Distributed Asynchronous Algorithms & Software Systems For Wide-Area Monitoring of Power Systems

Aranya Chakrabortty, Frank Mueller*, Rakesh Bobba+, Nitin Vaidya+ and Yufeng Xin++*

** North Carolina State University, +University of Illinois Urbana Champaign, and ++RENCI, University of North Carolina*

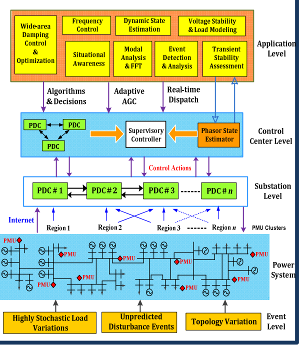
CPS Project numbers: 1329780, 1329745, 1329681

Project Goal

To translate current state-of-art centralized processing algorithms for wide-area monitoring of large power grids using large volumes of Synchrophasor data to a completely distributed cyber-physical architecture.

Intellectual Merits:

1. Distributed oscillation monitoring
2. Distributed voltage monitoring
3. Distributed middleware
4. Fault-tolerance
5. Experimental verification using Exo-GENI network
6. Real-time testing of QoS and cyber-security



Distributed Oscillation Monitoring

Problem statement: Compute power flow oscillation frequencies (eigenvalues), mode shapes (eigenvectors), damping, and residue from PMU measurements *using distributed algorithms* implemented via DRCP and DLAP.

Power System Dynamic Model

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

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

$$\Delta\theta_i(t) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_{2n} z^{-2n}}{1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_{2n} z^{-2n}}$$

$$\underbrace{\begin{bmatrix}\Delta\theta_i(2n)\\ \Delta\theta_i(2n+1)\\ \vdots\\ \Delta\theta_i(2n+l)\end{bmatrix}}_{c_i} = \underbrace{\begin{bmatrix}\Delta\theta_i(2n-1) & \cdots & \Delta\theta_i(0)\\ \Delta\theta_i(2n) & \cdots & \Delta\theta_i(1)\\ \vdots & & \vdots\\ \Delta\theta_i(2n+l-1) & \cdots & \Delta\theta_i(l)\end{bmatrix}}_{H_i}\underbrace{\begin{bmatrix}-a_1\\ -a_2\\ \vdots\\ -a_{2n}\end{bmatrix}}_{a}$$

Distributed LS problem

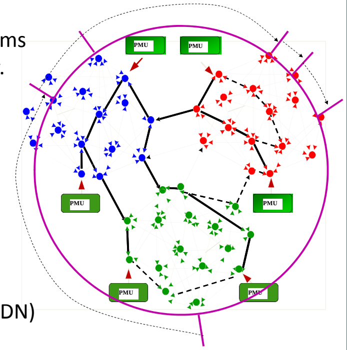
$$\underset{\mathbf{a}_1,\ldots,\mathbf{a}_N,\mathbf{z}}{\text{minimize}} \sum_{i=1}^{N}\frac{1}{2}\left\|\hat H_i \mathbf{a}_i - \hat{\mathbf{c}}_i\right\|_2^2$$

subject to $\mathbf{a}_i - \mathbf{z} = 0$, for $i = 1,\ldots,N$

Distributed Middleware

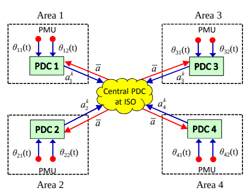
Problem statement: Develop distributed middleware to support DRCP and DLAP algorithms for oscillation monitoring and transient stability.

- Need recent PMU data from PDCs
- Idea: Develop real-time distributed storage
  - Fault-tolerant network overlays
  - RT-DHT: real-time distributed hash table
  - Chord-like ring + finger pointers
  - multiple replicas of data → faults OK
  - need deterministic wide -area networks
- ➢ Infrastructure: 1. Cloud computing
  2. Software Defined Networks (SDN)
- ➢ Experiments: BEN, Exo-GENI, and GENI

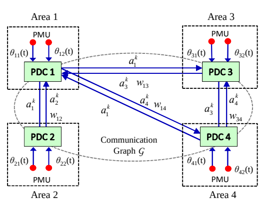


Technical Approach

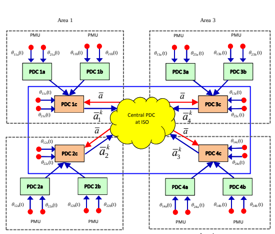
Proposed Distributed Cyber-Physical Architecture for PMU-PDC Communication:



- Dynamic Rate Control Problem (DRCP):
  - Find optimal PMU data exporting rates, and frequency of information exchange between local PDCs and inter-regional PDCs to minimize computation error between centralized and distributed estimation



- Dynamic Link Assignment Problem (DLAP):
  - Find optimal communication topologies in real-time connecting local and inter-regional PDCs to maximize computational speed for the overall global estimation/monitoring/control problem.



