Cyber-Physical Challenges in Wide-Area Control of Power Systems

Theory, Challenges, and Open Problems

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Internet2 Monthly Webinar

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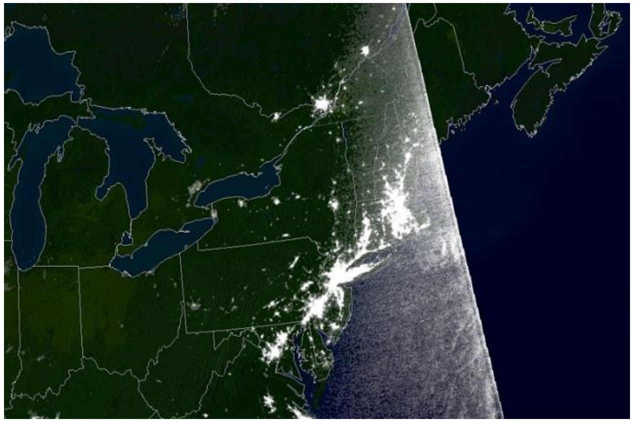
Main trigger: 2003 Northeast Blackout

NYC before blackout

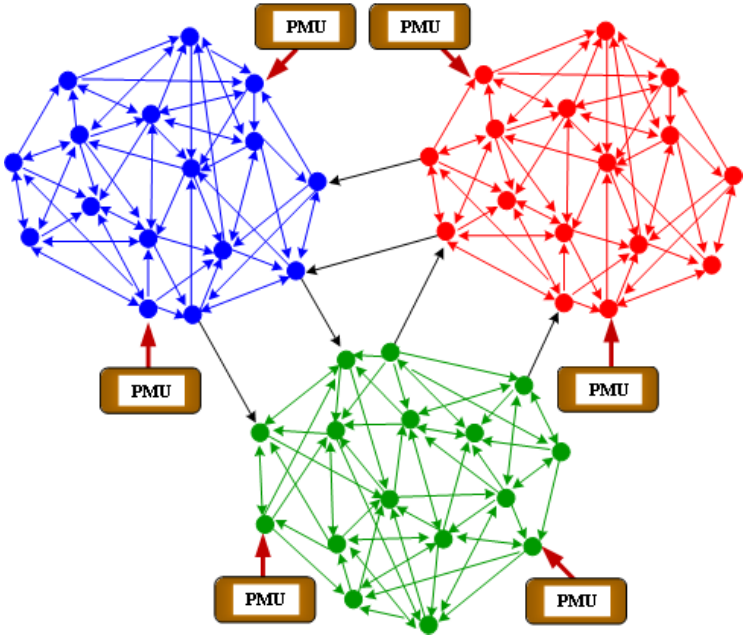


NYC after blackout

2 Main Lessons Learnt from the 2003 Blackout:

1. Need significantly higher resolution measurements

⇨ From traditional SCADA (System Control and Data Acquisition) to PMUs (Phasor Measurement Units)

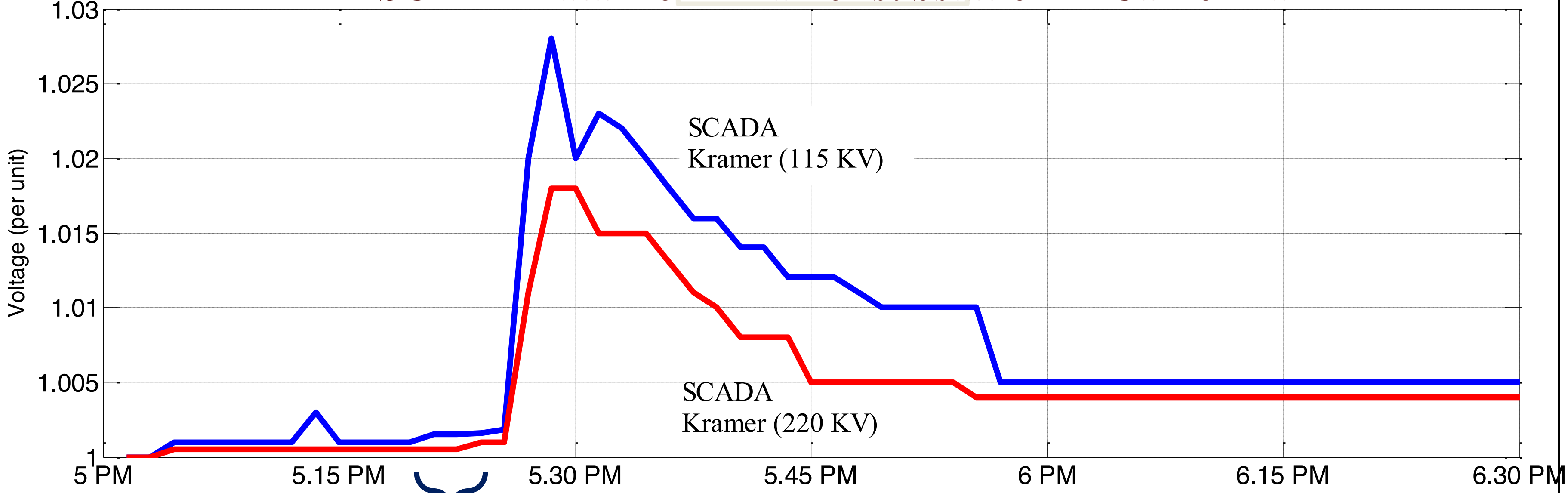


2. Local monitoring & control can lead to disastrous results

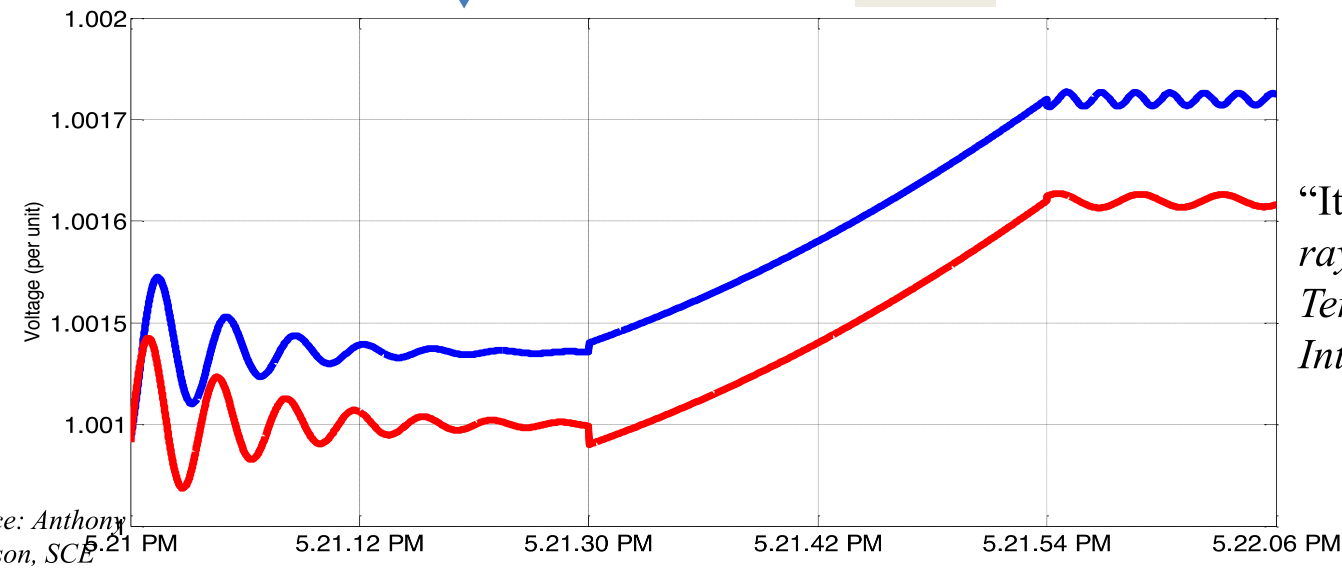
⇨ Coordinated control instead of selfish control

Hauer, Zhou & Trudnowsky, 2004
Kosterev & Martins, 2004

SCADA Data from Kramer substation in California



PMU Data



"It's like going from an *X-ray* to a *MRI* of the grid."
Terry Boston, CEO, PJM Interconnection

Source: Anthony Johnson, SCE

What is a PMU (Phasor Measurement Unit)?

• PMUs are digital data-recording devices that measure and export GPS-synchronized, high sampling rate (6-120 samples/sec) dynamic measurements of phase angles, voltages, currents and frequency

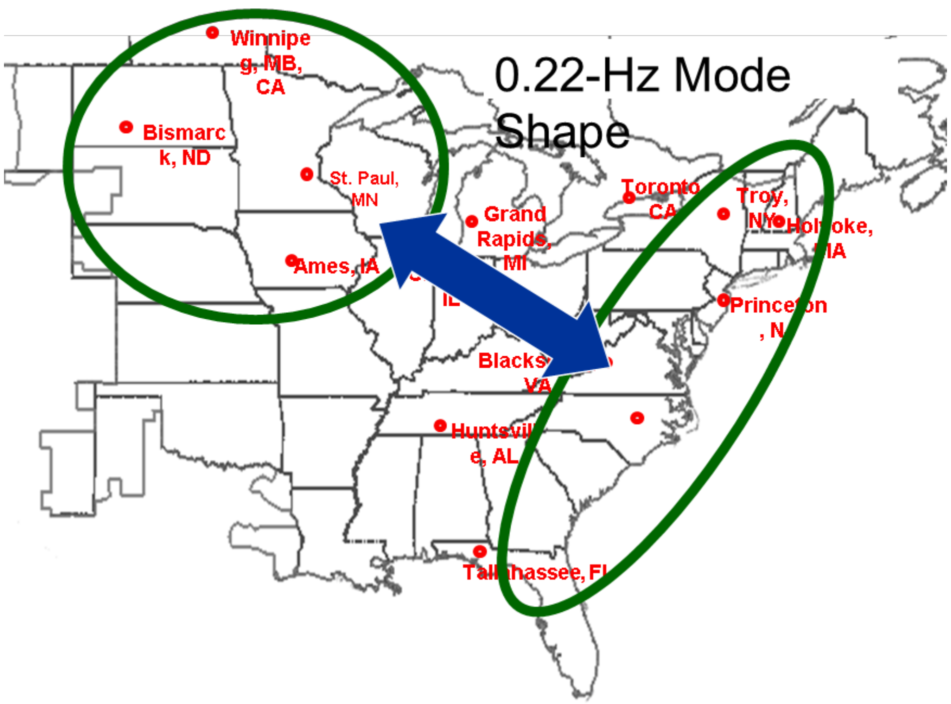
• Developed by Arun Phadke (VA Tech) and Jim Thorp (Cornell Univ.) in the 1980s.

3 **Development**

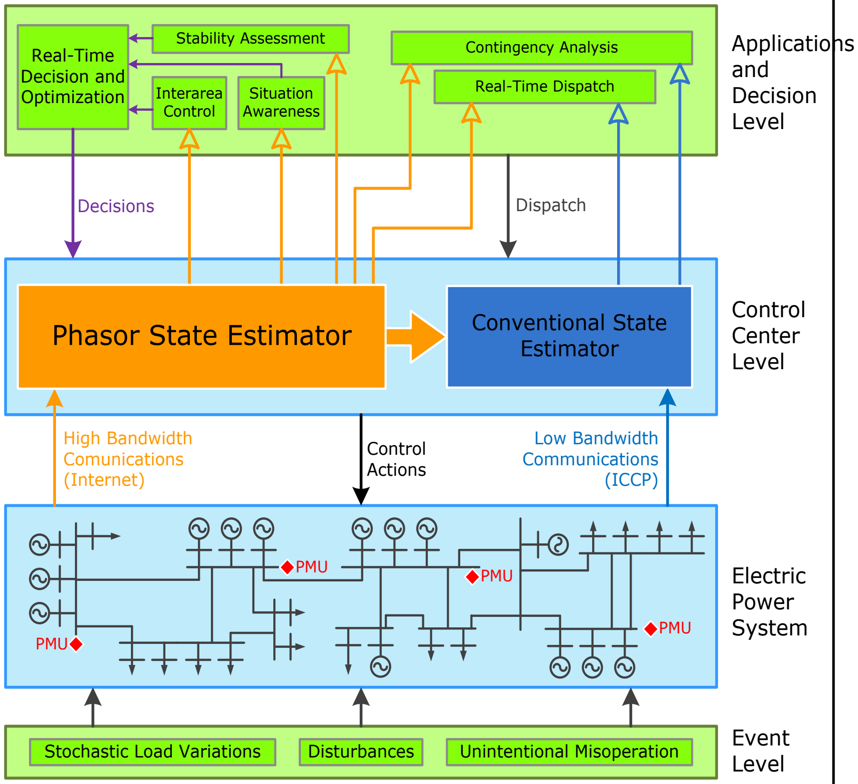
Subsequent Testing on the AEP Model Power System

Applications so far

1. Oscillation Monitoring Algorithms
   - 1.1 Mode meter – PNNL
   - 1.2 Real-time monitor – WSU, BPA
   - 1.3 Ringdown & ambient – UW, MTU
   - 1.4 Predictive models – RPI, NCSU, Imperial
   - 1.5 Mode shapes – WSU, KTH, SCE
   - 1.6 Voltage stability – ABB, SCE, Quanta



2. Phasor State Estimator
   - 2.1 Three-phase PSE – VA Tech, Dominion
   - 2.2 PMU placement algorithms – NEU, RPI
   - 2.3 Bad data detectors – NEU, RPI, ISO-NE
   - 2.4 Dynamic PSE – VA Tech, PNNL
   - 2.5 PSE installations - CURENT

