FRESCO: Fast, Resilient, and Cost-Optimal Co-Designs for Wide-Area Control of Power Systems

Aranya Chakrabortty[*], Alexandra Duel-Hallen[*], Anuradha Annaswamy[+], Alefiya Hussain[++]

[*] *North Carolina State University,* [+]*Massachusetts Institute of Technology, and* [++]*Information Sciences Institute at University of Southern California*

CPS Project Numbers:-1544871, 1544751, 1544742

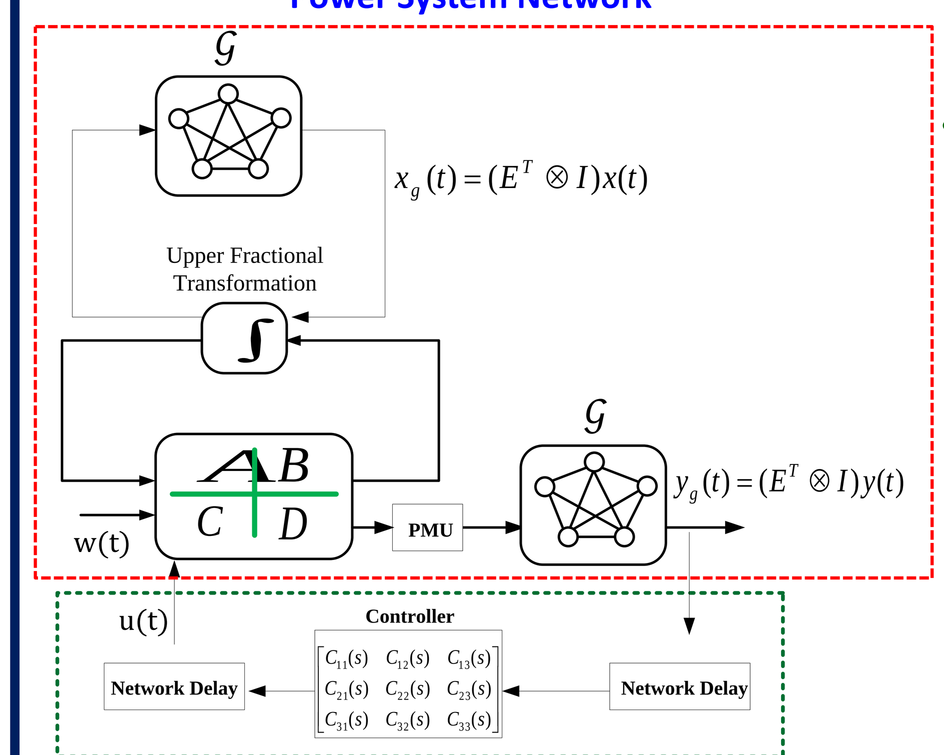
Project Goal

To co-design communication, control, and decision-making algorithms for fast, resilient and cost-optimal wide-area control of power systems using massive volumes of Synchrophasor data

- **Inter-area oscillation damping** – output-feedback based MIMO control design for large power transmission systems to shape the closed-loop dynamic responses of power flows and frequencies using real-time Synchrophasor data
- **System-wide voltage control** – PMU-measurement based MIMO control design for coordinated setpoint control of voltages across large inter-ties using FACTS controllers (SVC, CSC, STATCOM)
- **Safe islanding** – use PMU data to continuously track *critical cutsets* of the network graph – i.e., minimum set of tie-lines lines carrying max sets of dynamic power flows

Wide-Area Control

Coordination of multiple Phasor Measurement Units (PMUs) with multiple control actuators such as Power System Stabilizers (PSS) and FACTS devices to satisfy a global control goal in a distributed fashion over a secure communication network



