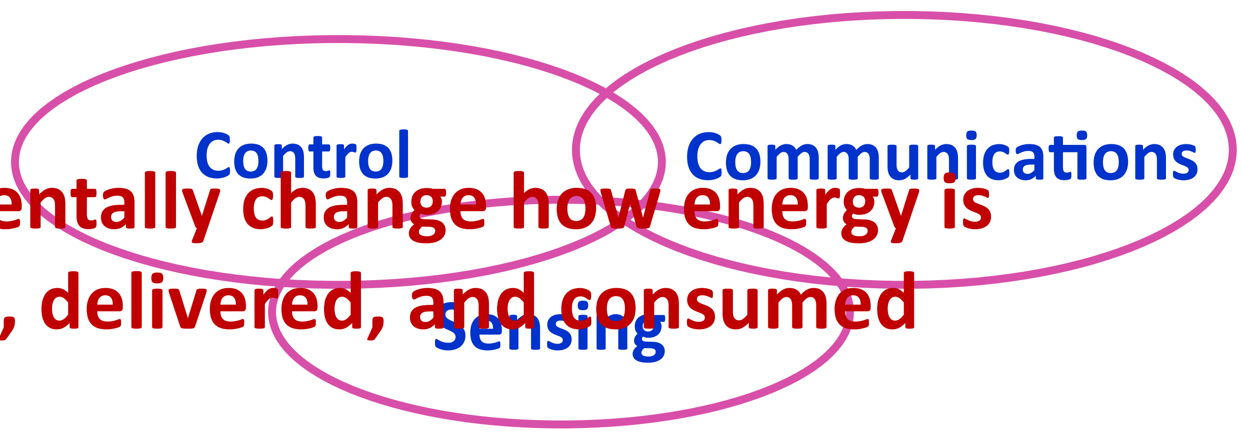
The Smart Grid … *in pictures*



The Smart Grid … *in words*

- A unified communications and control system overlay
- On top of the existing/emerging power infrastructure
  - To provide the right information
  - To the right entity (e.g. end-use devices, transmission and distribution systems, energy providers, customers, etc.)
  - At the right time
  - To take the right action



Fundamentally change how energy is stored, delivered, and consumed

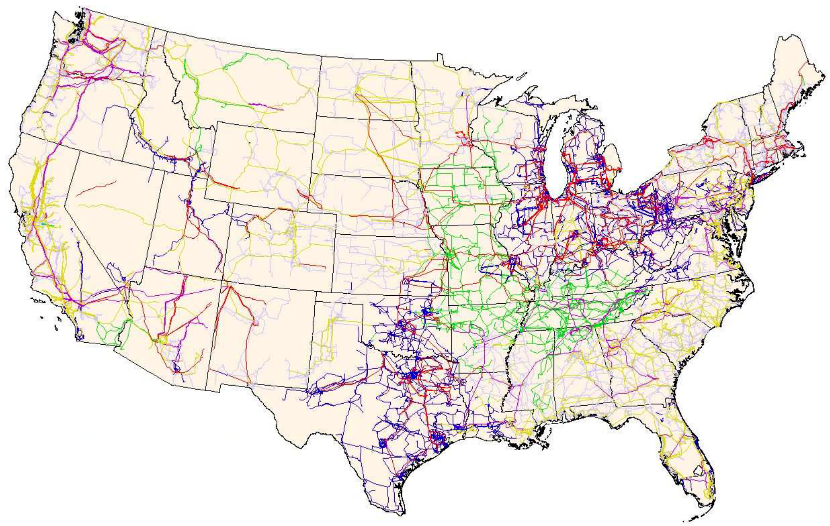
Much progress in some areas

- Smart metering
- Green buildings and structures
- Optimization
- Demand response
- Modeling and simulation
- Incentives and economics
- …