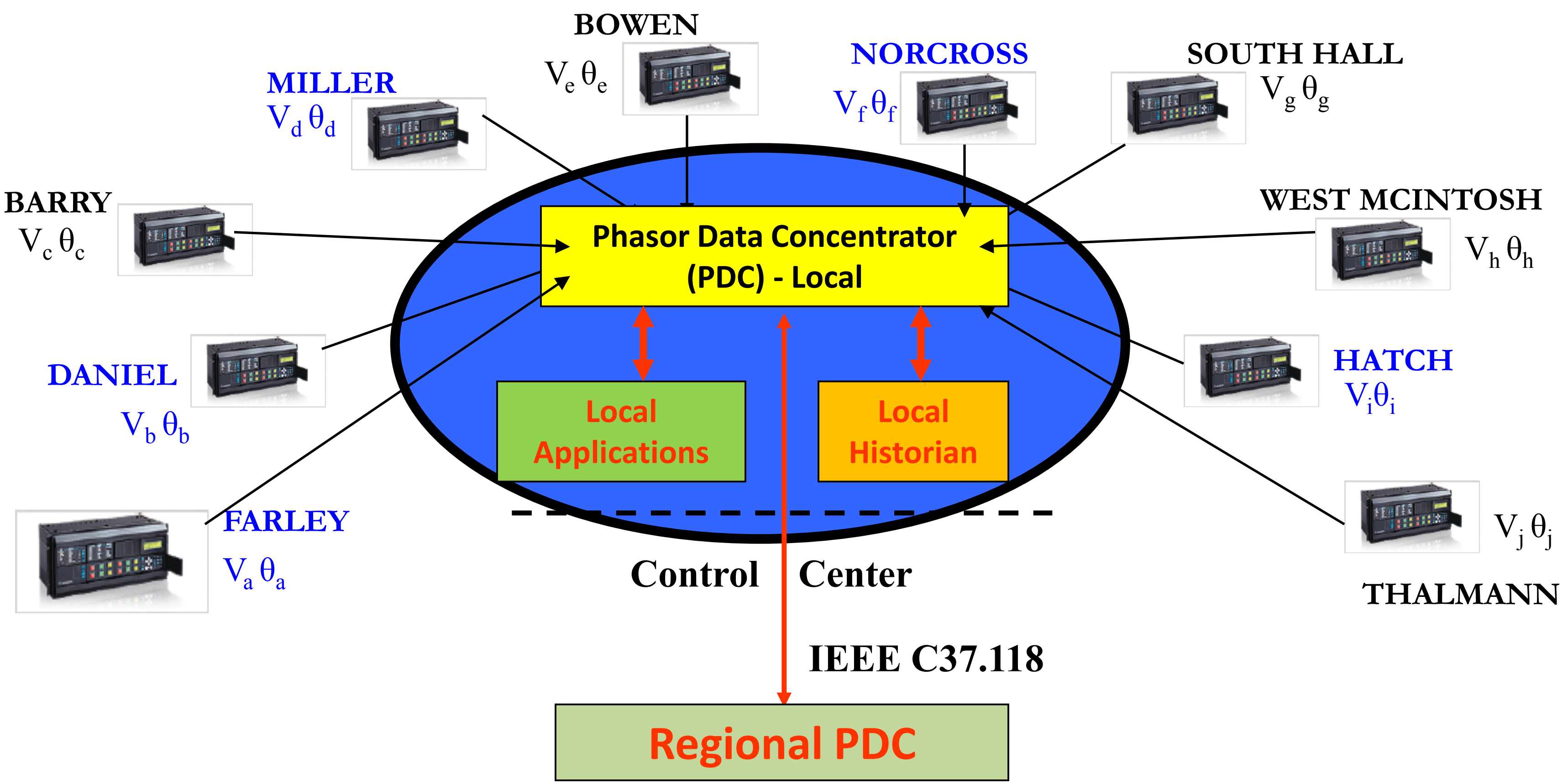


Source: Dan Trudnowski, Joe H. Chow

WAMS Architecture

- Mostly centralized sensing + computing architecture

WAMS architecture of Southern Company, GA



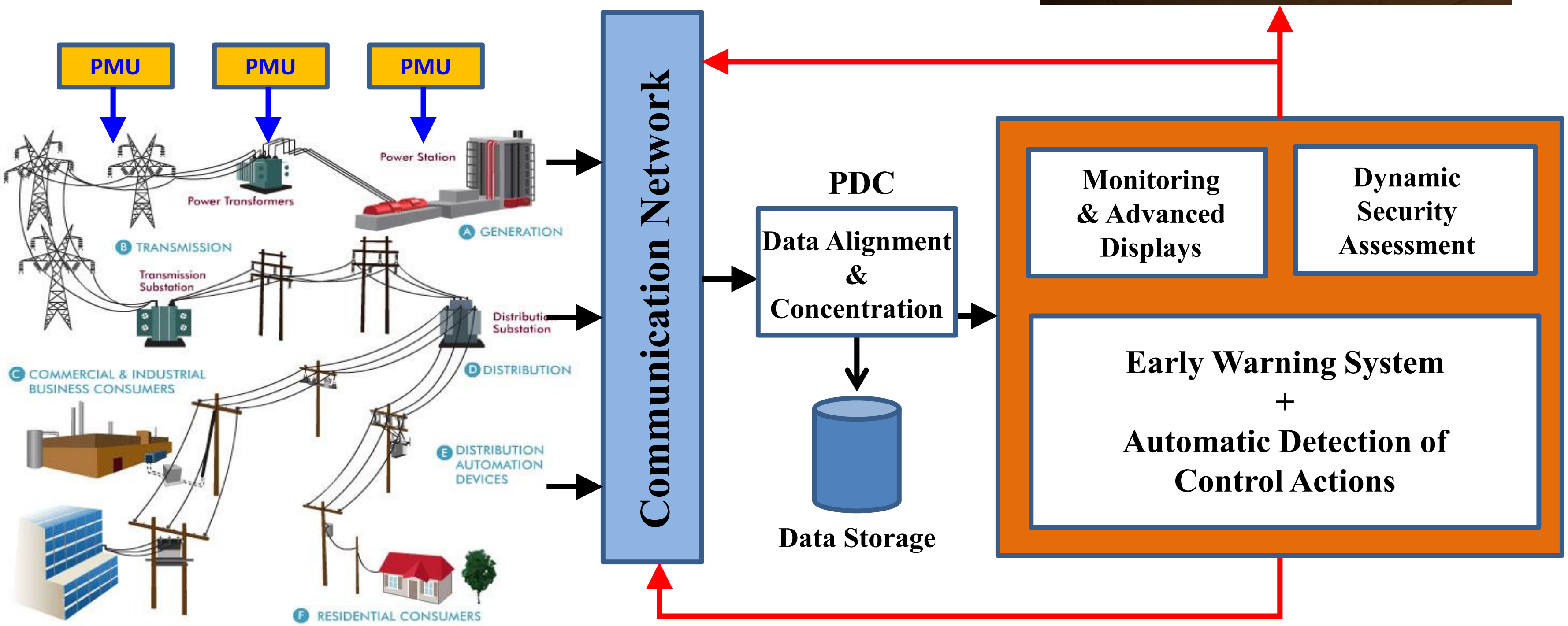
Architectures for Wide-Area Control

Scenario 1: Human-in-the-loop control

Measure → Communicate → Analyze → Determine preventive actions → Communicate → Control and protect

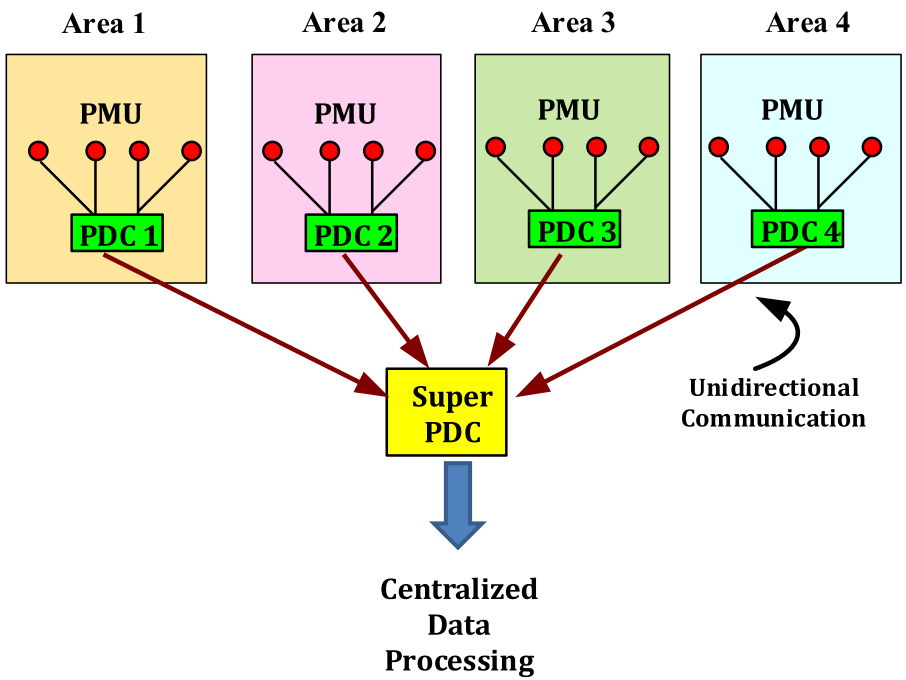
Examples: Wide-area protection, cascading failure control, wide-area AGC

Transmission System Control Room



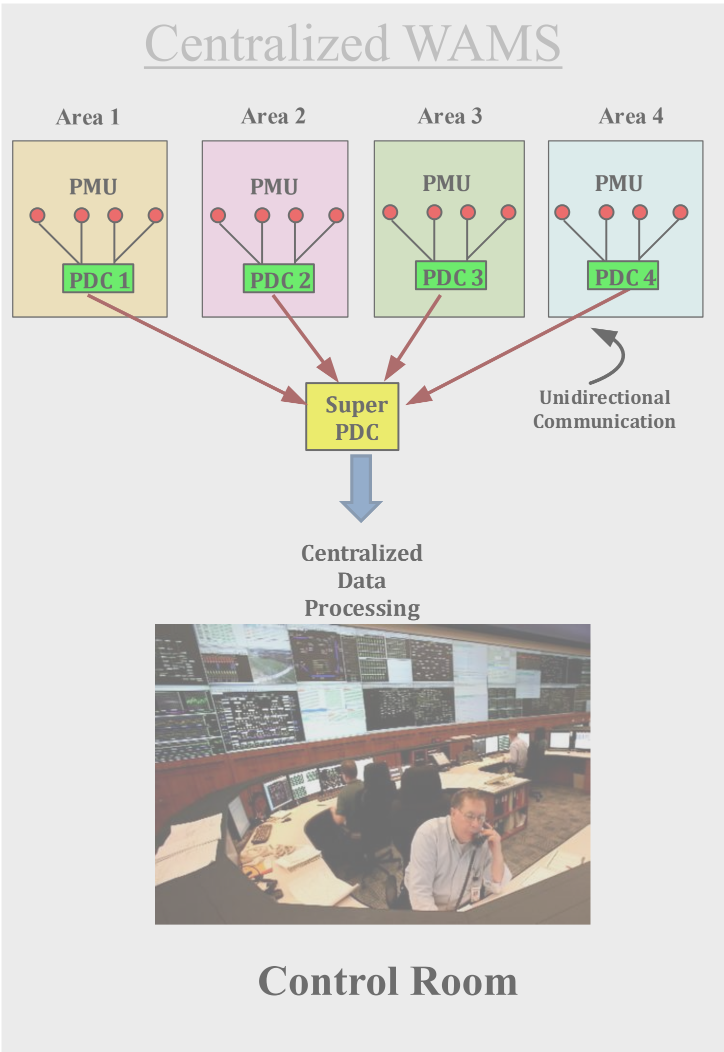
Centralized vs Distributed Architectures