New Algorithms and Results using ADMM

1: Update both primal and dual estimation variables at every local control center:

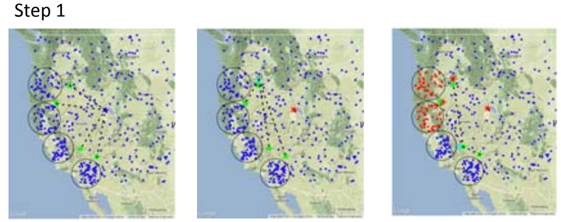
$$\beta_i^{(k+1)} = ((H_i^{(k)})^T H_i^{(k)} + \rho I)^{-1}((H_i^{(k)})^T c_i^{(k)} - w_i^{(k)} + \rho\bar\beta^{(k)})$$

$$w_i^{(k+1)} = w_i^{(k)} + \rho(\beta_i^{(k+1)} - \bar\beta^{(k+1)})$$

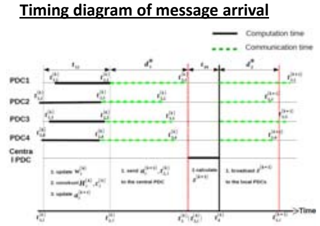
2: Gather the values of $\beta_i^{(k+1)}$ at the central ISO

3: Compute the average of $\beta_i^{(k+1)}$ at the central ISO

4: Broadcast the average to local control centers and iterate to Step 1



Timing diagram of message arrival



Mitigating Asynchrony in Wide-Area Communication

If a message doesn't arrive at ISO by a delay threshold d_1*

- **Strategy 1: Skip missing data**

$$z^{(k+1)} = \frac{1}{|S_1^{(k)}|}\sum_{i\in S_1^{(k)}}\left(a_i^{(k+1)} + \frac{1}{\rho}w_i^{(k)}\right)$$

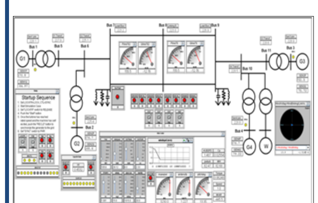
- **Strategy 2: Use zero-order hold**

$$z^{(k+1)} = \frac{1}{N}\left(\sum_{i\in S_1^{(k)}}\left(a_i^{(k+1)} + \frac{1}{\rho}w_i^{(k)}\right) + \sum_{i\in S_2^{(k)}}\left(a_i^{(k)} + \frac{1}{\rho}w_i^{(k-1)}\right)\right)$$

Fault-Tolerance & Cyber-Security

- Design application specific fault-tolerance mechanisms to meet real-time needs of the DRCP and DLAP monitoring algorithms
- ➢ Crash failures
- ➢ Byzantine failures – *Graph designs* to prevent arbitrary byzantine faults
- Leverage the redundancy of sensors and the correlation among sensor data to reduce the cost of fault-tolerance
- ➢ Protecting a small subset of PMU data may be necessary and sufficient to detect false data injection attacks
- Leverage application characteristics to design approximate or safe algorithms that can tolerate asynchrony and message loss

Experimental Testbed



- Participated in Smart America Challenge 2014 Initiative of NIST and US White House
- Federated *BEN-WAMS*: Multi-vendor PMU-based hardware-in-loop simulation testbed at NCSU and DETERLab at Univ. of Southern California to showcase resiliency of ADMM based wide-area oscillation monitoring

Broader Impacts

- Smart America Challenge 2014m US Ignite 2015 and 2016 demos
- Undergraduate, K-12 and minority education via Science House and FREEDM ERC programs at NC State
- Undergraduate summer internship at Information Trust Institute at UIUC
- Industry collaborations with power utilities and vendors such as SCE