But many of the hard research questions have not yet been asked

We focus on grid reliability

Motivation and Background



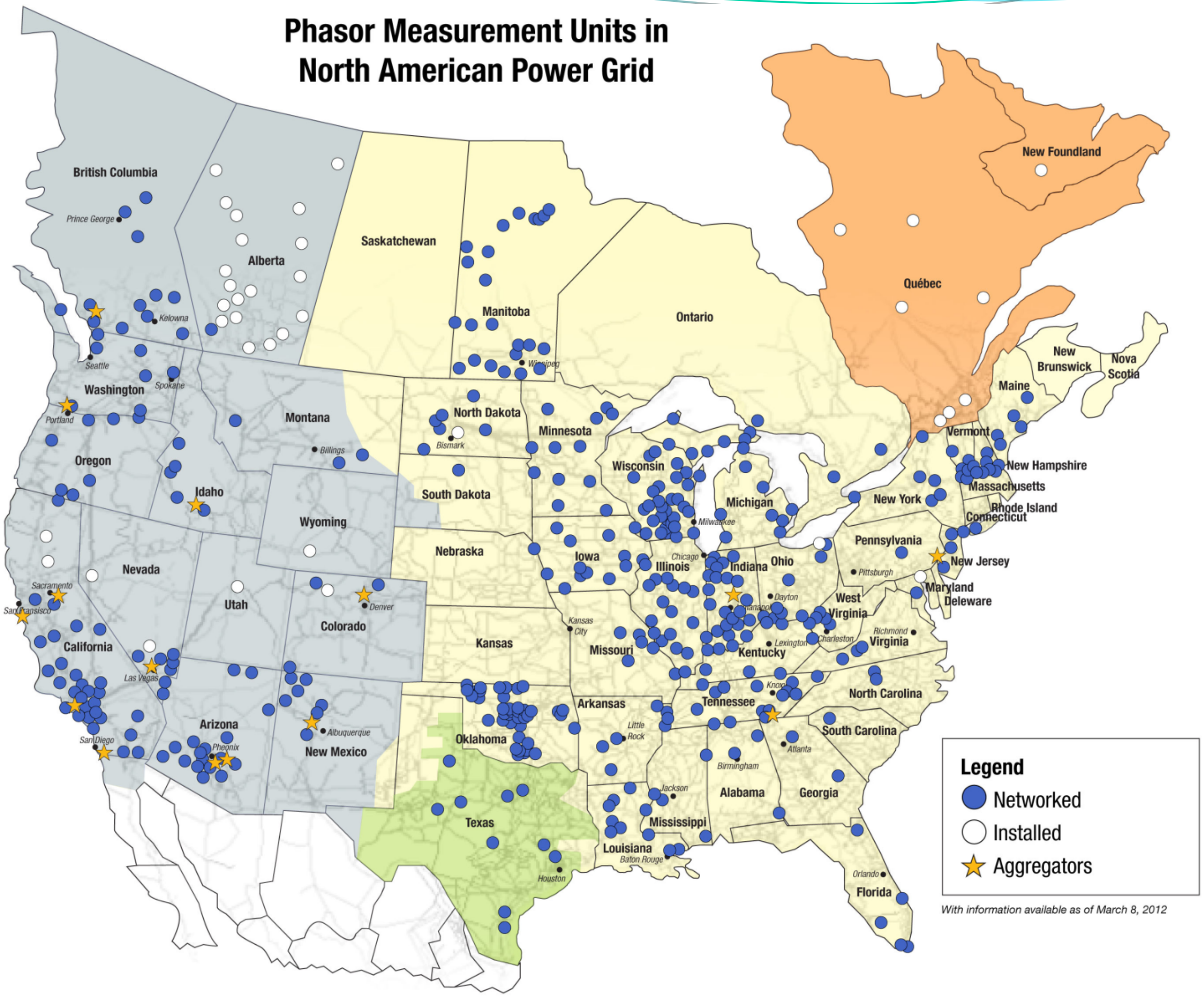
- Cascading failures in wide area transmission networks can cause large-scale blackouts.
- Near-sighted control actions can further deteriorate the grid stability.
- Wide area real-time situational awareness is needed for making the right control action to prevent cascading failures.
- Early detection of outages and attacks is needed.