Centralized WAMS

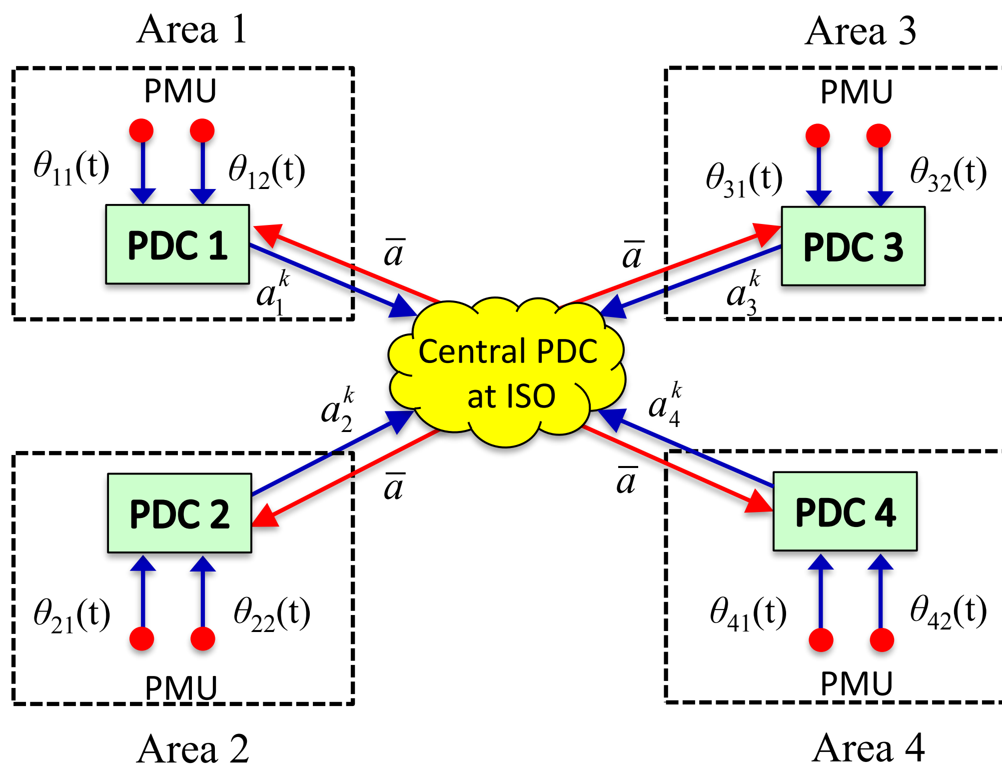


Control Room

Centralized vs Distributed Algorithms

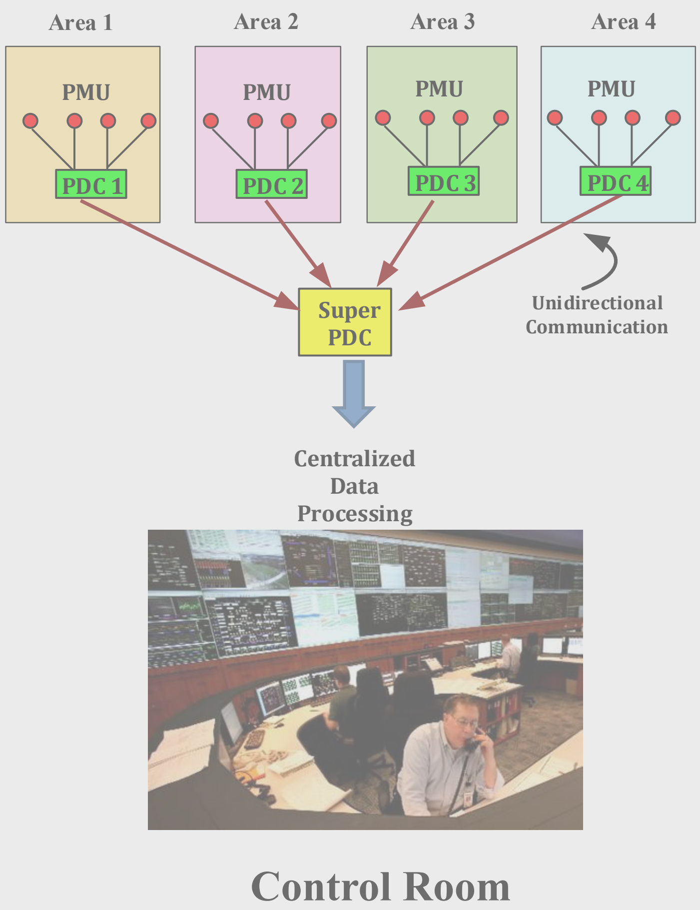


Semi-Distributed WAMS

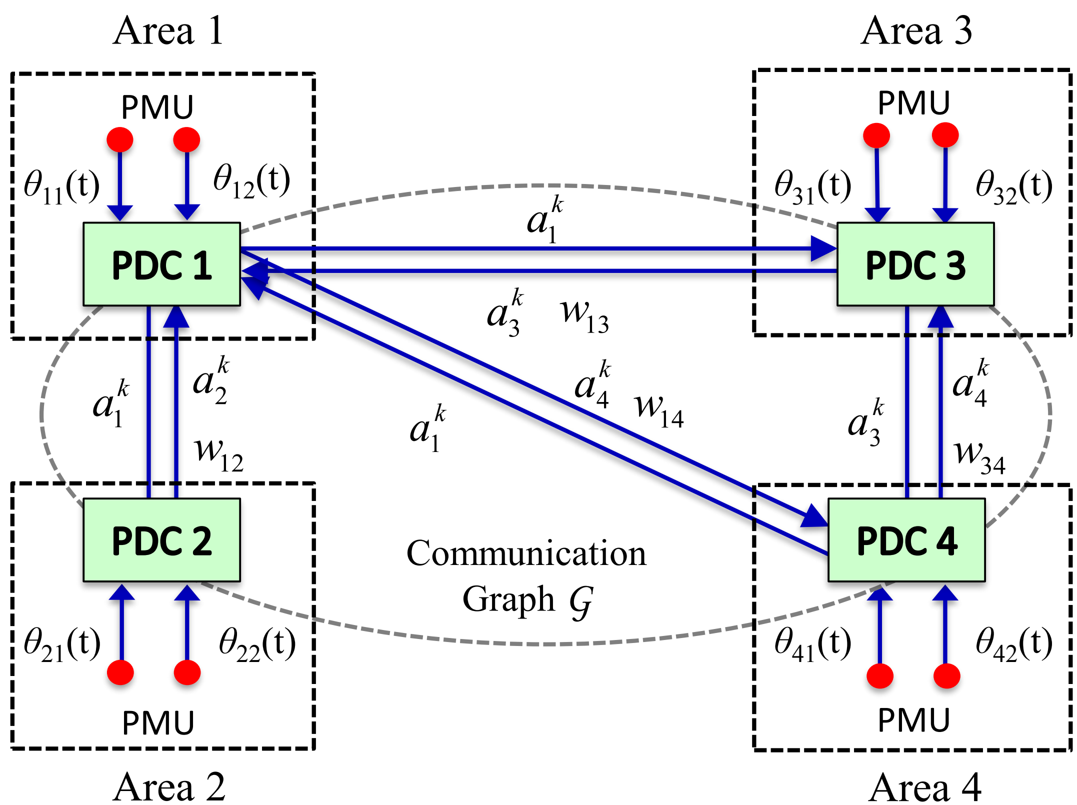


Centralized vs Distributed Algorithms

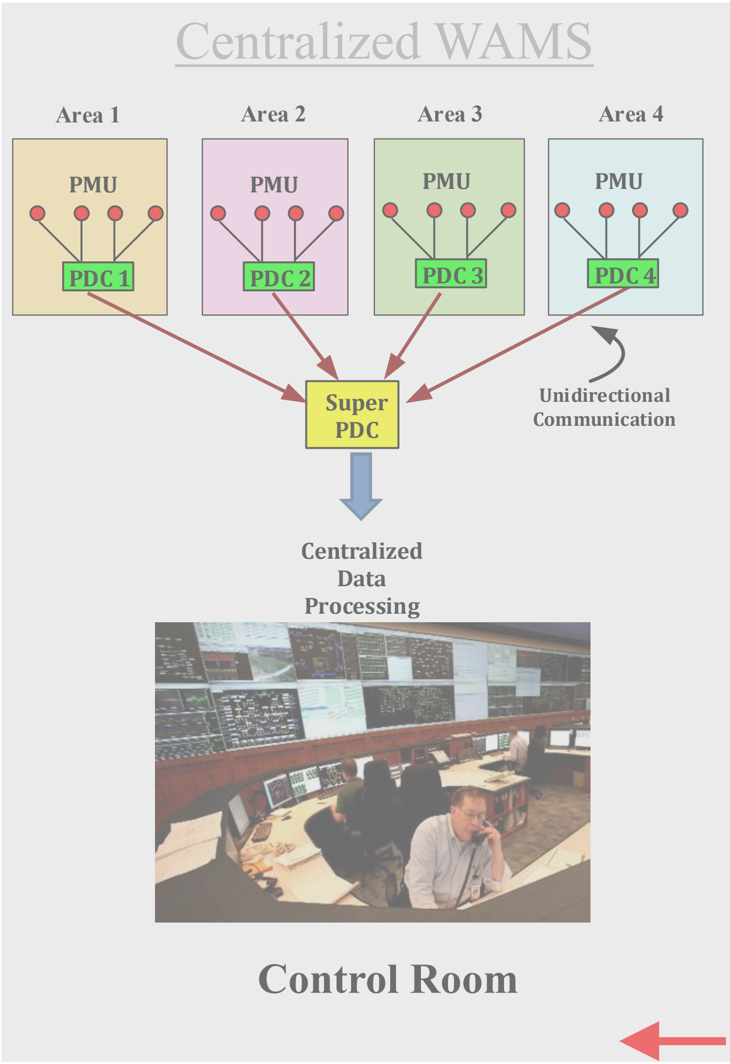
Centralized WAMS



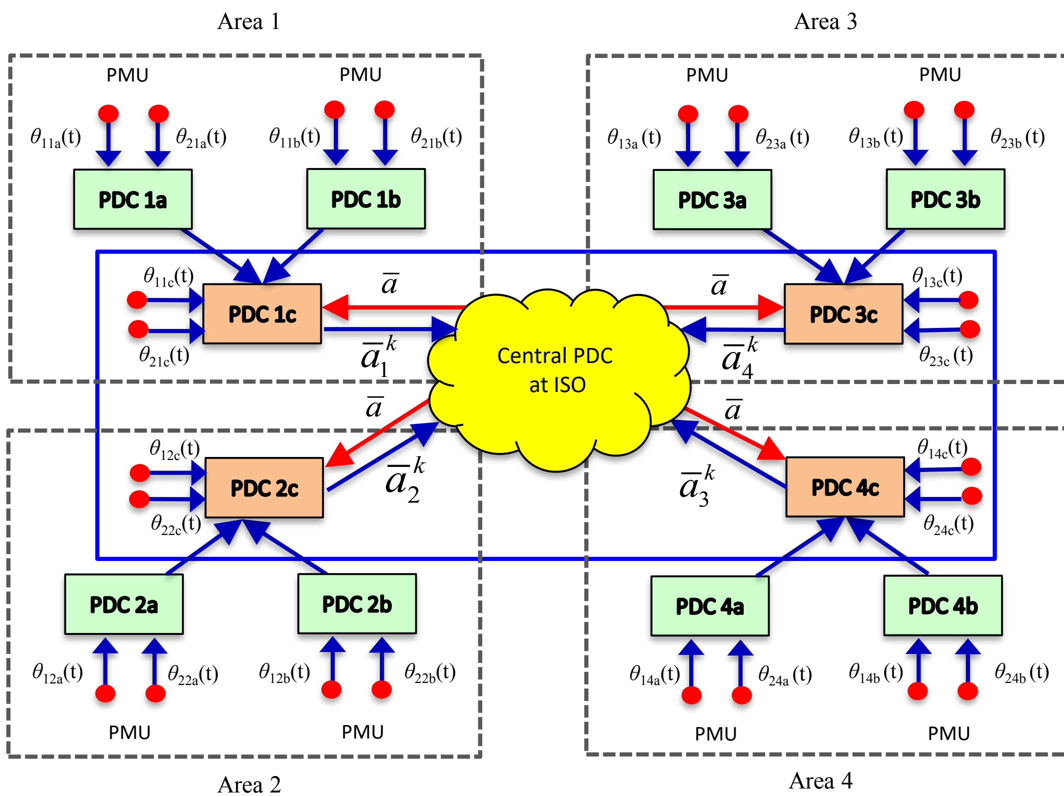
Distributed WAMS



Centralized vs Distributed Algorithms



Heirarchically Distributed

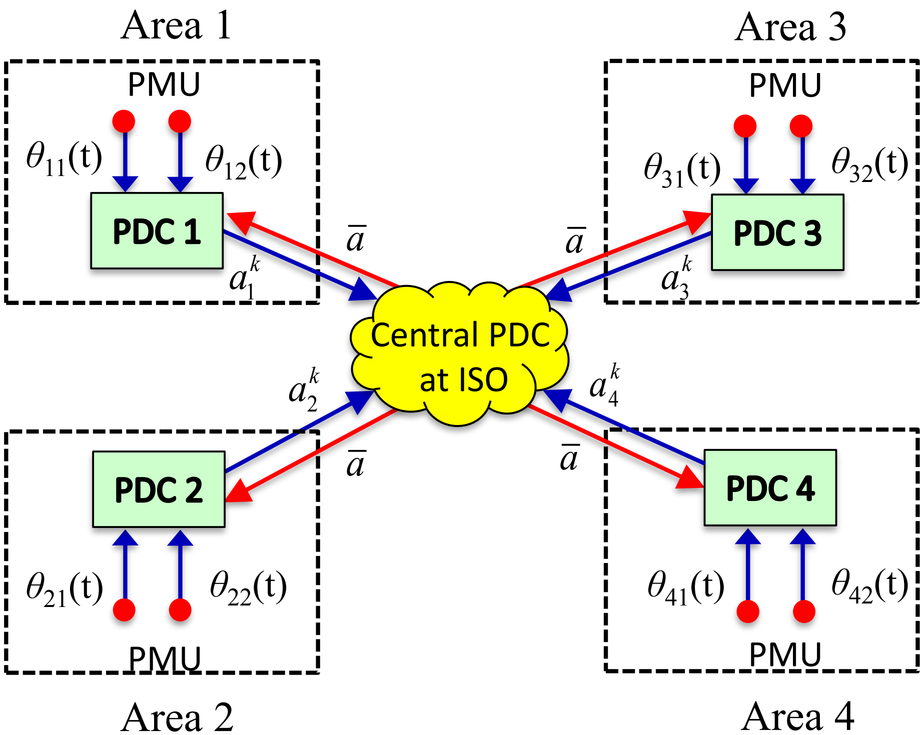


Specific application of interest for this talk:

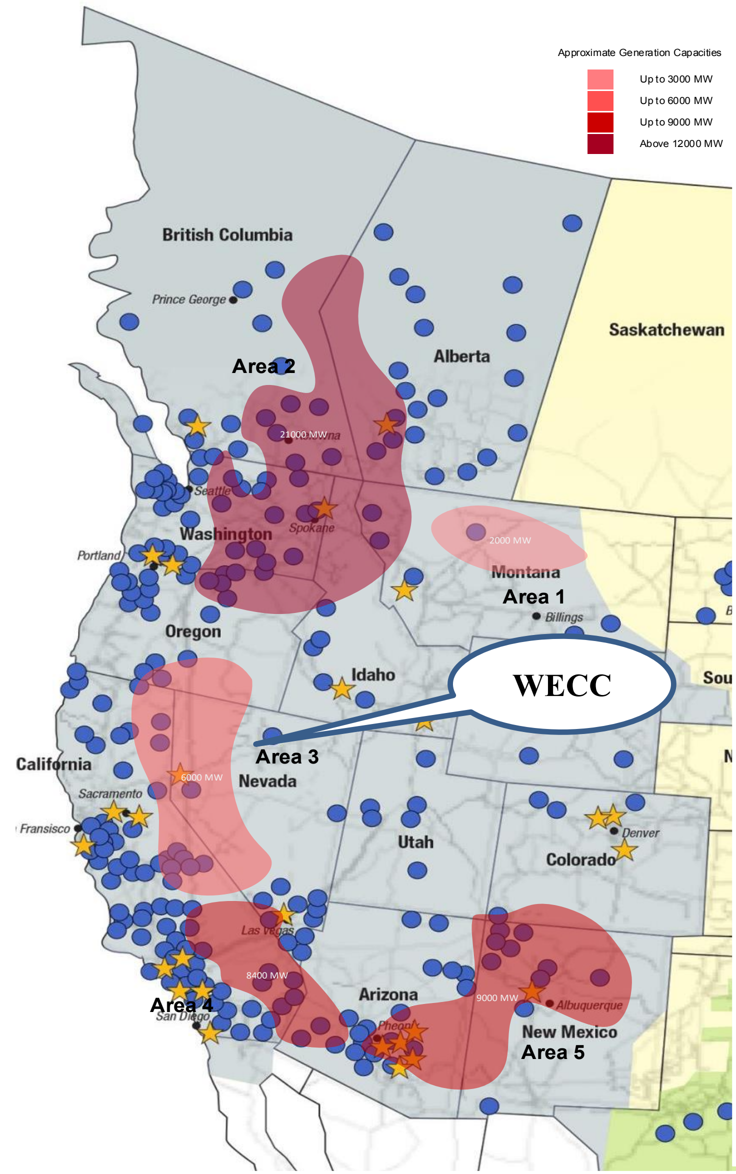
Wide-area oscillation monitoring

Semi-Distributed Architecture

Semi-Distributed WAMS

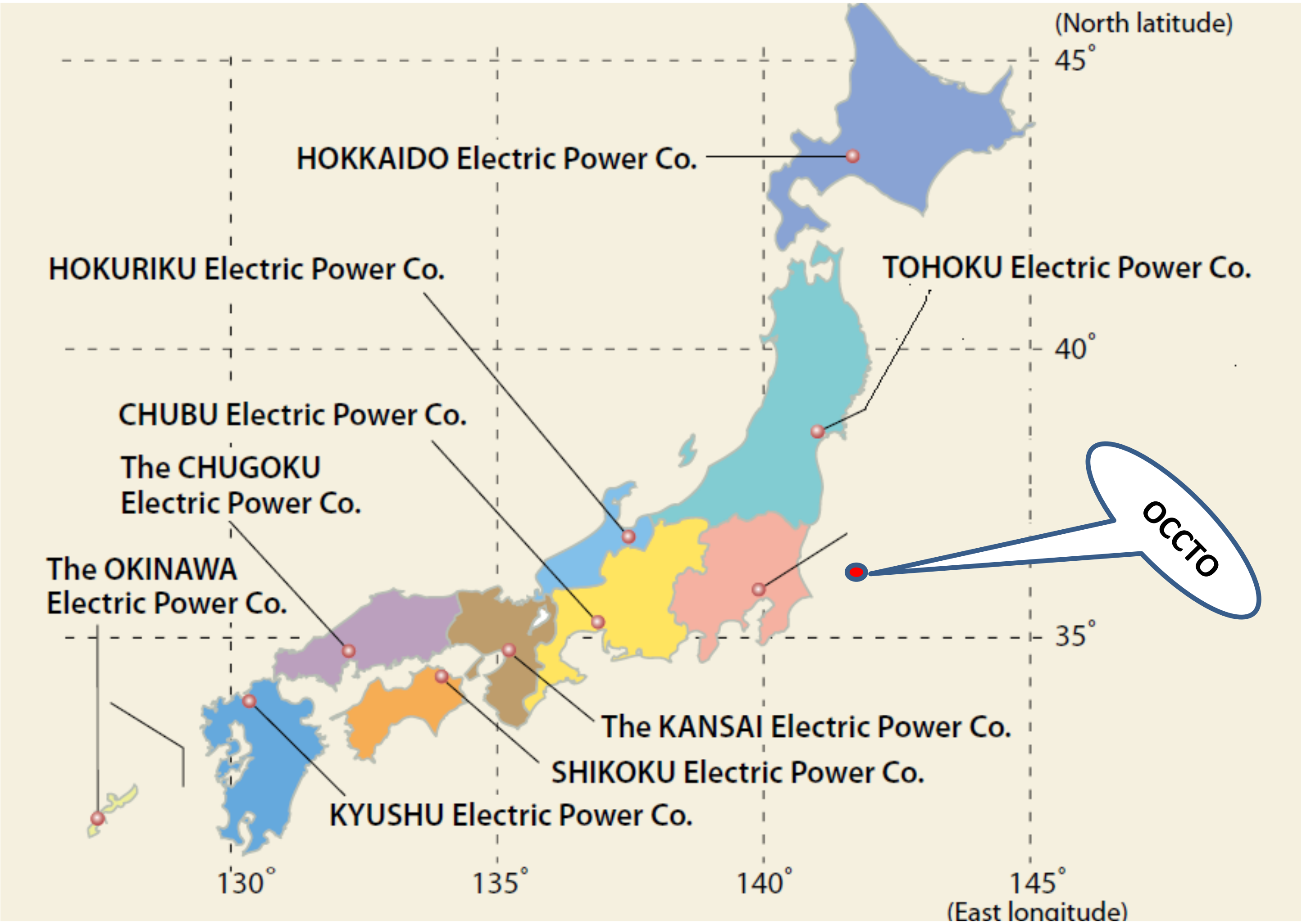


Example: US west coast

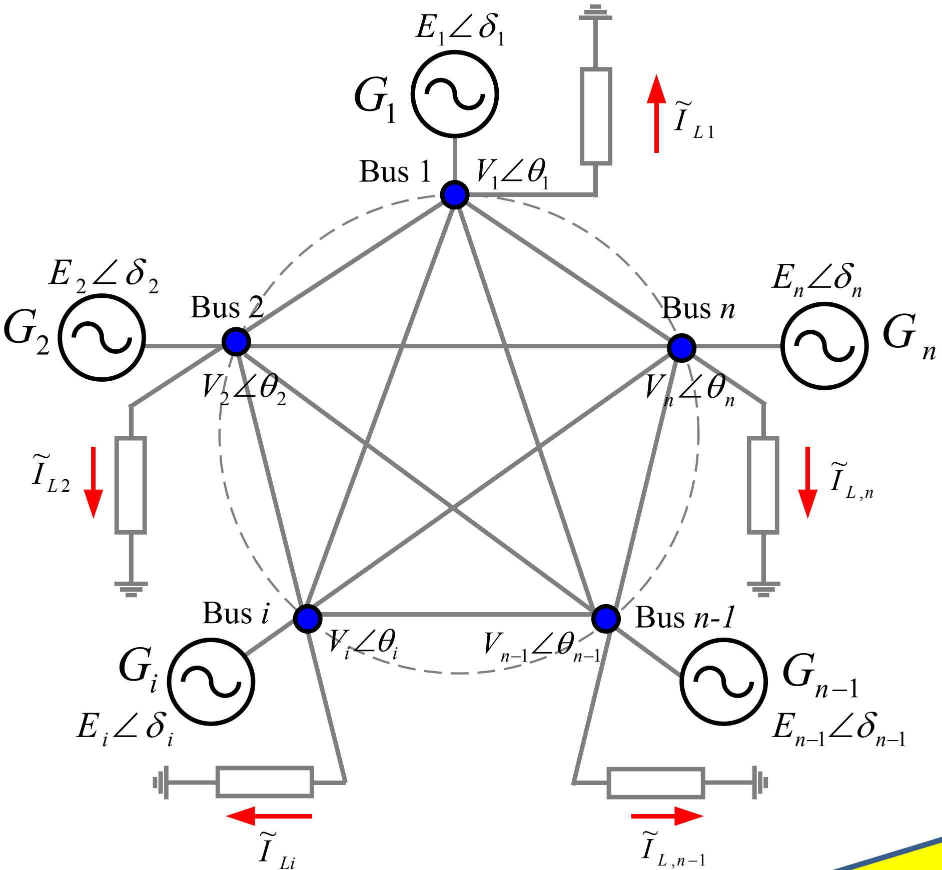


Semi-Distributed Architecture

Example: Japanese power grid



Power System Model



Measured variables from PMUs

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

Voltages, currents, and phase angles at different points in the grid

Recall Differential Equations from Calculus!

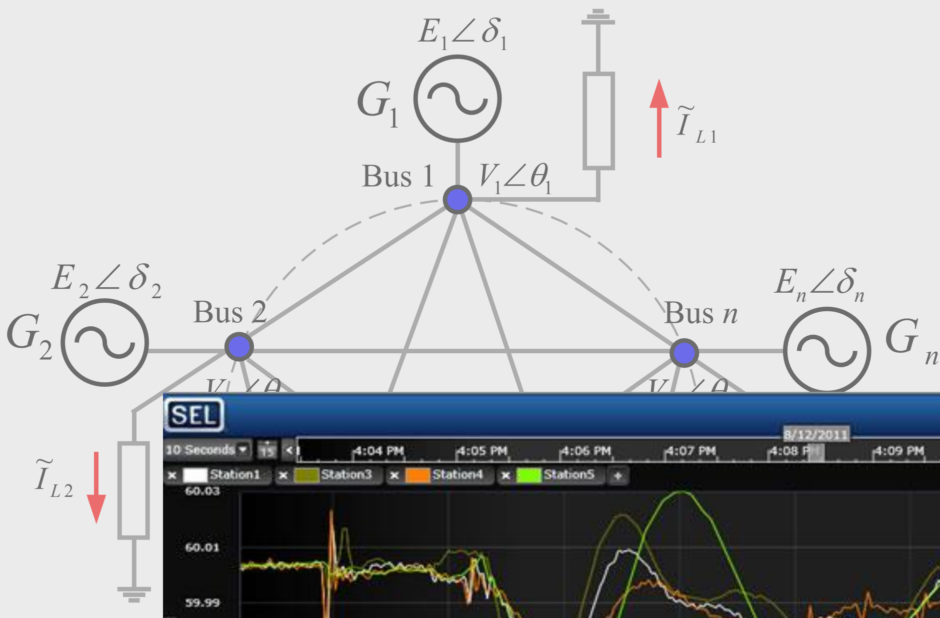
Swing equation model:

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

L(G) = fully connected network graph

Controllable inputs

Wide-Area Oscillation Estimation



Output Equation

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

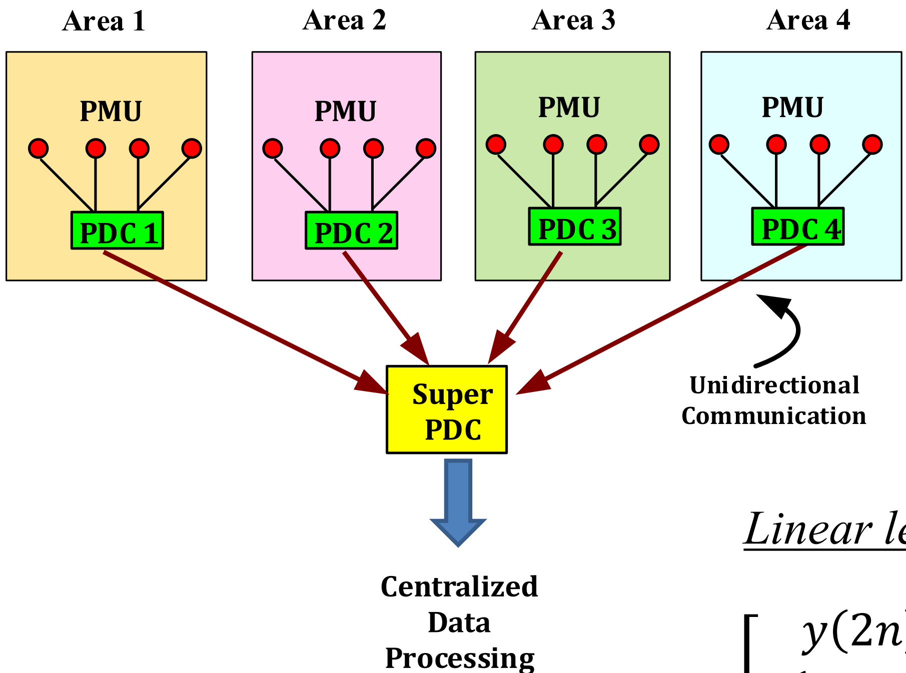
Swing e

$L(G)$ = fully connected network graph

due to load

Wide-Area Oscillation Estimation

Centralized:



- After the fault, wait for a few number of samples for the zero dynamics to die down
- Construct current output vector c, matrix of past samples H

Linear least squares problem:

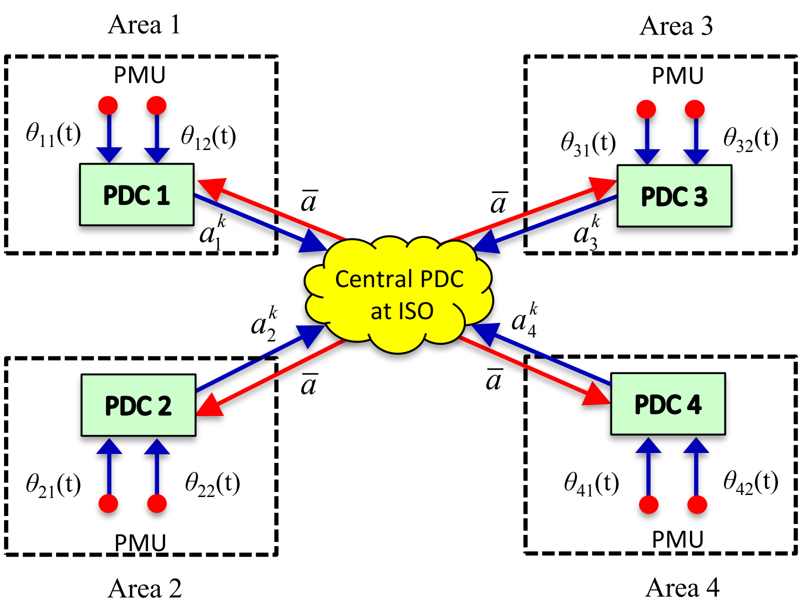
vectors of measurements from all areas

$$\underbrace{\begin{bmatrix} y(2n) \\ y(2n+1) \\ \vdots \\ y(2n+l) \end{bmatrix}}_{c} = \underbrace{\begin{bmatrix} y(2n-1) & \cdots & y(0) \\ \vdots & \ddots & \vdots \\ y(2n-1+l) & \cdots & y(l) \end{bmatrix}}_{H} \underbrace{\begin{bmatrix} -a_1 \\ -a_2 \\ \vdots \\ -a_n \end{bmatrix}}_{a}$$

$$\hat{a} = \arg\min_{a} \|Ha - c\|^2$$

Wide-Area Oscillation Estimation

Distributed:



Multiple Computational Areas

$$\text{Area 1}: \hat{\theta}_1 = \{\theta_{30}, \theta_{66}\} \rightarrow (\hat{H}_1 = \begin{bmatrix} H_{30} \\ H_{66} \end{bmatrix}, \hat{\mathbf{c}}_1 = \begin{bmatrix} \mathbf{c}_{30} \\ \mathbf{c}_{66} \end{bmatrix})$$

$$\text{Area 2}: \hat{\theta}_2 = \{\theta_{16}, \theta_{53}\} \rightarrow (\hat{H}_1 = \begin{bmatrix} H_{16} \\ H_{53} \end{bmatrix}, \hat{\mathbf{c}}_1 = \begin{bmatrix} \mathbf{c}_{16} \\ \mathbf{c}_{53} \end{bmatrix})$$

$$\text{Area 3}: \hat{\theta}_3 = \{\theta_{68}\} \rightarrow (\hat{H}_3 = H_{68}, \hat{\mathbf{c}}_3 = \mathbf{c}_{68})$$

$$\text{Area 4}: \hat{\theta}_4 = \{\theta_{56}\} \rightarrow (\hat{H}_4 = H_{56}, \hat{\mathbf{c}}_4 = \mathbf{c}_{56})$$

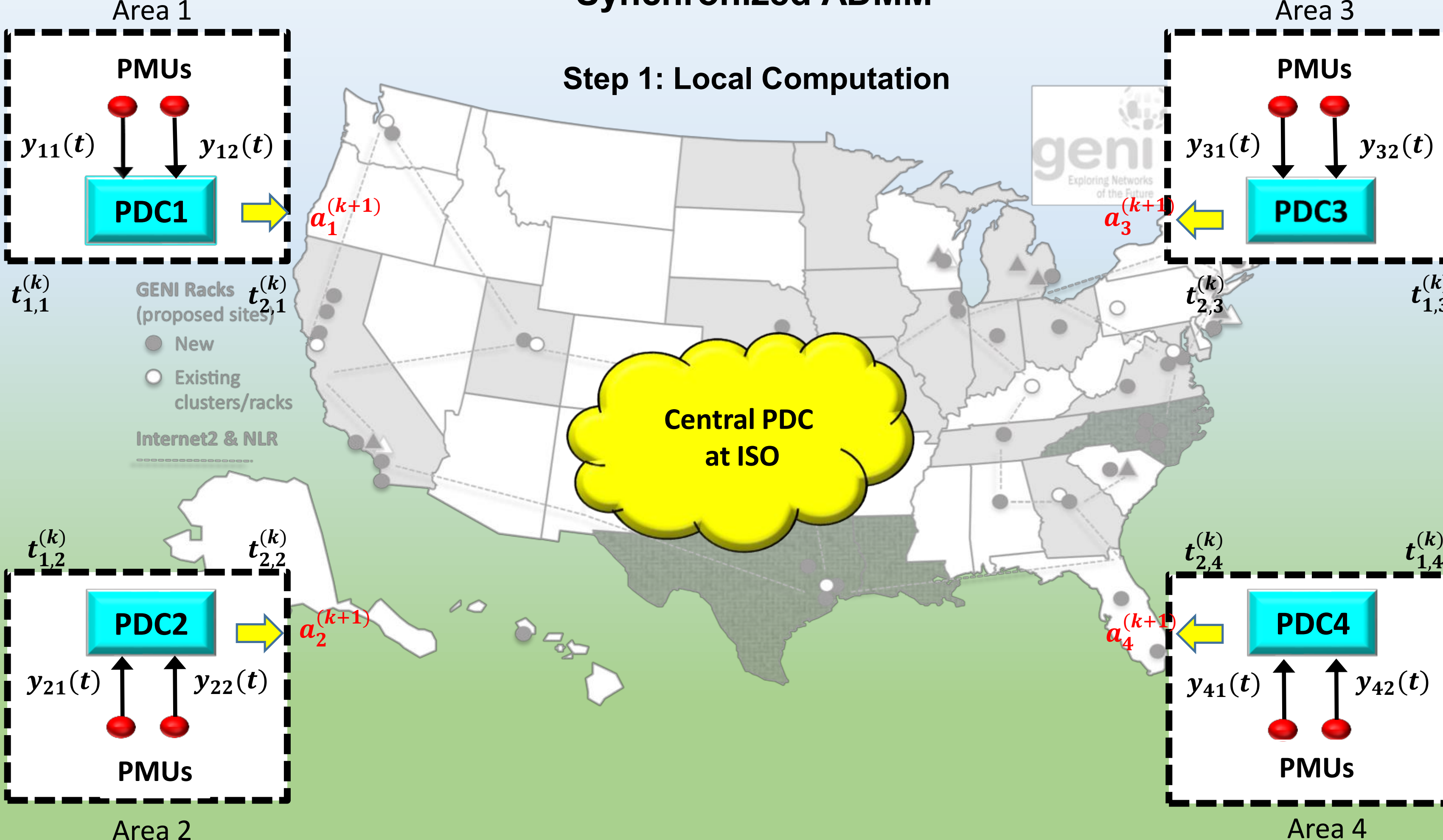
Global Consensus Problem:

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

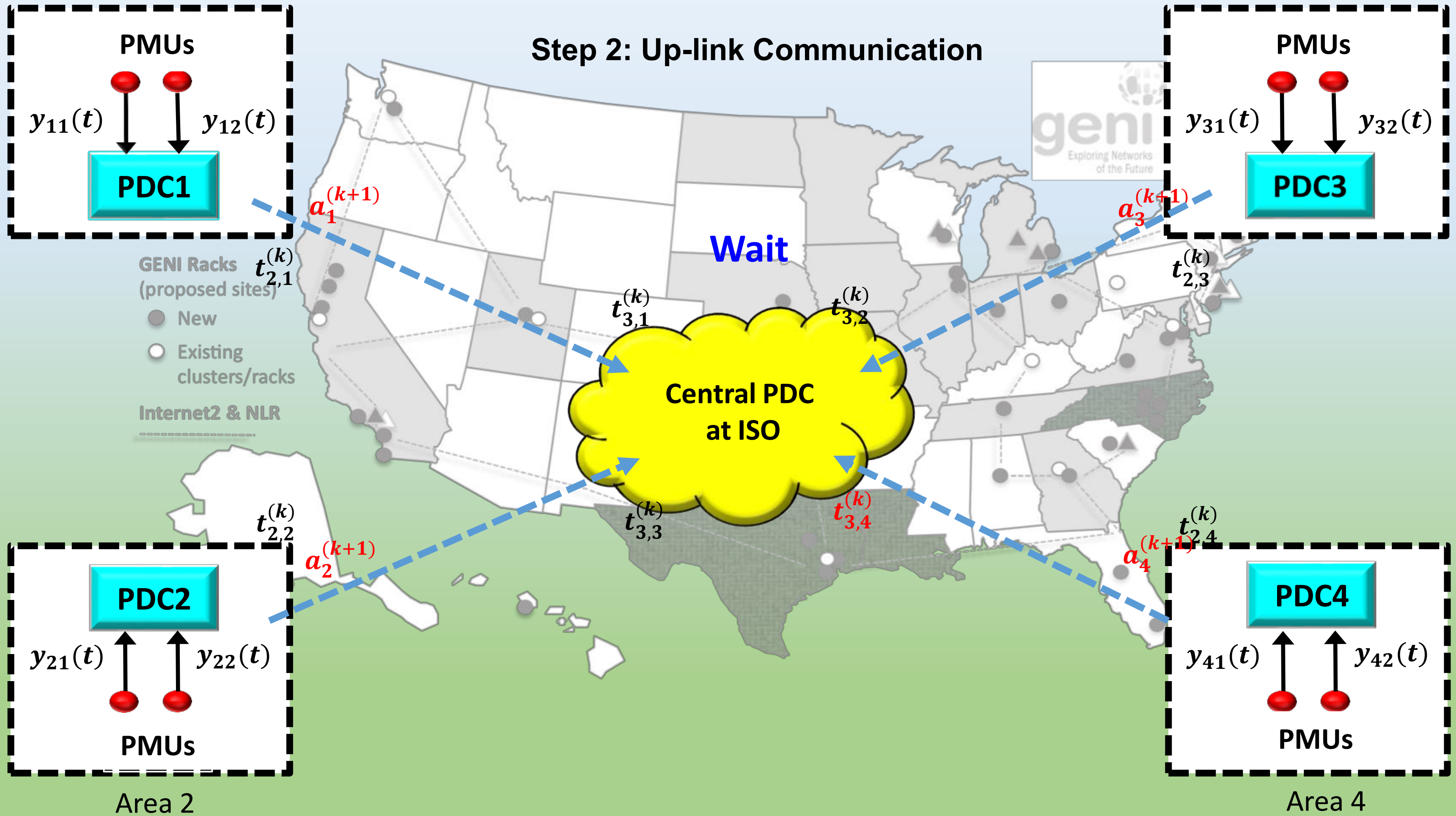
$$\text{subject to } \mathbf{a}_i - \mathbf{z} = 0, \text{ for } i = 1, \ldots, N$$

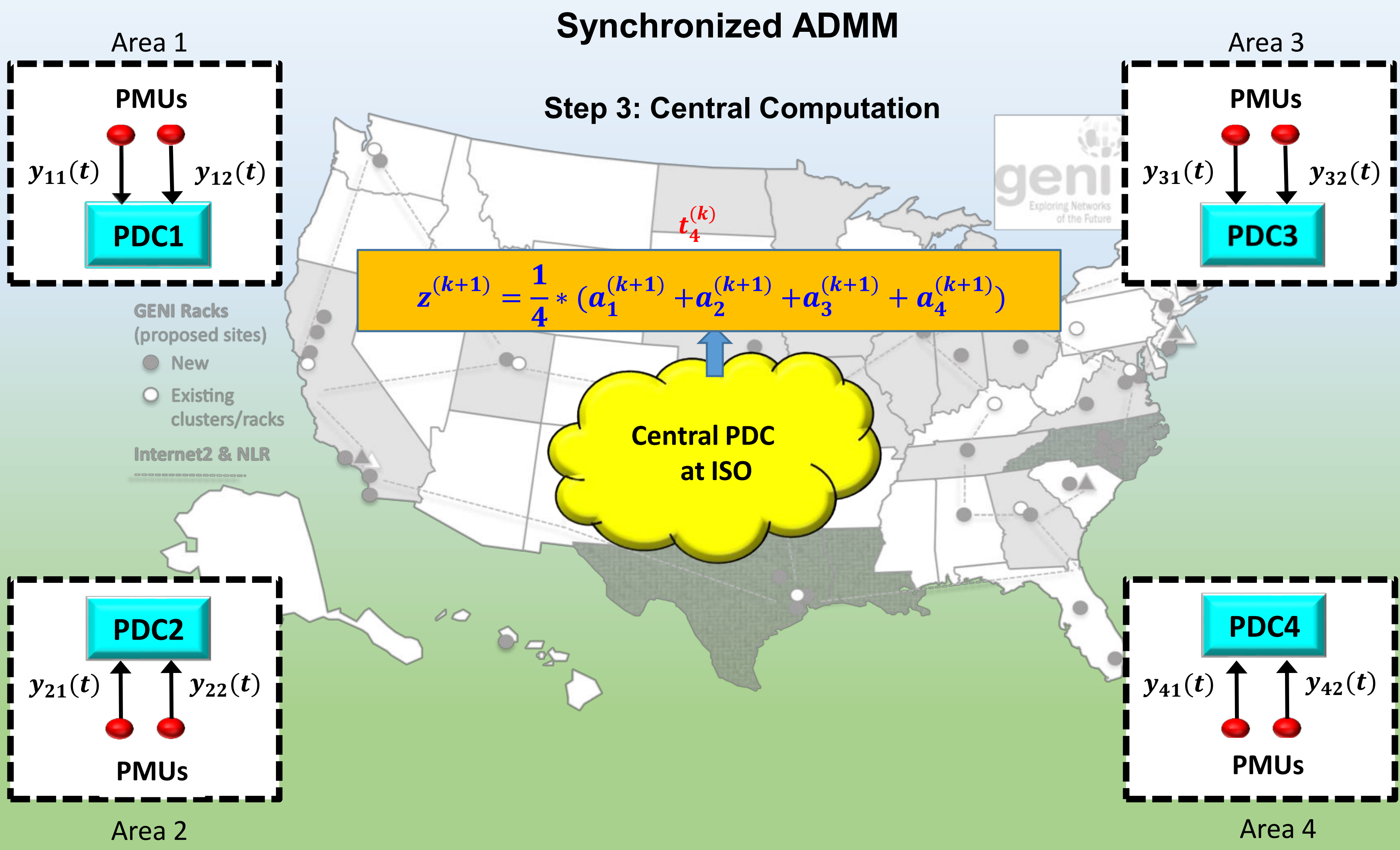
Solve the above optimization problem in a distributed way