Research Challenges

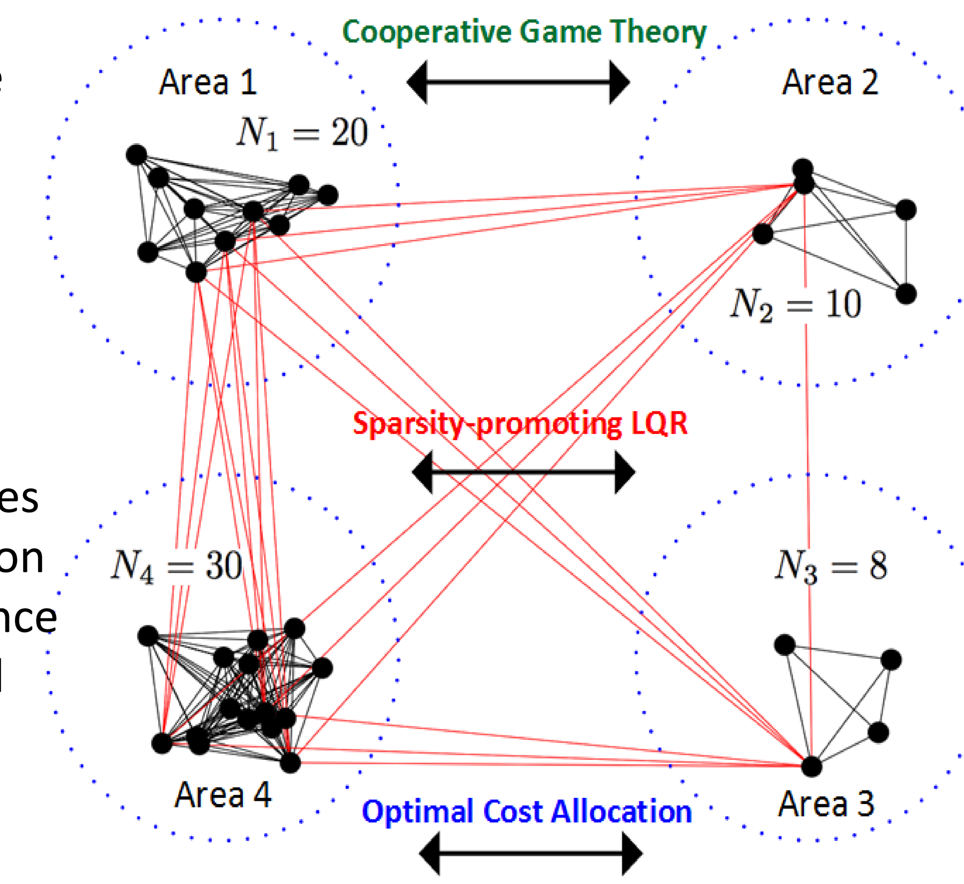
- **Time-scale for computation**
  Real-time computing, fast numerical algorithms
- **Communication costs and uncertainties**
  Multi-cast, routing, jitters, cyber-security
- **Control designs**
  Robust, output-feedback, distributed, delay-aware versus delay-tolerant, co-designed in sync with time-scales of comm. network

Game Theory for Cost Effectiveness

The cost for *renting* bandwidth and channel links vary depending on the criticality of the scenario and on the need for feedback.

The main question is - how much is each company willing to pay off in sharing the network cost?

Our approach is to treat the utility companies as *players in* a cooperative network formation game to jointly minimize a global performance metric, and thereby determine the required communication cost and its fair allocation using Nash Bargaining Solution