Current Sensing in the Grid

- Conventional sensors and SCADA systems:
  - Neither temporally nor spatially dense.
  - Not synchronized, diverse and not easy to integrate.

- Next generation sensors - Phasor Measurement Units (PMU):
  - GPS-synchronized temporally-dense measurements
  - Measure voltage and current phasors.

- Key question: how many sensors is enough?
  - Installing sensors is costly
  - Communication harder with more sensors
  - What price is paid for fewer sensors?

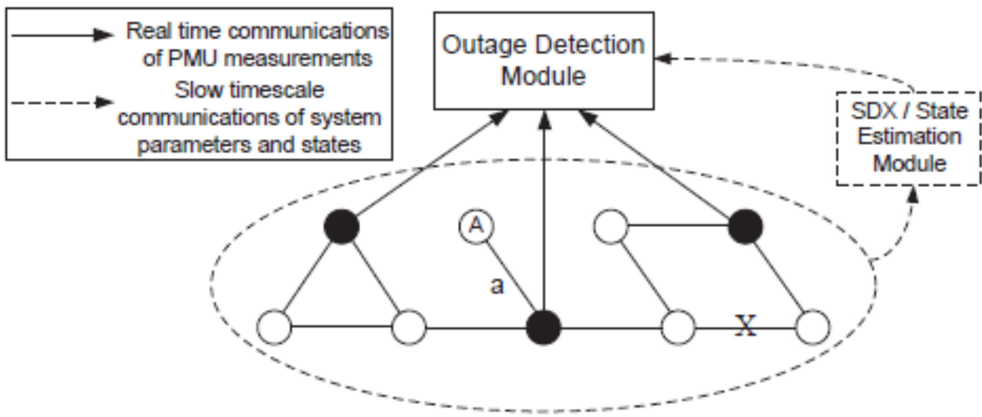


“New technology can improve electric power system efficiency and reliability”
US Energy Information Administration, March 30, 2012 (figure from NASPI)

Doing more with less

- Can we detect transmission line outages using voltage phase angles measured by a "small" number of PMUs?
- What is the optimal trade-off between the number of PMUs and the outage detection performance?
- Where should the PMUs be located?
- Related work:
  - Possibility of line outage detection using a relatively small number of PMUs [Tate, Overbye 08 09].
  - PMU location selection for other purposes: facilitating state estimation, dynamic security assessment [Li et al. 11] [Sun et al. 07].

Problem Formulation



- $\mathcal{L} = \{1, 2, \ldots, L\}$: the set of all transmission lines.
- $\mathcal{E} = \{E_1, E_2, \ldots, E_K\}$: the set of outage events of interest. $\bar{\mathcal{E}} = \mathcal{E} \cup E_0$.
- Outage signatures $\{\boldsymbol{\theta}^{(k)}\}$,

$$\boldsymbol{P} = \boldsymbol{B}^{(k)}\boldsymbol{\theta}^{(k)}, k = 0, 1, \ldots, K, \tag{1}$$

$$\boldsymbol{\theta} = \boldsymbol{\theta}^{(0)} + \boldsymbol{z}^0, \; \tilde{\boldsymbol{\theta}} = \boldsymbol{\theta}^{(\kappa)} + \boldsymbol{z}^1, \tag{2}$$

Detection Methods

- Optimal detection: exhaustive search
  - Observe pre-outage and post-outage phase angle vectors
  - Identify which event has occurred by comparing observations with every outage signature
  - Highly reliable detection, with high complexity
- Can also exploit sparsity to reduce detection complexity (compresses sensing techniques, e.g. Zhu/Giannakis'11)

Given optimal detection, where to place the sensors?