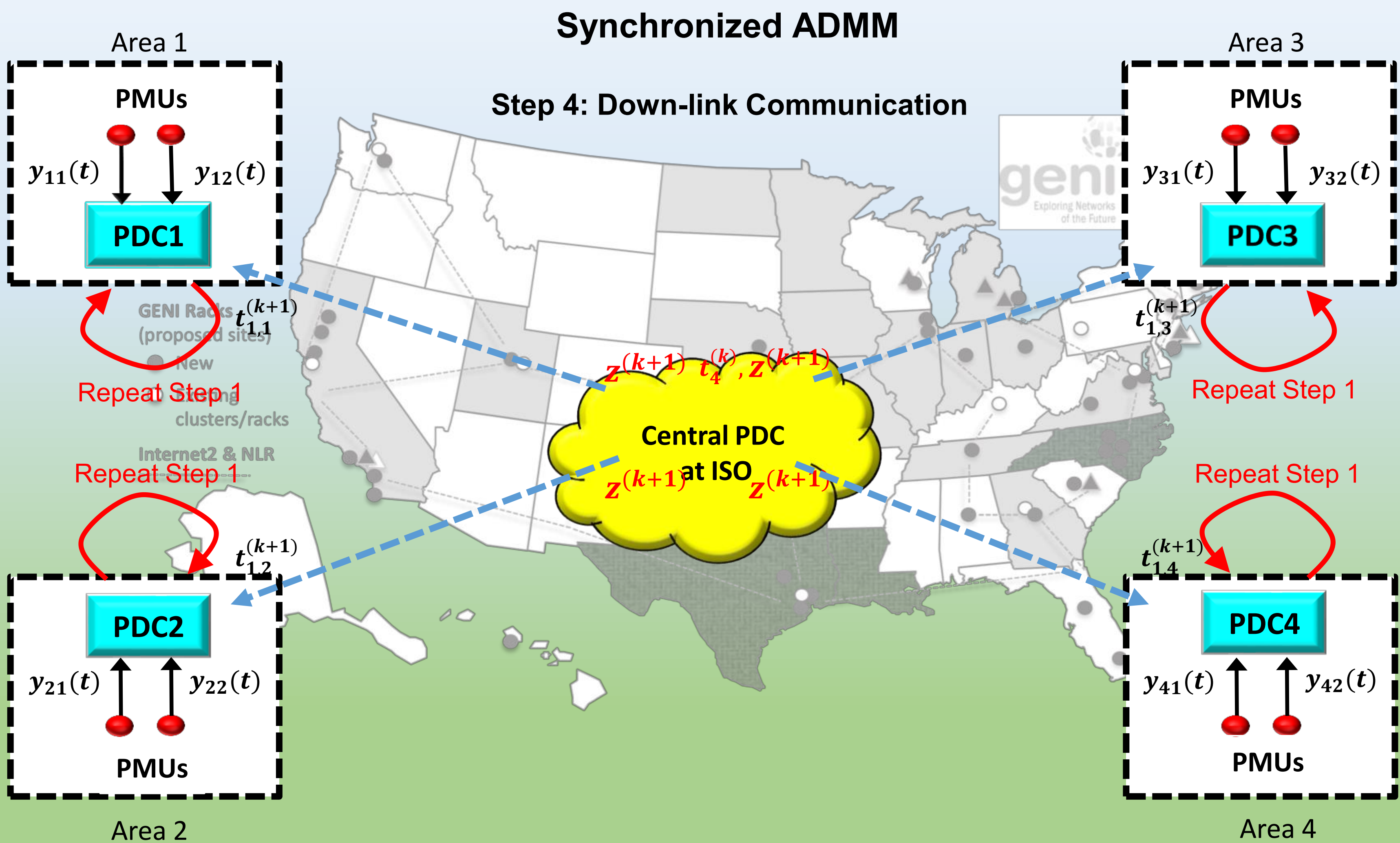
Synchronized ADMM



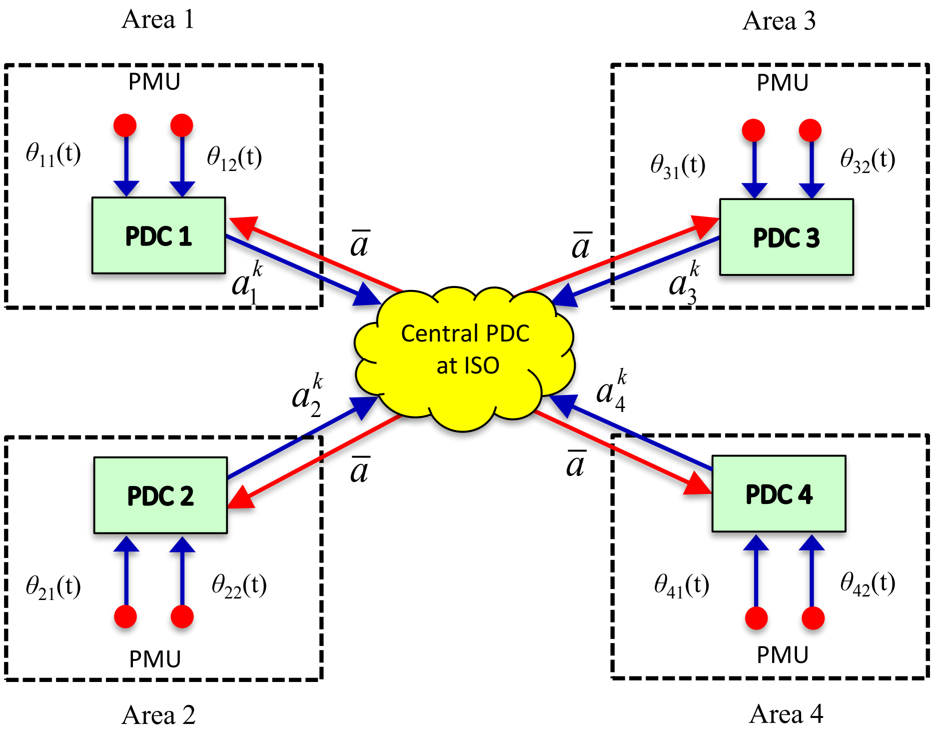
Synchronized ADMM




Synchronized ADMM
Step 3: Central Computation
Area 1
PMUs
$y_{11}(t)$
$y_{12}(t)$
PDC1
Area 3
PMUs
$y_{31}(t)$
$y_{32}(t)$
PDC3
$t_4^{(k)}$
$z^{(k+1)} = \frac{1}{4} * (a_1^{(k+1)} + a_2^{(k+1)} + a_3^{(k+1)} + a_4^{(k+1)})$
Central PDC at ISO
GENI Racks (proposed sites)
New
Existing clusters/racks
Internet2 & NLR
geni
Exploring Networks of the Future
PDC2
$y_{21}(t)$
$y_{22}(t)$
PMUs
Area 2
PDC4
$y_{41}(t)$
$y_{42}(t)$
PMUs
Area 4


Synchronized ADMM
Step 4: Down-link Communication
Area 1
PMUs
$y_{11}(t)$
$y_{12}(t)$
PDC1
Repeat Step 1
$t_{1,1}^{(k+1)}$
Area 3
PMUs
$y_{31}(t)$
$y_{32}(t)$
PDC3
Repeat Step 1
$t_{1,3}^{(k+1)}$
Central PDC at ISO
$z^{(k+1)}$ $t_4^{(k)}, z^{(k+1)}$
$z^{(k+1)}$ $z^{(k+1)}$
Area 2
PDC2
$y_{21}(t)$
$y_{22}(t)$
PMUs
Repeat Step 1
$t_{1,2}^{(k+1)}$
Area 4
PDC4
$y_{41}(t)$
$y_{42}(t)$
PMUs
Repeat Step 1
$t_{1,4}^{(k+1)}$
GENI Racks (proposed sites)
New
Existing clusters/racks
Internet2 & NLR
geni
Exploring Networks of the Future

Cyber-Physical Coupling:
Incorporating Asynchronous Wide-Area Communication



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

- **Strategy 1:**

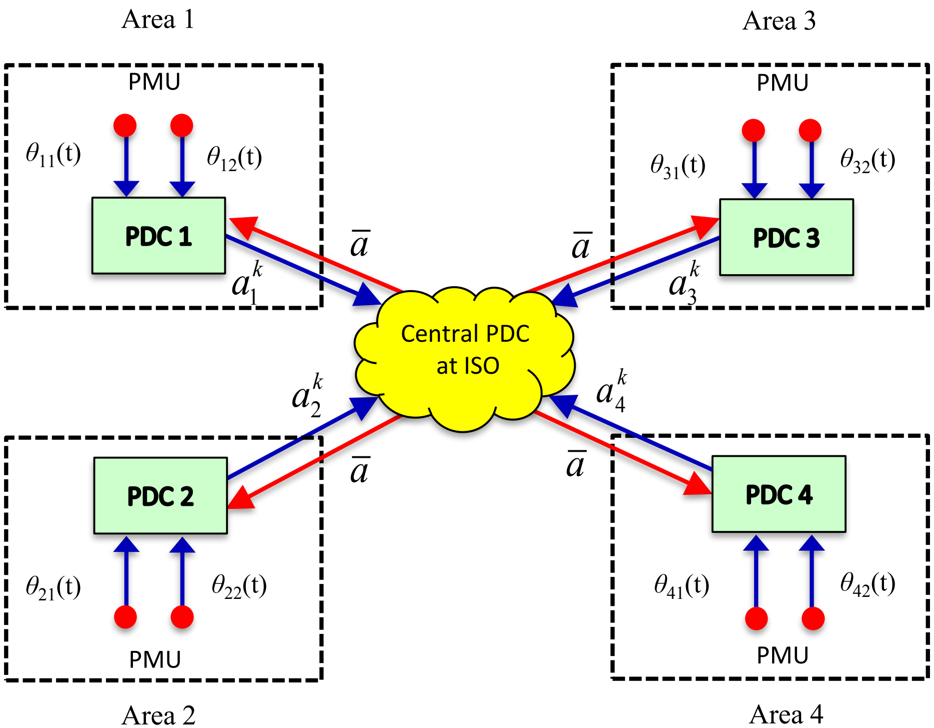
$$z^{(k+1)} = \frac{1}{|S_1^{(k)}|} \sum_{i \in S_1^{(k)}}^{N} (a_i^{(k+1)} + \frac{1}{\rho} w_i^{(k)})$$

→ **Can easily lead to divergence**

Traffic Models for Internet Delays:

$$P(t) = \frac{1}{2}[\text{erf}(\frac{\mu}{\sqrt{2}\sigma}) + \text{erf}(\frac{t-\mu}{\sqrt{2}\sigma})] + \frac{(1-p)}{N} e^{(\frac{1}{2}\lambda^2\sigma^2 + \mu\lambda)} [\text{erf}(\frac{\lambda\sigma^2 + \mu}{\sqrt{2}\sigma}) + \text{erf}(\frac{t - \lambda\sigma^2 - \mu}{\sqrt{2}\sigma})]$$

Cyber-Physical Coupling:
Incorporating Asynchronous Wide-Area Communication



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

- **Strategy 2:**

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

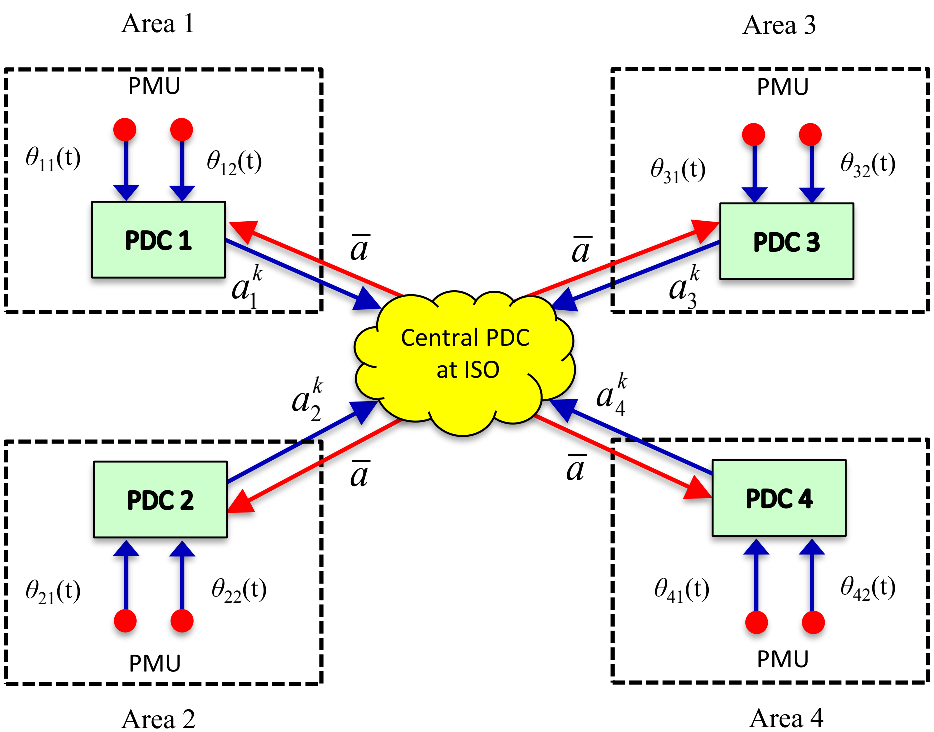
Substitute values from previous iteration

Convergent, but slow

Traffic Models for Internet Delays:

$$P(t) = \frac{1}{2}[\mathrm{erf}(\frac{\mu}{\sqrt{2}\sigma}) + \mathrm{erf}(\frac{t-\mu}{\sqrt{2}\sigma})] + \frac{(1-p)}{N}e^{(\frac{1}{2}\lambda^2\sigma^2+\mu\lambda)}[\mathrm{erf}(\frac{\lambda\sigma^2+\mu}{\sqrt{2}\sigma}) + \mathrm{erf}(\frac{t-\lambda\sigma^2-\mu}{\sqrt{2}\sigma})]$$

Cyber-Physical Coupling:
Incorporating Asynchronous Wide-Area Communication



- **Strategy 3: Keep a correlation log at central PDC**

$$C_k = \begin{bmatrix} \xi(a_1{}^k, a_1{}^k) & \xi(a_1{}^k, a_2{}^k) & \xi(a_1{}^k, a_3{}^k) & \xi(a_1{}^k, a_4{}^k) \\ \xi(a_2{}^k, a_1{}^k) & \xi(a_2{}^k, a_2{}^k) & \xi(a_2{}^k, a_3{}^k) & \xi(a_2{}^k, a_4{}^k) \\ \xi(a_3{}^k, a_1{}^k) & \xi(a_3{}^k, a_2{}^k) & \xi(a_3{}^k, a_3{}^k) & \xi(a_3{}^k, a_4{}^k) \\ \xi(a_4{}^k, a_1{}^k) & \xi(a_4{}^k, a_2{}^k) & \xi(a_4{}^k, a_3{}^k) & \xi(a_4{}^k, a_4{}^k) \end{bmatrix}$$

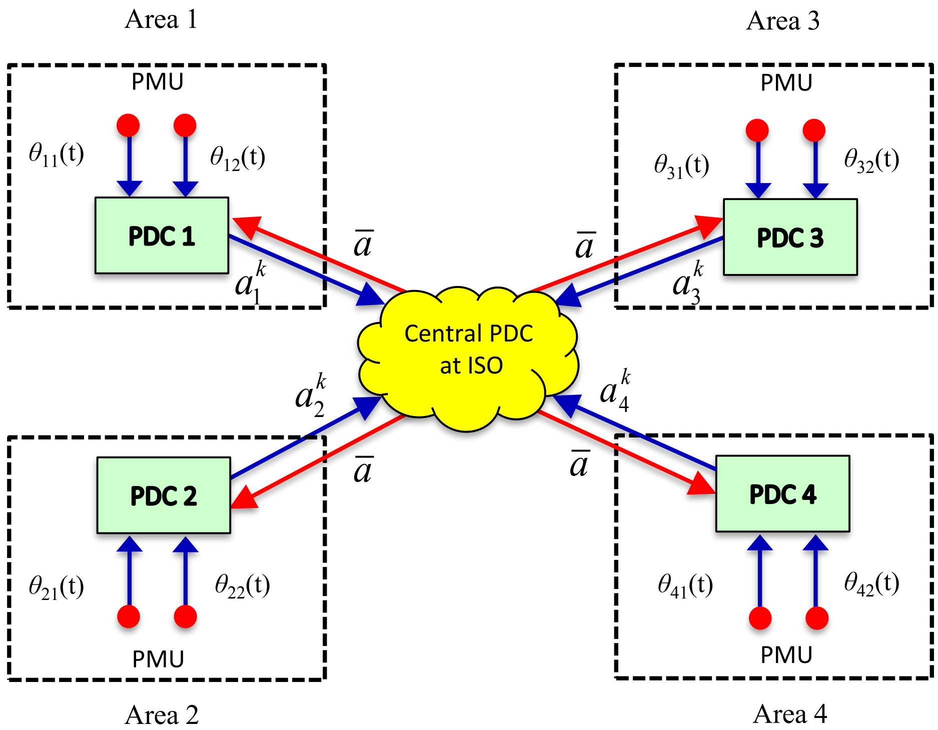
$$z^{(k+1)} = \frac{1}{N}\Big(\sum_{i\in S^{(k)}}^{N} (a_i{}^{(k+1)} + \frac{1}{\rho} w_i{}^{(k)}) + \sum_{i\notin S^{(k)}}^{N} (a_j{}^{(k)} + \frac{1}{\rho} w_i{}^{(k-1)})\Big)$$

Substitute value of iterate with highest correlation from from previous iteration

Traffic Models for Internet Delays:

$$P(t) = \frac{1}{2}[\text{erf}(\frac{\mu}{\sqrt{2}\sigma}) + \text{erf}(\frac{t-\mu}{\sqrt{2}\sigma})] + \frac{(1-p)}{N} e^{(\frac{1}{2}\lambda^2\sigma^2 + \mu\lambda)} [\text{erf}(\frac{\lambda\sigma^2 + \mu}{\sqrt{2}\sigma}) + \text{erf}(\frac{t - \lambda\sigma^2 - \mu}{\sqrt{2}\sigma})]$$

Cyber-Physical Coupling:
Incorporating Asynchronous Wide-Area Communication



- **Open questions:**

1. Both waiting and not waiting for a delayed packet impacts overall convergence time

When to wait, and when not to wait?