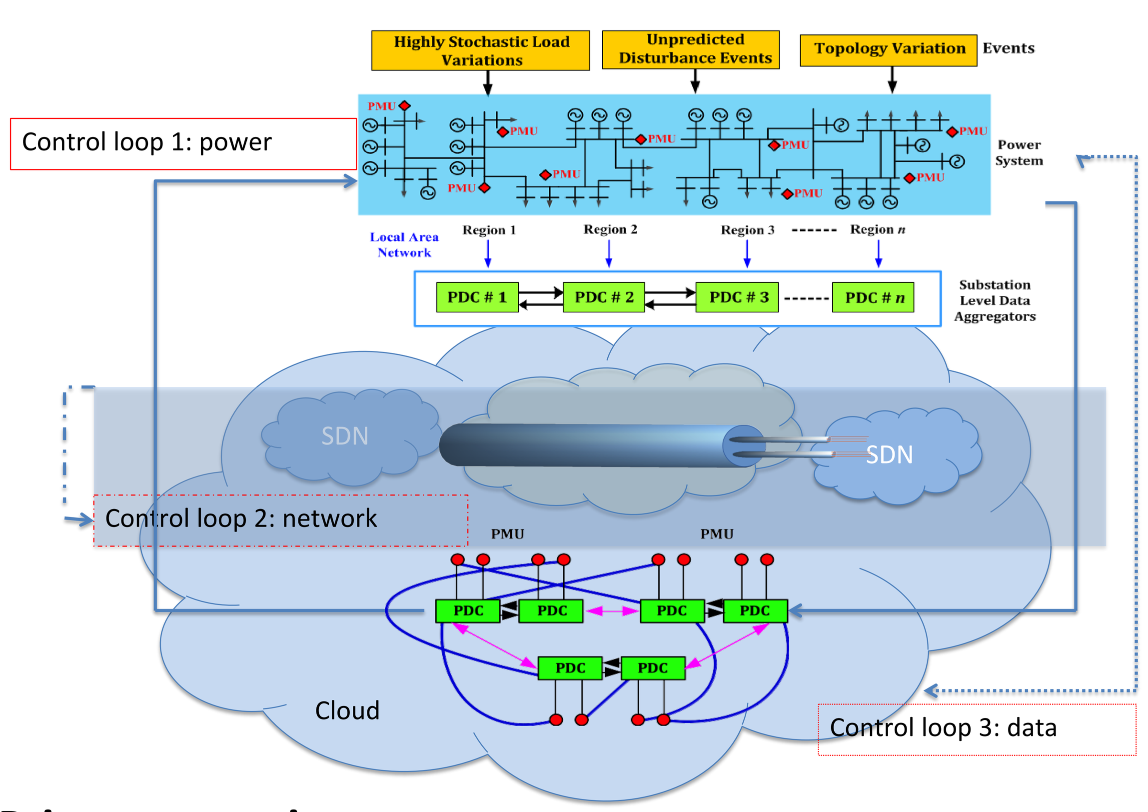


Technical Approach

Intellectual Merits:

1. Distributed power oscillation damping control
2. Distributed voltage control
3. Distributed middleware
5. Experimental verification using DETER security testbed

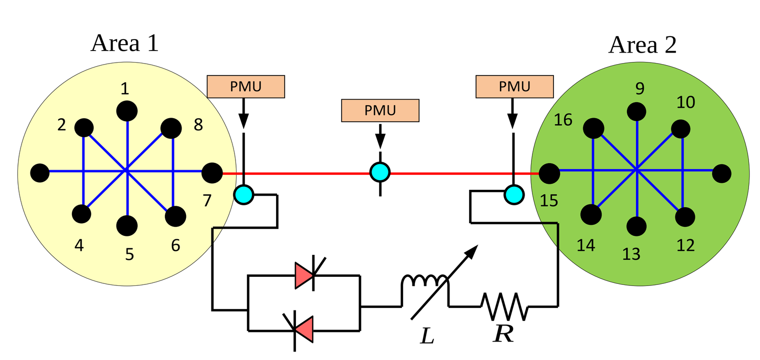
Proposed Distributed Cyber-Physical Architecture for Wide-Area Control:



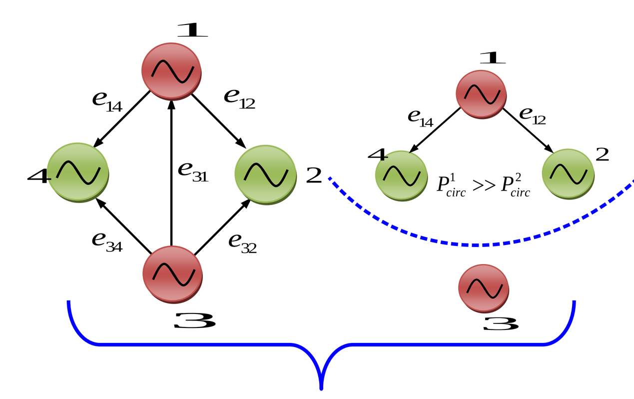
Primary questions:

1. How to co-design distributed optimal controllers in sync with delay bounds of wide-area comm. networks
2. How to optimally allocate investment costs of communication infrastructure to different utility companies
3. How to make WAMS resilient to Denial-of-Service, data manipulation, and other forms of cyber attacks.

New Control Algorithms



FACTS/PSS based damping control



Smart Islanding and fast control actions

Consider the power system model with swing + excitation dynamics:

$$\begin{bmatrix}\Delta\dot\delta\\ M\Delta\dot\omega\\ \Delta\dot E\end{bmatrix} = \begin{bmatrix}0 & I & 0\\ -L(G) & -D & -P\\ K & 0 & J\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega\\ \Delta E\end{bmatrix} + \underbrace{\begin{bmatrix}0\\ \mathrm{col}_{i=1(1)n}(\gamma_i)\\ \mathrm{col}_{i=1(1)n}(\rho_i)\end{bmatrix}}_{\text{due to load}} + \begin{bmatrix}0&0\\0&I\\I&0\end{bmatrix}\begin{bmatrix}\Delta P_m\\ \Delta E_F\end{bmatrix}$$

$$y = \mathrm{col}_{i\in\mathcal{S}}(\Delta V_i,\ \Delta\theta_i).$$

Choose *m* generators for implementing wide-area control via ΔE_F. Let the measurements available for feedback for the j^{th} controller be $y_j(t)$. Let $Y(t,\tau) = [y(t-\tau_j)]$ where τ_j is signal transmission delay. Let τ be the vector of all such delays.