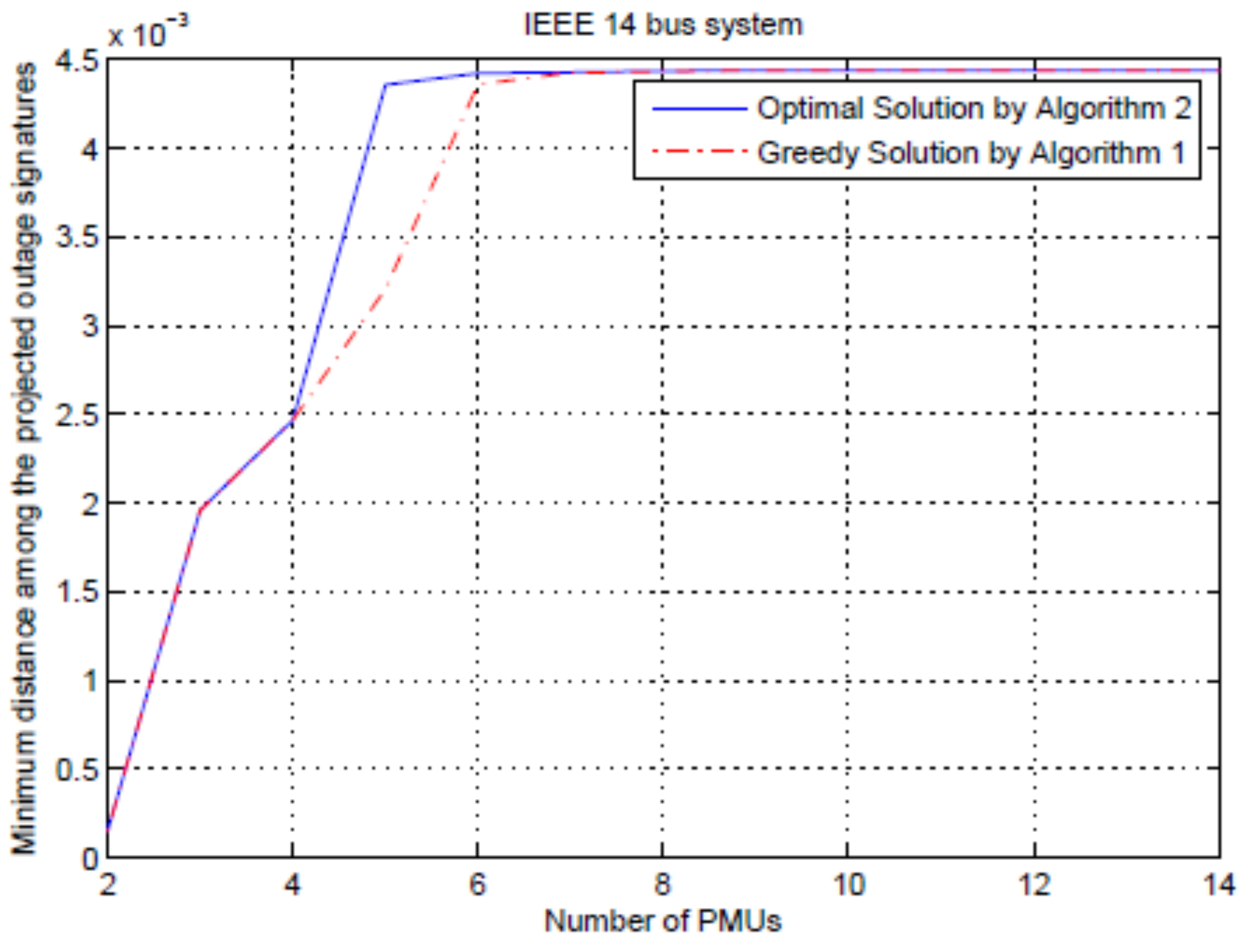
- Use coding ideas: maximize the "separation" of the outage signatures.
- Find the set of buses $\mathcal{M}$ to collect PMU measurements, given that $|\mathcal{M}| = M << N$.
- Goal is to maximally separate the projected signatures
- Different criteria can be used to capture separation:
  - Criterion I: Min. Distance Among the Outage Signatures (Integer Programming Problem)
  - Criterion II: Percentage of Indistinguishable Outage Pairs

