NSF 0931978: A Computing Framework for Distributed Decision Making to Ensure Robustness of Complex Man-Made Network Systems: The Case of the Electric Power Networks

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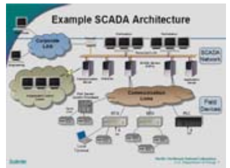
Motivation

- Electric power grid is arguably the ***largest cyber-physical system in operation***
- US grid:300,000 km of high voltage lines, 15000 generators,5000 distribution facilities, 500 companies
- The physical grid is carefully monitored and controlled using a cyber-infrastructure of meters, communication lines and control centers (***SCADA***)
- SCADA must evolve: Grid is hitting capacity limits; smart grid concept; renewable energy (wind, etc.) and better meters (PMU) now available
- Consequences of error: Equipment failures, blackouts, economic loss (80B annual loss est.)



Approach

- Our team has combined expertise in power systems, network analysis, high performance computing, and machine learning
- ***Control*** of power grid is paramount: Architecture for communication and control? Distributed control? Scheduling strategies?
- State ***estimation*** required for control: New paradigms for estimation? Estimation using new types of meters? Estimation using non-linear models?
- ***Modeling*** required: Using graphical models to incorporate highly random sources such as wind power? Machine learning for data-driven modeling?
- High performance ***computing***: Modern modeling, estimation, control is computer-intensive. Fast implementation using new computing paradigms?
- ***Implications for CPS***: How can a large, complex system based on physical laws (PhyNet) be effectively monitored and controlled?

Research activities

Control of electric grid

- Automatic generation control using minimal communication
- Scheduling for electric vehicle charging in distribution grid
- Scheduling in smart grid

Computing in electric grid

- Monte Carlo state estimation using high performance computing (HPC)
- Speeding up distributed algorithms using HPC

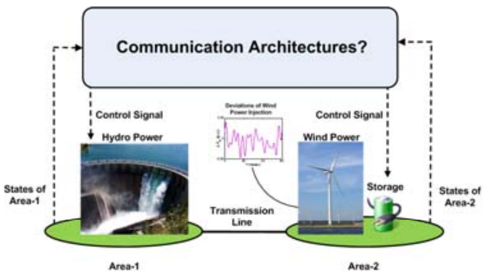
Estimation in electric grid

- Robust state estimation
- Distributed state estimation
- Semi-definite programming for estimation in non-linear models
- Optimal placement of PMUs to improve state estimation

Modeling of electric grid

- Graphical models of electric grid
- Predicting faults in graphical model of electric grid using machine learning

Communication for Enhanced-AG Control

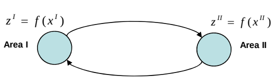


Motivation

- Automatic Generation Control (AGC) problems in coordinating/utilizing control resources for frequency regulation
- Communication architecture design for enhanced AGC needs to know physical characteristics of electric grid
- Requirement for minimum information exchange between control areas and the protection of private information

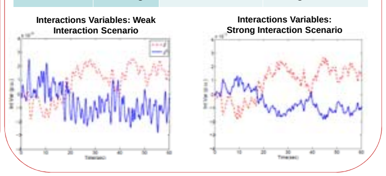
Interactions Variable Approach

- Identify interaction strength among control areas
- Decide needed inter-area information exchange
- Exchanged variables are functions of internal states ("x") of control area, associated with zero eigen-values of the singular system
- Choice protects privacy of control area

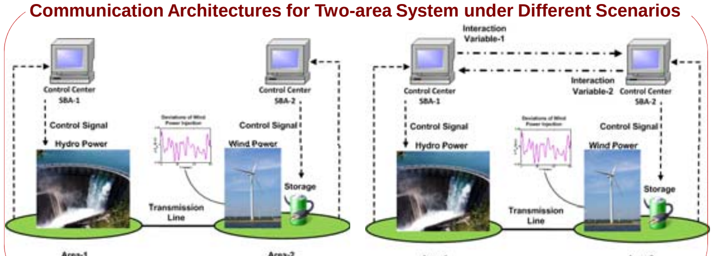


Four Power System Cases

		External Electrical Distance	
		Weak	Strong
Internal Electrical Distance	Weak	Weak Interaction	Strong Interaction
	Strong	Weak Interaction	Strong Interaction



Communication Architectures for Two-area System under Different Scenarios



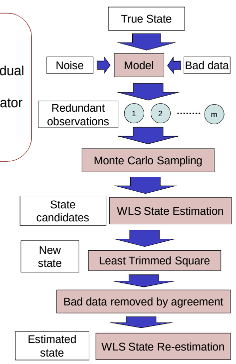
Weak Interaction Scenario

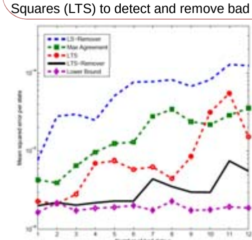
Strong Interaction Scenario

LTS for Robust State Estimation (SE)