Define a performance metric $\mathcal{J}$ to quantify the closed-loop damping of the slow eigenvalues of *A*. Let $\mathcal{P}$ denote the set of all possible models resulting from parameter/structural variations in the system. Design an output-feedback dynamic controller $F(Y(t,\tau))$ that solves:

$$\min_{\mathcal{F}}\max_{\mathcal{P}} \mathcal{J}$$

Potential approaches:

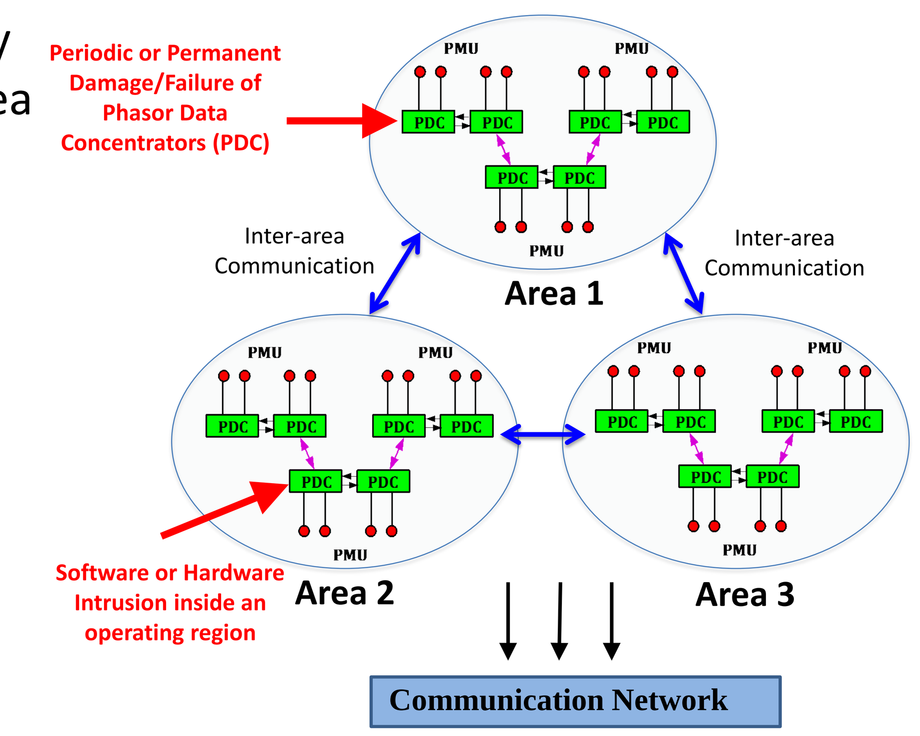
1. Delay-aware and sparsity-promoting optimal control designs
2. Distributed MPC
3. Graph-theoretic control designs for shaping eigenvalues and eigenvectors (convex optimization)

Cyber-Security of Wide-Area Control

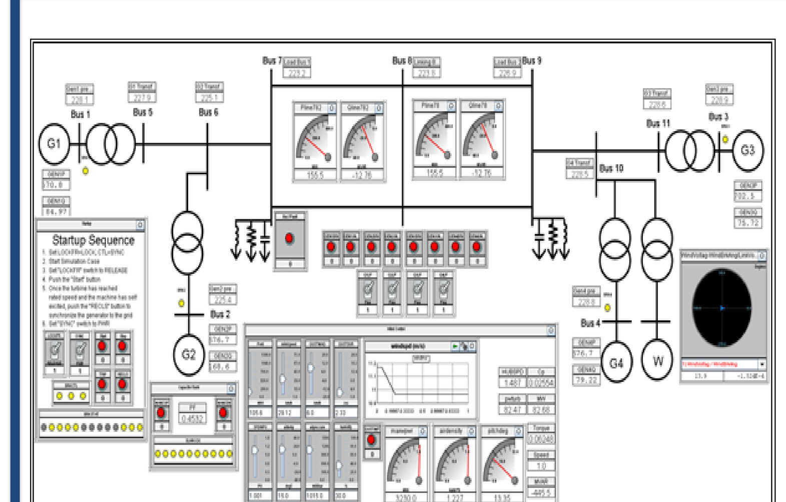
Develop security solutions that operate efficiently under different real-world constraints of wide-area communication, and that cyber-security defense design has to be done strategically with an understanding of economic constraints.

Proposed approaches:

1. Threat Modeling
2. Enumerating the Attack Space from PMU data and Controller Signals
3. Intrusion Resilience via Response Graphs
4. Allocating Cost of Resilience via Game Theory



Experimental Testbed



- Participated in Smart America Challenge 2014 Initiative of NIST and US White House
- Federated *DETER Cyber-Security Testbed*
- Multi-vendor PMU-based hardware-in-loop simulation testbed at NCSU and DETERLab at Univ. of Southern California to showcase resiliency of distributed wide-area control

Broader Impacts

- Undergraduate, K-12 and minority education via Science House and FREEDM ERC programs at NC State
- Women's education program at MIT and USC
- Undergraduate summer internship at Information Science Institute at USC
- Industry collaborations with power utilities and software vendors via TTP