Min Distance Algorithms

- Global Optimal Exhaustive Search:
  - We propose a branch and bound algorithm for exhaustive search to find the global optimal

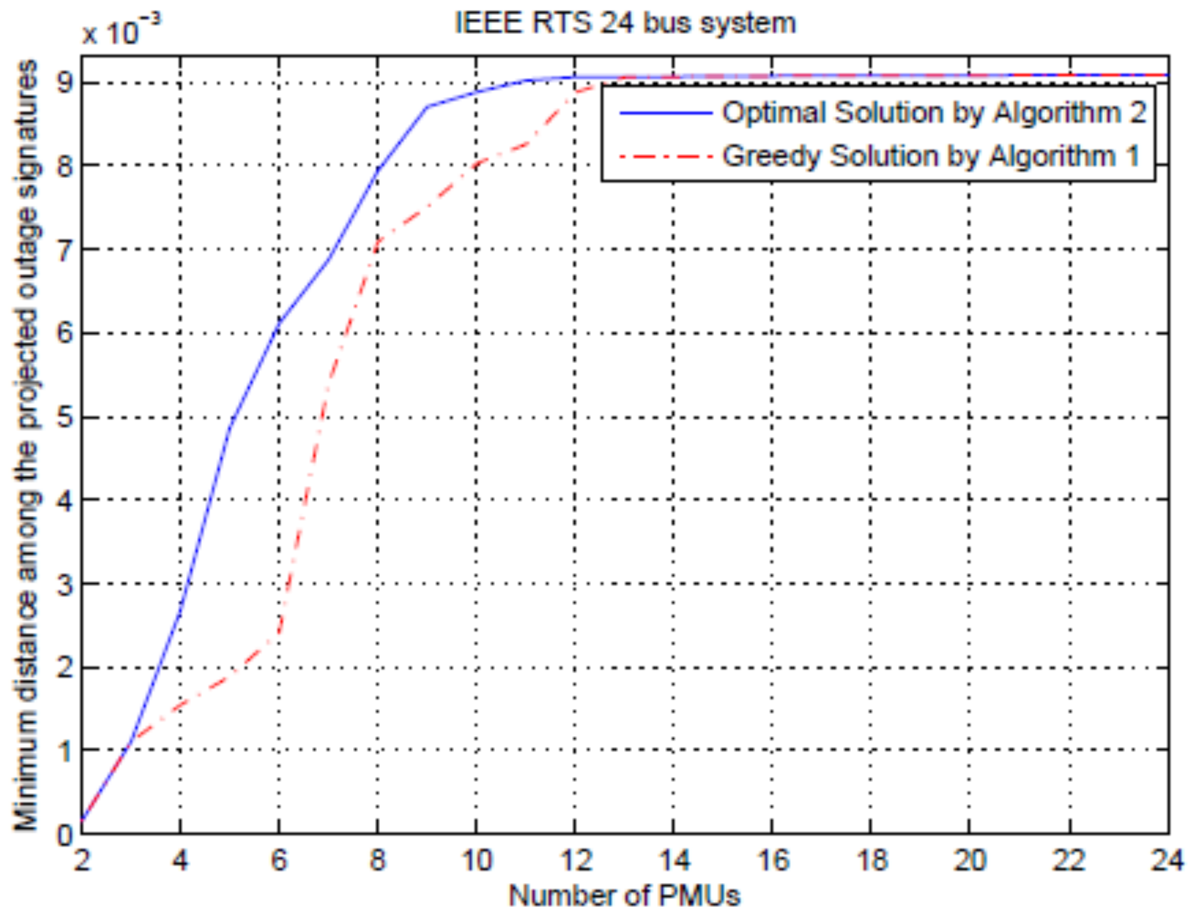
- Lower bound
  - We propose a greedy heuristic algorithm that approximates the locations that achieve the minimum distance