Motivation

- Using real-time measurements, State Estimation serves as the foundation for monitoring and then controlling the power grid
- ***Classical method***: Weighted least squares (WLS) with largest residual removed used to deal with non-Normal errors (bad data)
- ***Problem***: When the bad data are correlated or bounded, this estimator has poor performance in detecting bad data.
- ***New approach***: Using Robust Estimator built using Least Trimmed Squares (LTS) to detect and remove bad data.

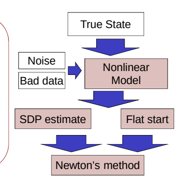


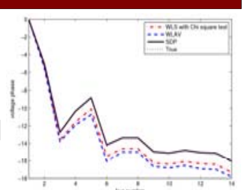


SDP for non-linear AC system SE

Motivation

- Newton's iterative method for AC power system SE using WLS
- Initial guess is the key
- No guarantees (Especially when system is started/restarted)
- ***Approach***: Convex (SDP) relaxation of WLS as approximation

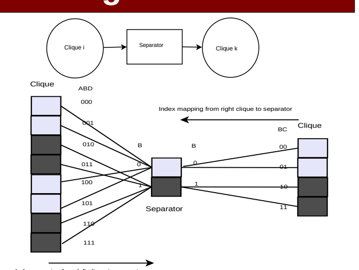




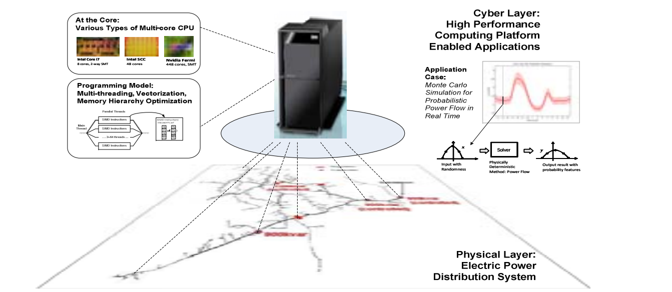
Parallel Message Passing for SE

Motivation

- Power system can be modeled as ***graphical model***
- Then, SE can be done by machine learning methods, such as belief propagation (BP) using equivalent junction tree
- But, BP over a junction tree is computationally intensive
- ***Approach***: Investigate parallel message passing algorithms for BP, to take advantage of advances in parallel computing (GPU, etc.)
- Substantial gain for large cliques and separators are large.



High Performance Computing in Power Grid



Motivation

Advances in High Performance Computing

- Peak performance grows ***exponentially.*** Multicore CPUs and GPUs:Tflop/s (10^{12}) under USD 1,000
- **Hard to leverage this performance:** parallelism, memory hierarchy, special instructions

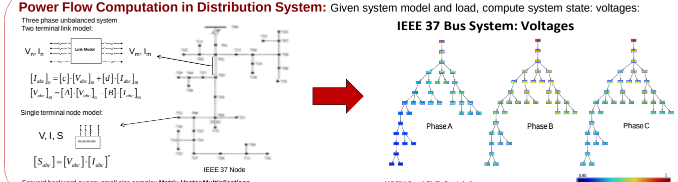
Challenges in Power System

- Uncertainties in electric power distribution system: Wind power, DG, PHEV, responsive load, etc.
- Probabilistic power flow: report power system states with confidence interval or PDF

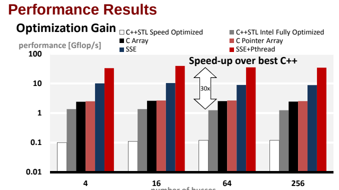
Leveraging Emerging Computer Architectures in Smart Grids: Monte Carlo Simulation

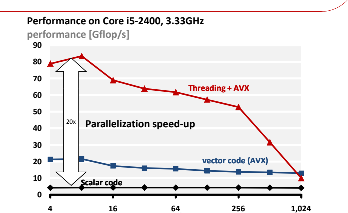
- Monte Carlo simulation: *Gold standard* for probabilistic power flow. Extensible to contingency analysis, etc.
- Maps well to modern multi-core and many-core platforms

Power Flow Computation in Distribution System: Given system model and load, compute system state: voltages:



Performance Results





Shows potential of well-optimized Monte Carlo code

1 million Monte Carlo solution samples within SCADA cycle (4s) for IEEE123