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

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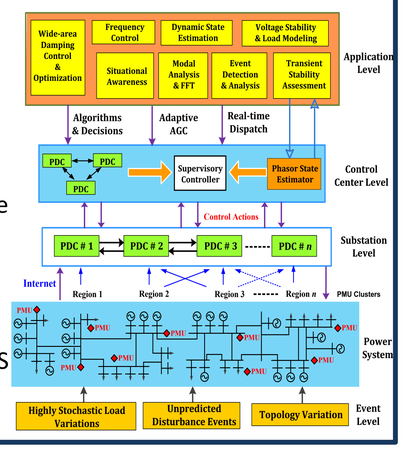
## Project Goal

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

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

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

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

Sparse distributed optimization:

1. ADMM, Stochastic Gradient
2. Round-Robbin ADMM for fault tolerant optimization

**Distributed LS problem**

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

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

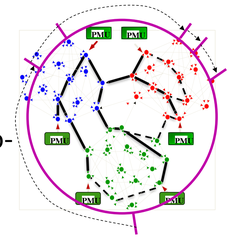
## Distributed Middleware

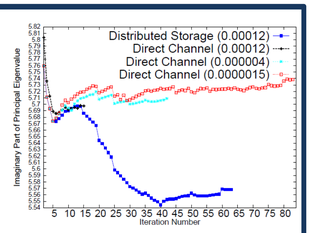
Integrated two classes of important applications into Resilient Real Time Distributed System (R2TDS):

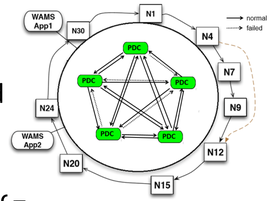
- Single server measurement for electro-mechanical oscillation mode parameter estimate
- Fully distributed wide-area feedback control

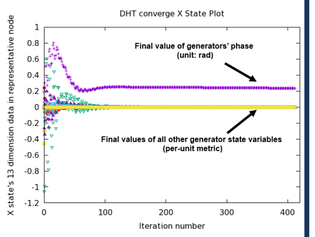
➢Alternative access points of R2TDS guarantee continual data storage and retrieval

➢The decreasing of convergence accuracy and speed or even divergence can be avoided by using R2TDS



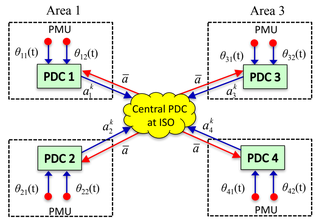




## Fault-Tolerance & Cyber-Security

- 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

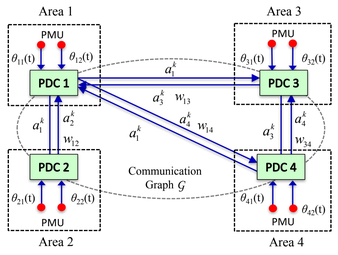
## Technical Approach

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



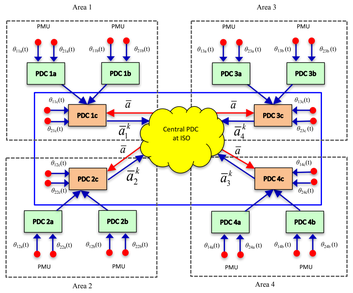

- Dynamic Rate Control Problem (DRCP):

  - 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:

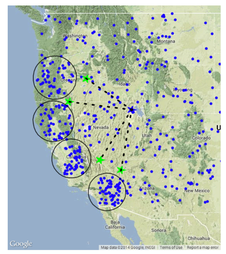
$$\beta_i^{(k+1)} = ((H_i^{(k)})^T H_i^{(k)} + \rho I)^{-1}((H_i^{(k)})^T c_i^{(k)} - w_i^{(k)} + \rho\overline{\beta}^{(k)})$$

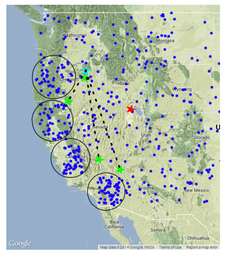
$$w_i^{(k+1)} = w_i^{(k)} + \rho(\beta_i^{(k+1)} - \overline{\beta}^{(k+1)})$$

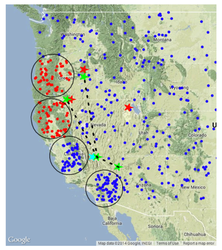
**2**: Gather the values of $\beta_i^{(k+1)}$ at the central ISO

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

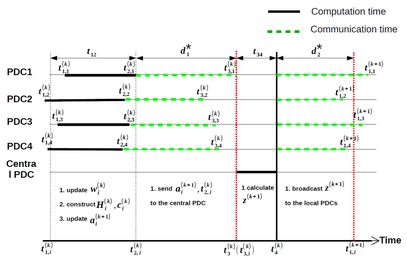
**4**: Broadcast the average to local control centers and iterate to Step 1







**Timing diagram of message arrival**




**Mitigating Asynchrony in Wide-Area Communication**

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

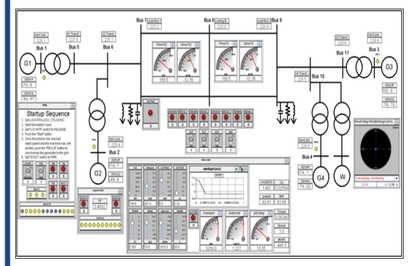
- **Strategy 1: Skip missing data**

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

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

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

## Experimental Testbed



- Participated in US Ignite Application Summits 2013-2017, and in Smart America Challenge 2014 Initiative of NIST and US White House
- Federated *ExoGENI-WAMS*: Multi-vendor PMU-based hardware-in-loop simulation testbed at NCSU to showcase wide-area oscillation monitoring and control

## Broader Impacts

- Smart America Challenge 2014, US Ignite 2013-2017 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