Outage Signature Distance vs. Number of PMUs (14 buses)



At most 17 iterations to reach convergence of optimal algorithm

Outage Signature Distance vs. Number of PMUs (24 buses)



At most 400 iterations to reach convergence of optimal algorithm

Observations

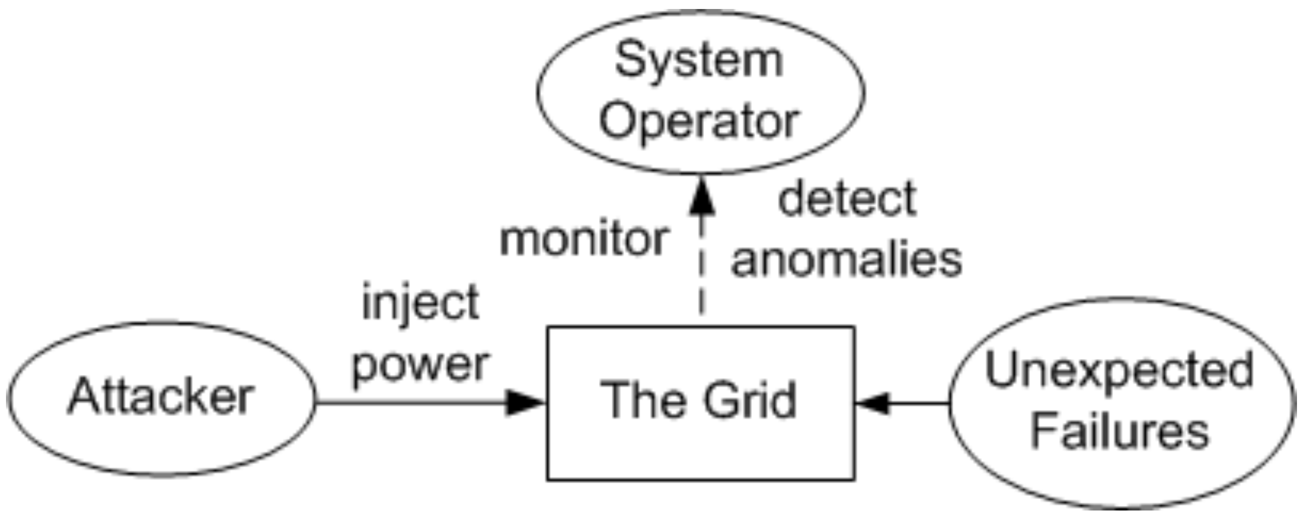
- Using PMUs on roughly one third of the buses is sufficien for near-optimal performance.
- The branch and bound algorithm finds the optimal PMU locations in a small number of iterations.
- The greedy heuristic achieves the global optimum when the number of PMUs is sufficiently large.

Extensions and next steps

- Can the model be generalized to
  - An AC power flow model?
  - More sophisticated sensing?
  - A more heterogenous and dynamic network model?
  - A more general communication network structure?
- Can a control model be superimposed on this framework?
- Can the ideas be extended to physical attacks?

Outage vs. Physical Attack

- Outages – unintended component failures.
- Physical attacks – intended and optimized power injections.



Model Differences

- Outage model
  - Prior probabilities of outages

    --- can be estimated by power engineering analysis.
  - Design the monitoring system based on the priors of the outages.

- Physical attack model
  - Attacker: minimize its effort and maximize its impact without being observed by the monitoring system.
  - System operator: design the monitoring system to maximize the difficulty of forming an attack.