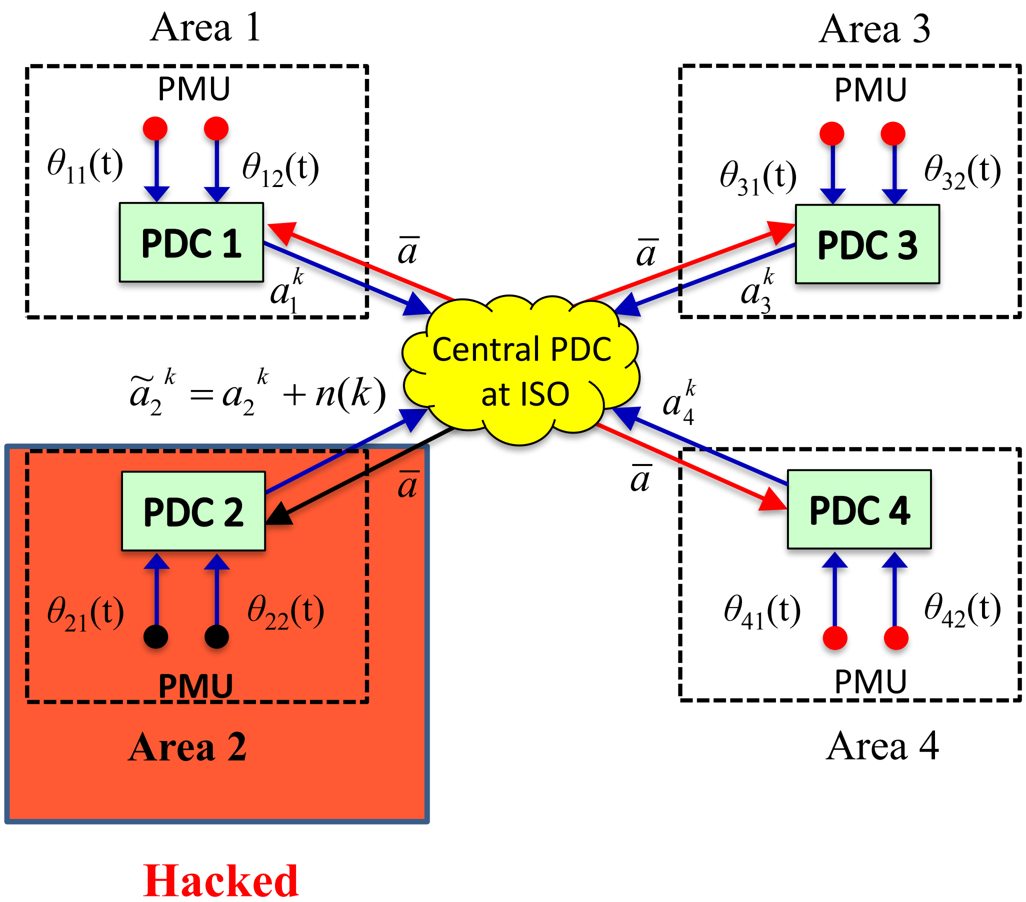
2. Co-designing the communication network using software-defined network (SDN) principles

Minimize delay in each link while other processes are running in the cloud (resource allocation problem)

Traffic Models for Internet Delays:

$$P(t) = \frac{1}{2}[\mathrm{erf}(\frac{\mu}{\sqrt{2}\sigma}) + \mathrm{erf}(\frac{t-\mu}{\sqrt{2}\sigma})] + \frac{(1-p)}{N} e^{(\frac{1}{2}\lambda^2\sigma^2 + \mu\lambda)} [\mathrm{erf}(\frac{\lambda\sigma^2 + \mu}{\sqrt{2}\sigma}) + \mathrm{erf}(\frac{t - \lambda\sigma^2 - \mu}{\sqrt{2}\sigma})]$$

Detecting Malicious Data-Manipulators



- Correct values of

  $a_1^{\,k},\ a_3^{\,k},\ a_4^{\,k}$

  are communicated to the ISO

- But incorrect value of $a_2^{\,k}$

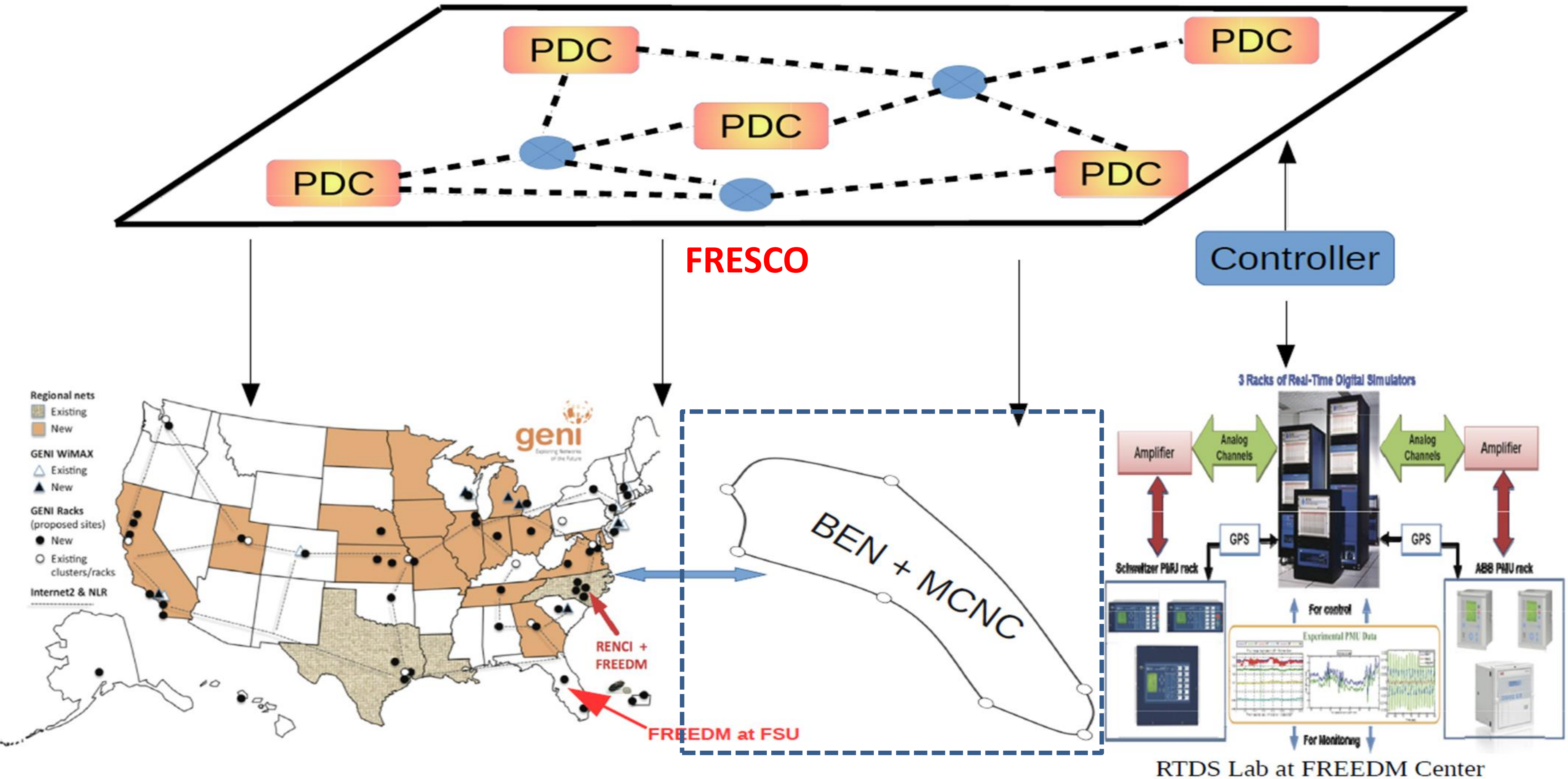
  $\tilde{a}_2^{\,k} = a_2^{\,k} + n(k)$

  is communicated, ISO does not know that this is incorrect

- Trajectories of the estimates will start diverging as the bias excites the consensus eigenvalue

M. Liao and A. Chakrabortty, IEEE TCST, ACC 2016, CDC 2016, ACC 2017.

ExoGENI-WAMS Testbed at NC State & RENCI/UNC Chapel Hill

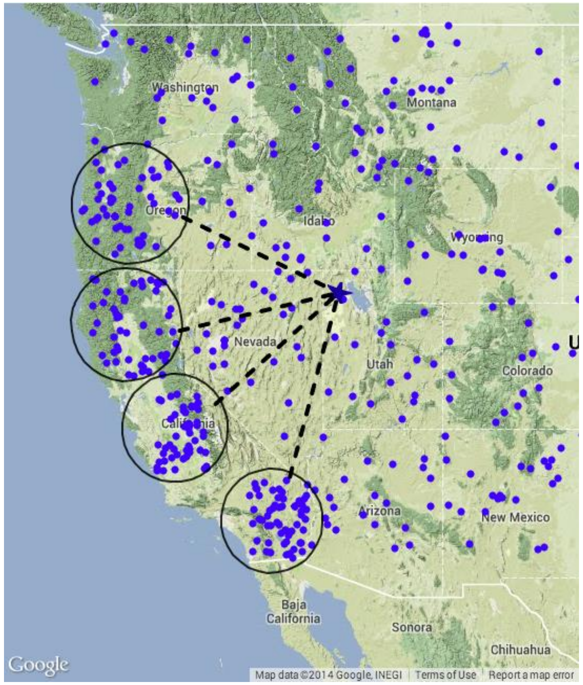


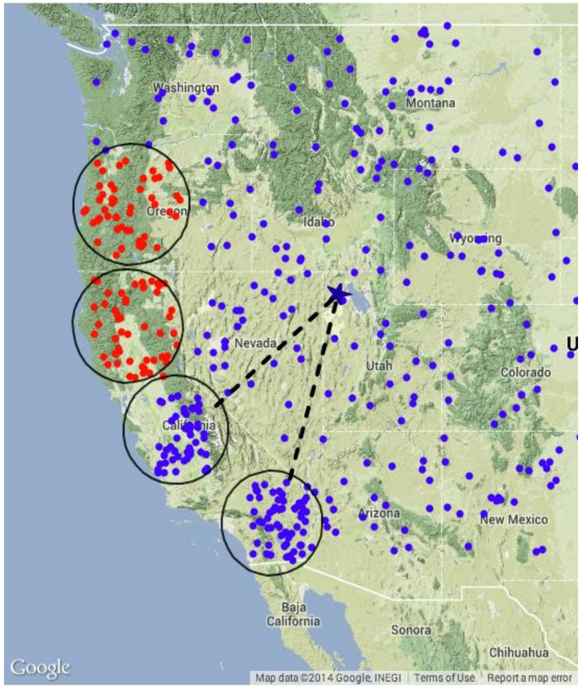
Middleware provided by Green Energy Corporation and RTI

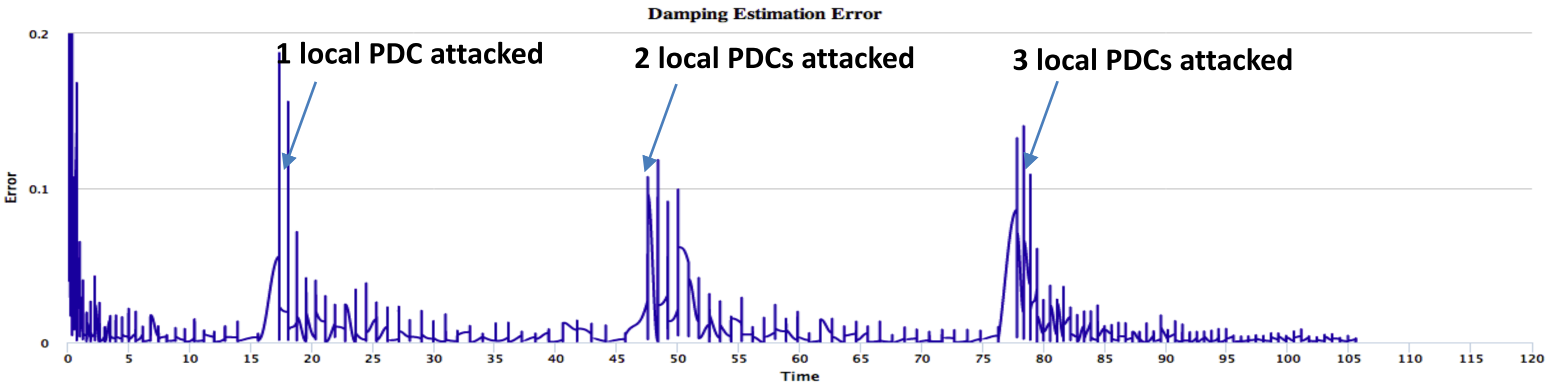
Experimental Validation on Federated Testbeds

Federated Testbeds: *RTDS Lab of NC State + DETER Lab of Univ. of South California*

Centralized Architecture

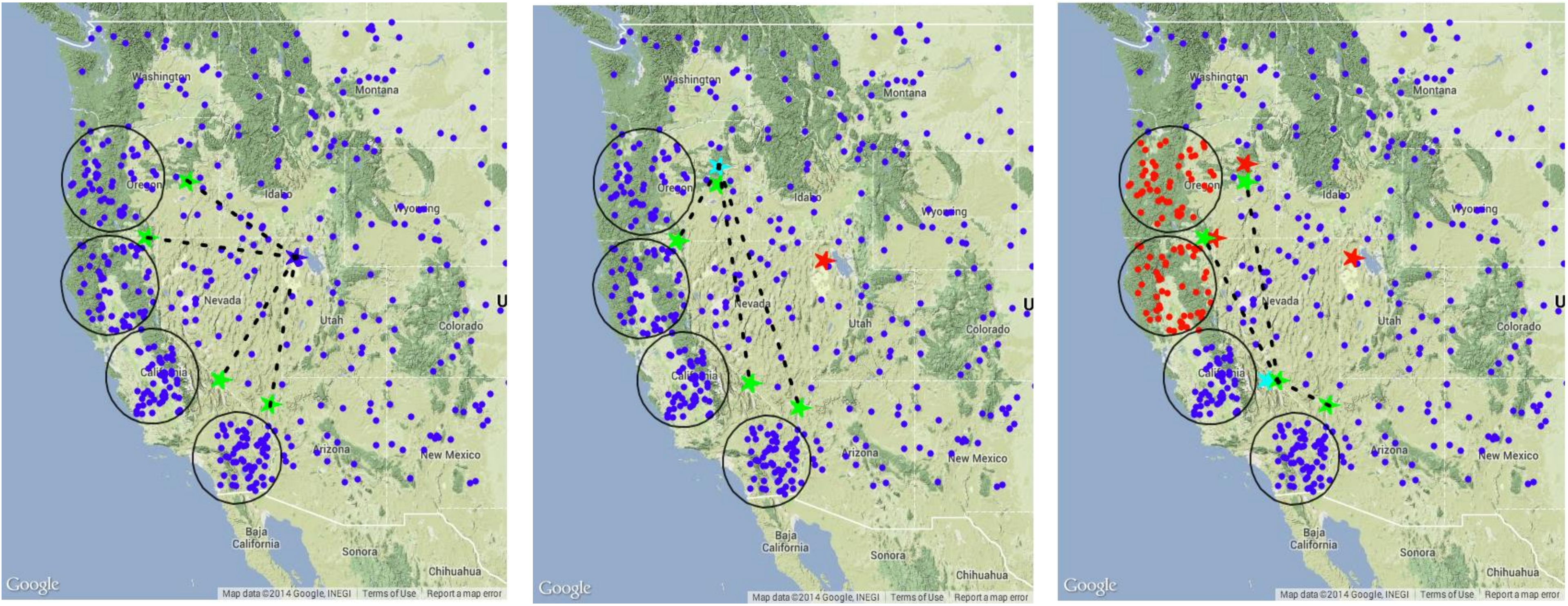


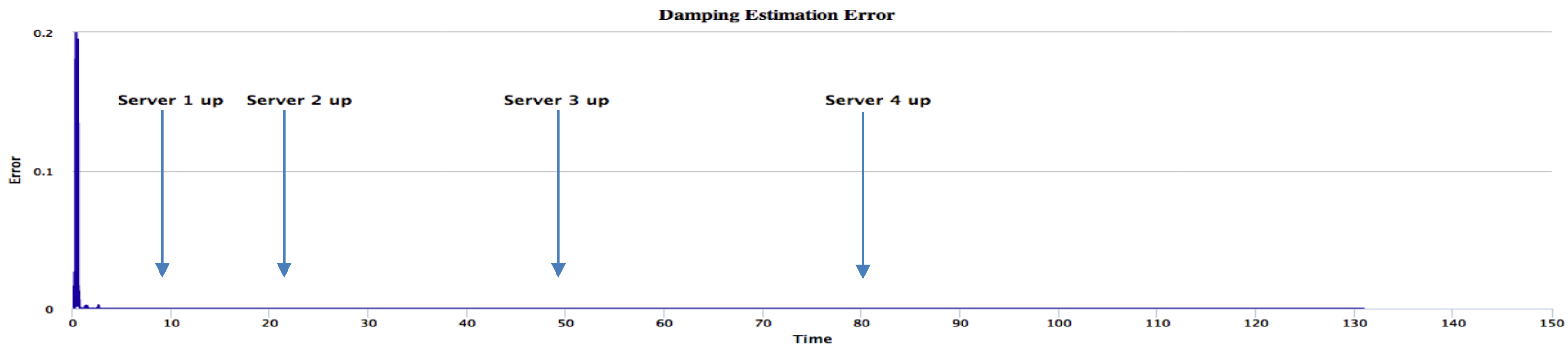




Experimental Validation on Federated Testbeds

Distributed Architecture

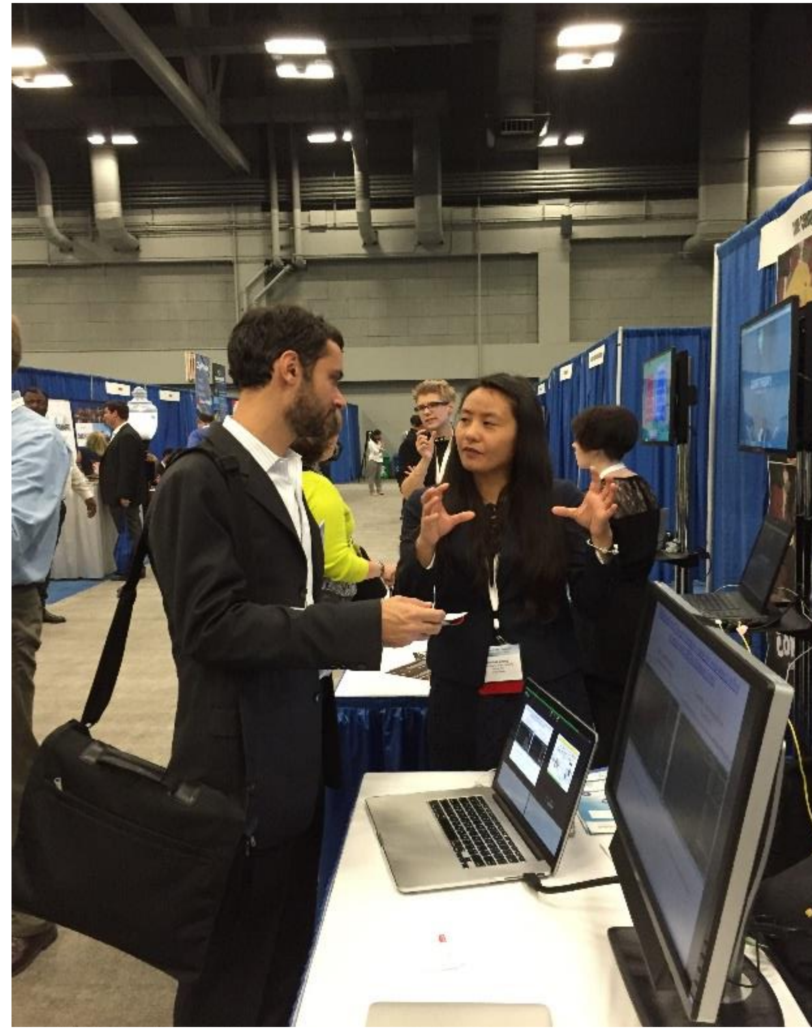




Project Demos:

DETER Demo at Smart-America 2014

Best Energy App Award at US Ignite 2015



US Ignite & NIST
Smart Cities Application
Summit, Austin, TX, 2016

ExoGENI-WAMS Testbed

Bring Concepts of Cloud Computing and Software Defined Networking into Research of Wide-Area Monitoring and Control with PMU data

- **Wide-Area Monitoring and Control is a typical cyber-physical system**

- **Problems of the physical subsystem**
  1. Accessing of real PMU measurements due to privacy and non-disclosure issues
  2. Not sufficient for studying dynamics of the entire system due to limited coverage

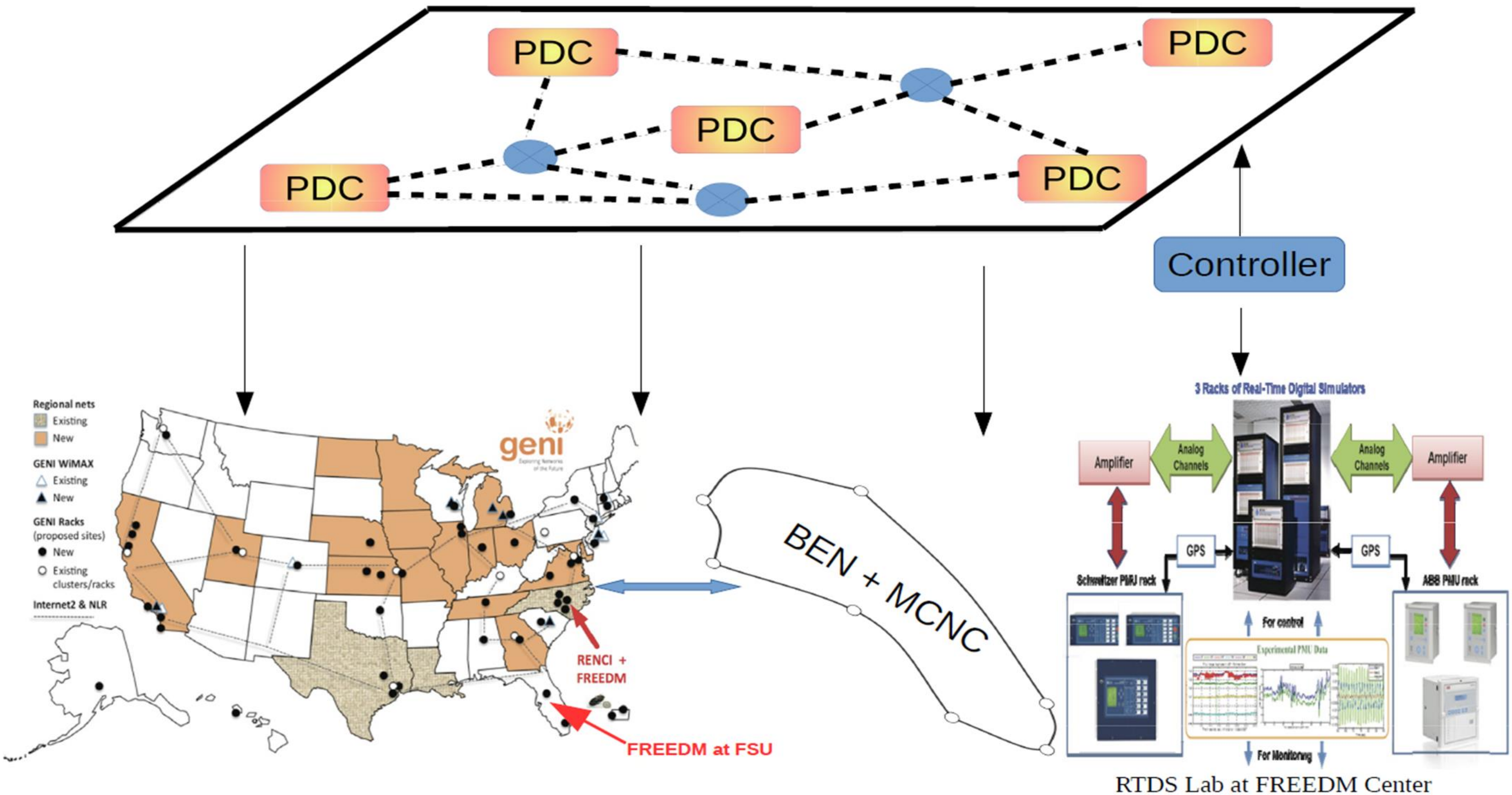
- **Requirements of the cyber subsystem**
  To utilize next-generation cyber-infrastructure technologies:
  1. high-speed virtual networking
  2. high performance networked cloud computing
  3. virtualization and data management

Objective: ***build up a perfect cyber-physical testbed for WAMS research***

Result: ExoGENI-WAMS Testbed

Physical subsystem – Hardware-In-Loop Framework (RTDS + PMU-based WAMS)
Cyber subsystem – Networked Cloud Computing Platform (ExoGENI)

Architecture of ExoGENI-WAMS Testbed



US-wide ExoGENI at RENCI/UNC Chapel Hill

PMU based WAMS at NC State

Components: RTDS-PMU based WAMS

RTDS – two racks, 50 us of time step,

RSCAD – software to develop models for the RTDS to simulate

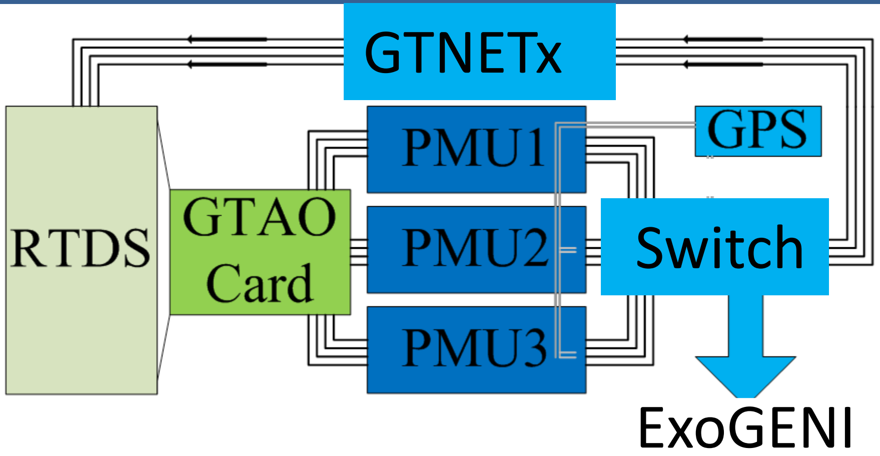
GATO – hardware interface of Gigabit Transceiver Analog Output to generate voltage and current waveforms to the PMUs

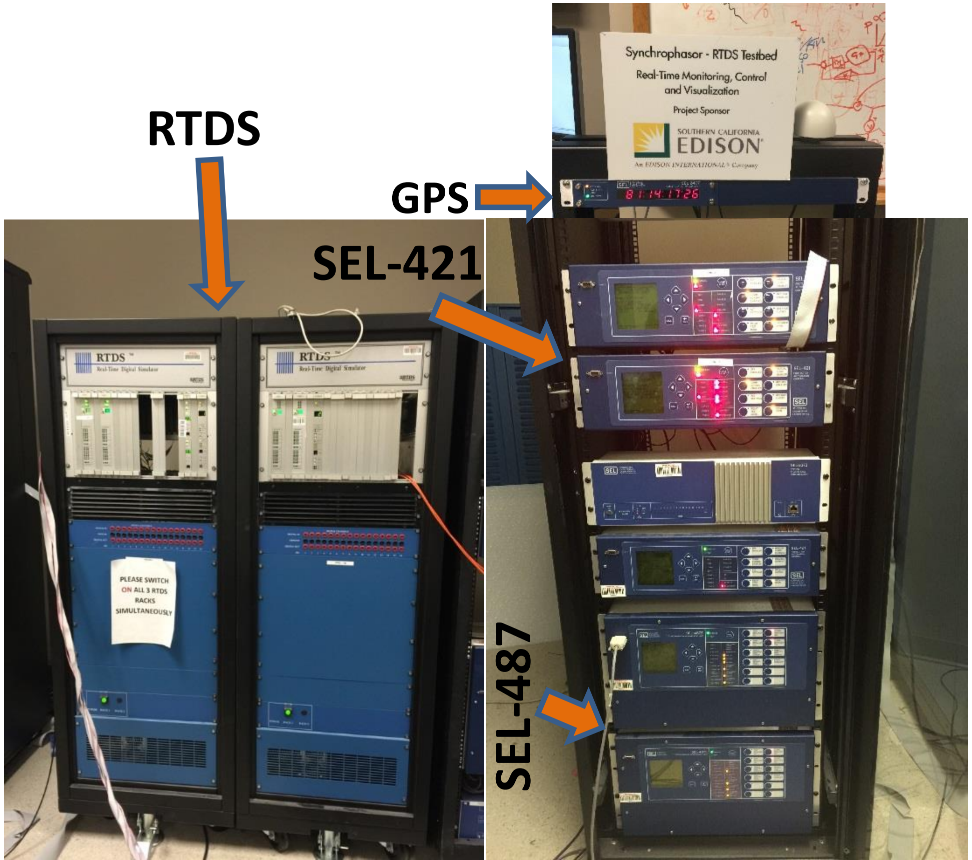
GTNETx2 – Gigabit Transceiver Network interface card to communicate with remote station. Multiple protocols (TCP socket, DNP, …) IEEE 754 floating-point and integer type.

PMU – 5 units: 3 SEL-421 & 2 SEL-487

Functions: accepting IRIG-B signal for satellite synchronization

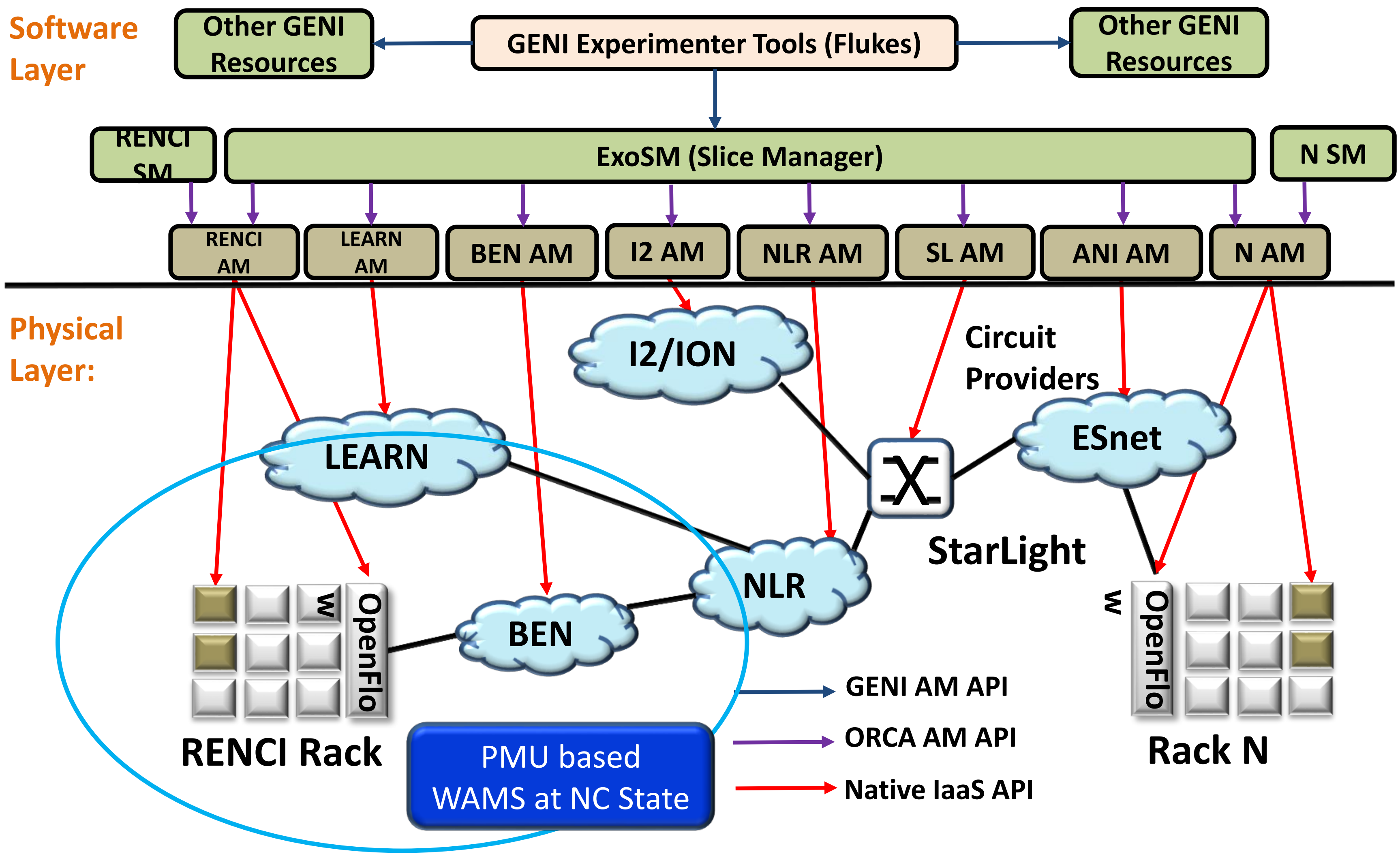
GPS – SEL-2407 Satellite-Synchronized Clock





Networked Cloud Computing Testbed—ExoGENI

ExoGENI provides in virtual IaaS services for innovative research on distributed applications for Wide-Area Monitoring and Control (14 rack sites at universities & labs over the US)



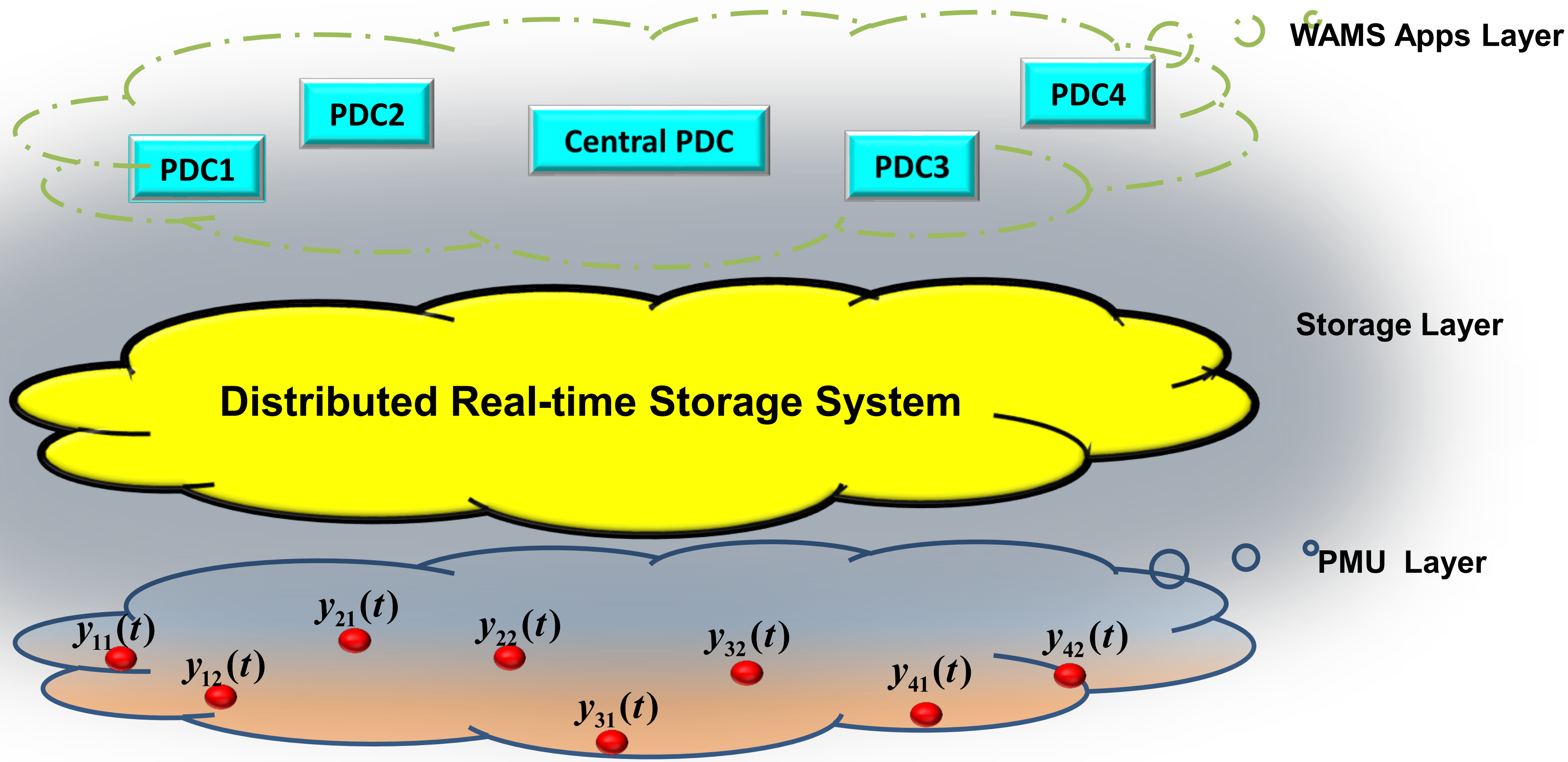
Validations of ExoGENI-WAMS testbed

- **Visualization of Power Grid**
- **Delay Evaluation of CLS, DLS and RLS**
- **Distributed Oscillation Monitoring Algorithm**
- **Distributed Storage System (DSS) for Multiple Applications**
- **Distributed Control Algorithm**

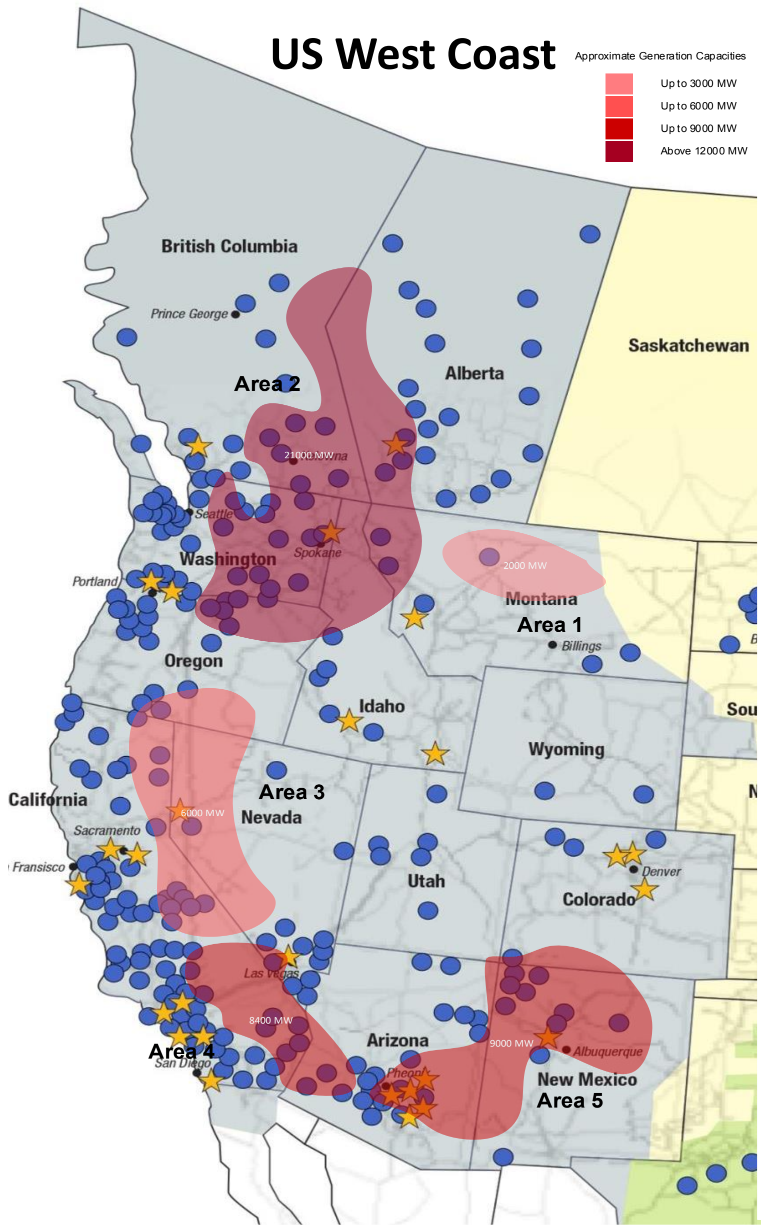
Case Study I — Distributed Storage System with S-ADMM

Synchronized ADMM + Storage System

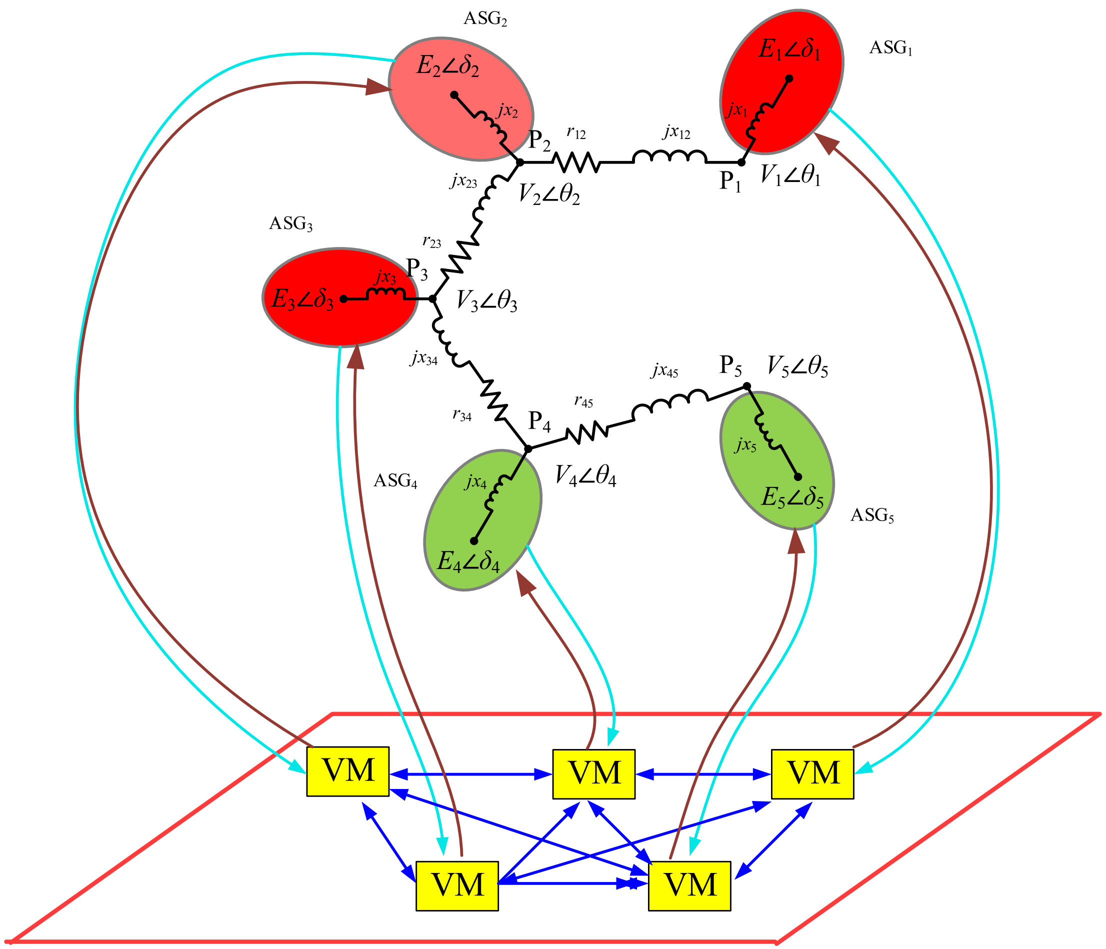
Step 1: PMUs keep storing data into Storage System



Case Study II - Distributed Control Algorithm



Close the loop from cloud to grid

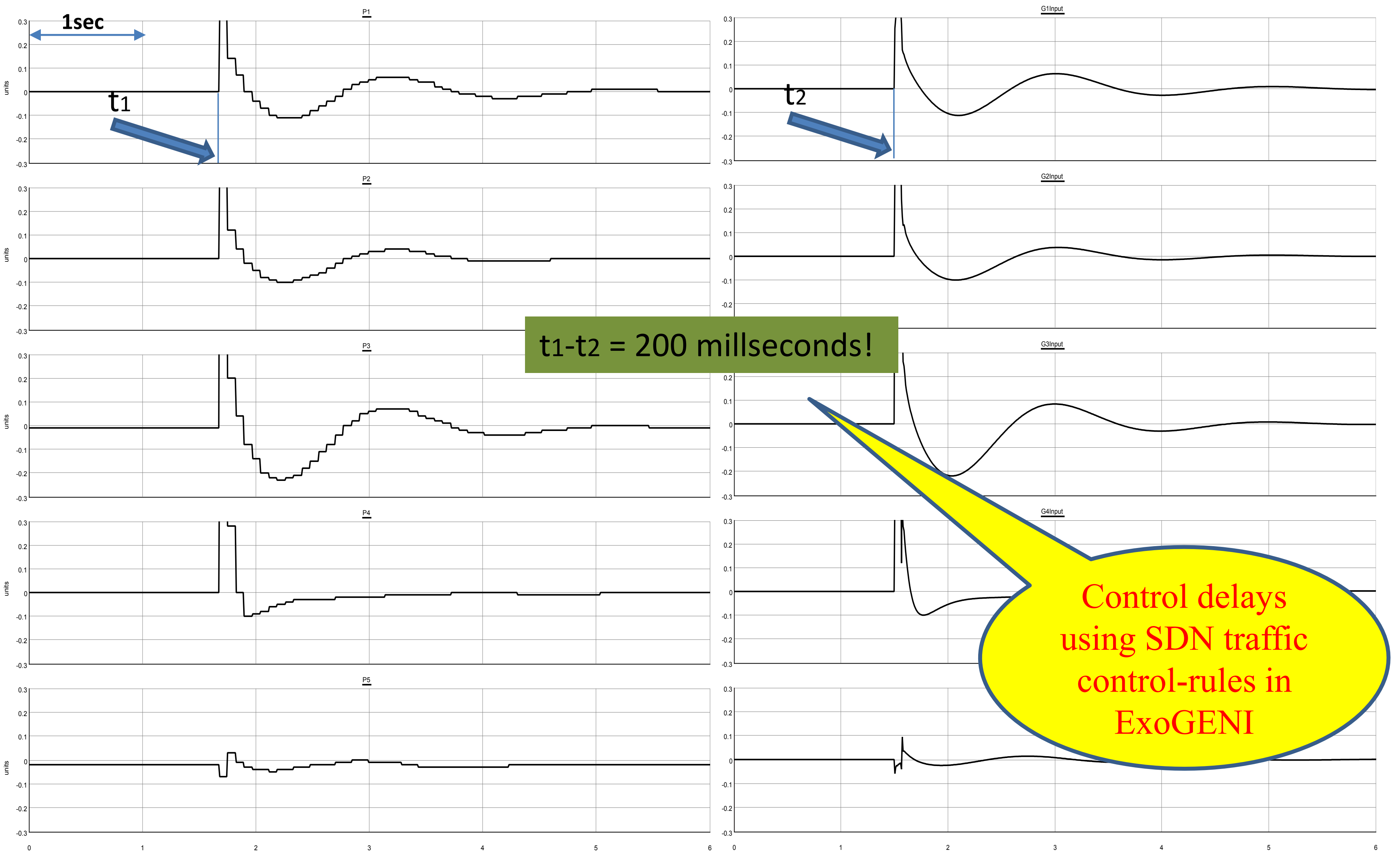


Third-Party Private Cloud
+ Controllable Network

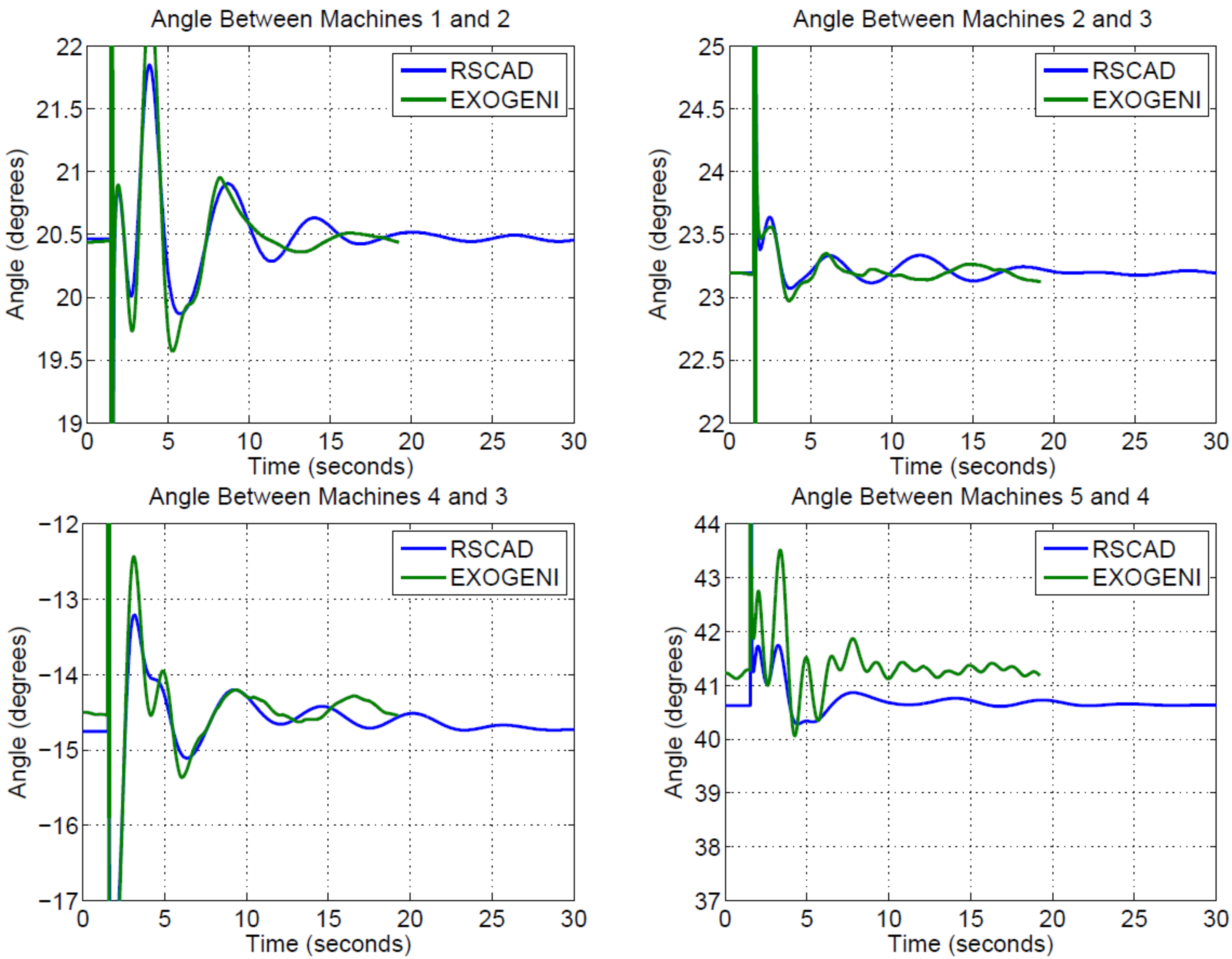
Implementation of Distributed Control Algorithm

Control Signals from ExoGENI

Control Signals from RSCAD



Comparison of Controller Performance



Performance of offline controller compared against a cloud-computing implementation using the ExoGENI Network.

Summary of Experiments done so far:

- Develop distributed delay-robust algorithms for wide-area oscillation mode monitoring of power systems
- Investigate the convergence performance of these distributed algorithms on delay distribution parameters and different variants of asynchronous strategies
- ExoGENI-WAMS-DETER testbed federation
- Validations of these distributed architecture using distributed cloud computing

Ongoing & Future Work with GENI & Internet2

- Investigate the scalability of distributed algorithms
- Resilience and Cyber-security of ExoGENI using SDN principles
- Delay management in ExoGENI using SDN principles

Conclusions

1. WAMS is a tremendously promising technology for control researchers
2. Control + Communications + Computing must merge
3. Plenty of new research problems – EE, Applied Math, Computer Science
4. Plenty of new control engineering problems
5. Right time to think mathematically – Network theory is imperative
6. Right time to pay attention to the bigger picture of the electric grid
7. Needs participation of young researchers!
8. Promises to create jobs and provide impetus to power engineering

Thank You

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