Physical Attack Model

- Attacker: a sparse vector design problem.

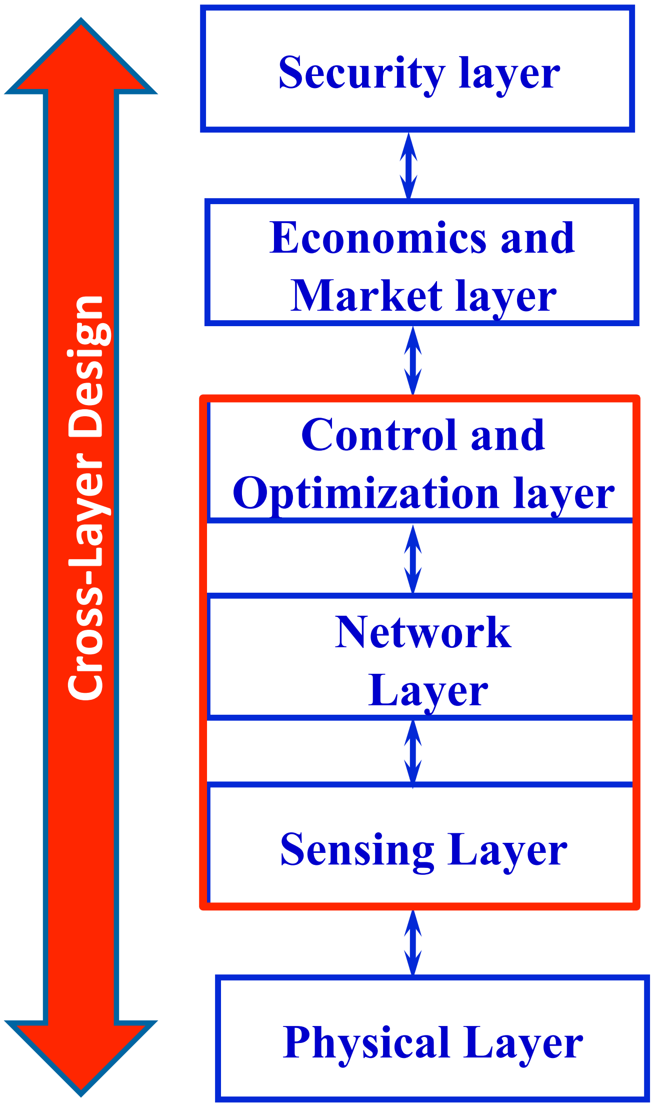
$$\begin{aligned} \min_{\mathbf{a}} \quad & \|\mathbf{a}\|_0 \\ s.t. \quad & \left\| \left(\mathbf{B}^{+}\mathbf{a}\right)_{\boldsymbol{M}} \right\|_\infty \leq \varepsilon, \\ & \text{Impact}(\mathbf{a}) \geq C. \end{aligned}$$

- System operator: a max-min subset selection problem.

$$\begin{aligned} \max_{\boldsymbol{M}} \quad & \left\|\mathbf{a}^*\right\|_0 \\ s.t. \quad & \left|\boldsymbol{M}\right| \leq M. \end{aligned}$$

Currently extending the PMU location problem to maximize detection probability of attacks

Possible Dichotomy for Smart Grid Design



Encryption, antijam, denial of use, impersonation, cyber-physical security, …

Pricing, incentives, markets, …

Real-time/embedded control, demand-response, resource allocation, fault tolerance, …

Sensor networks, HAN, Wifi, Wimax, Cellular, …

Electric, gas, and water sensors, HVAC, …

Photovoltaics, switches, storage, fuel cells, …

Summary

- Smart grids provide a tremendous opportunity for changing the way power is delivered and consumed

- The design of smart grids is a challenging interdisciplinary problem with many questions and few answers to date

- Capitalizing on new sensor technology and sophisticated optimization tools can significantly improve robustness in the grid.