Cyber-Physical Implementation of Wide-Area Control using ExoGENI-WAMS Testbed

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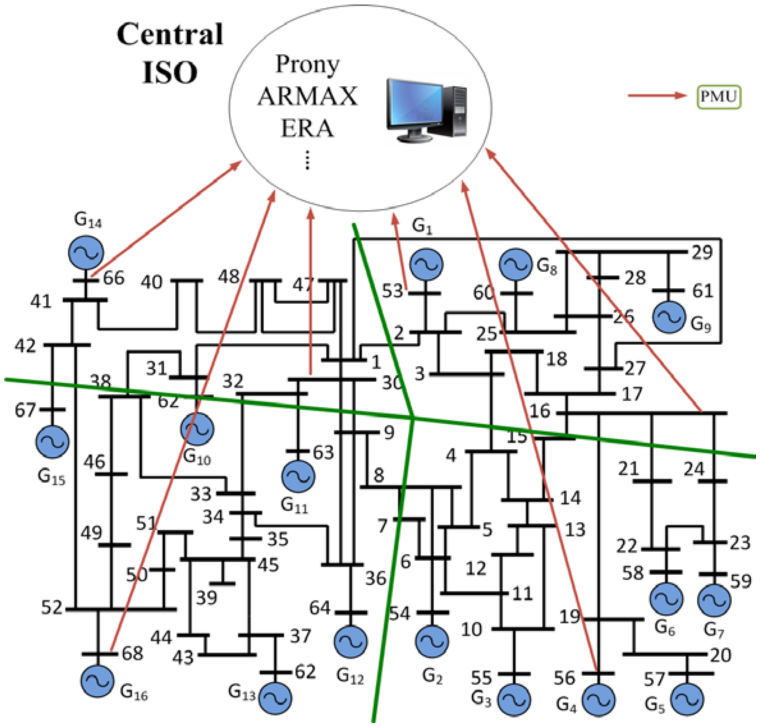
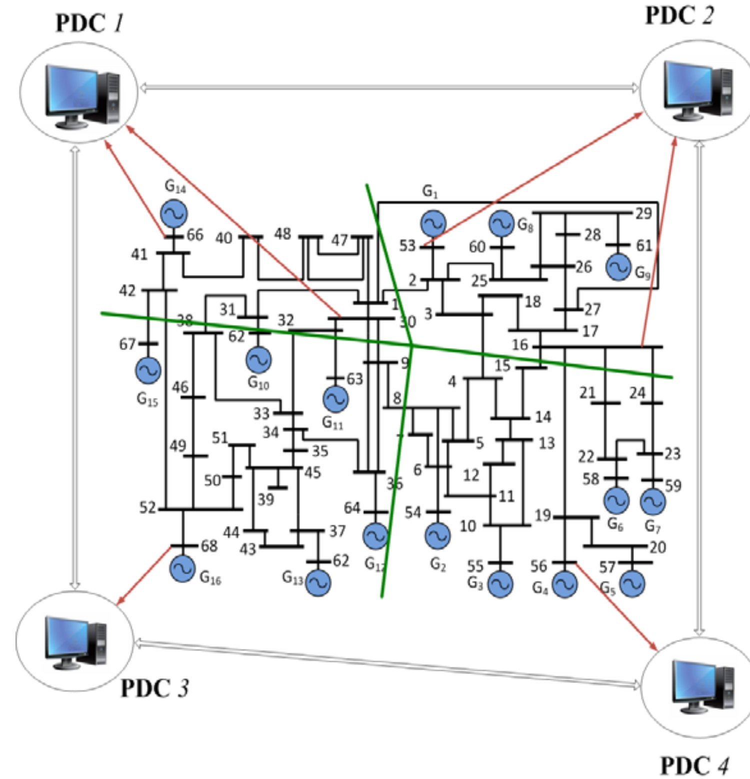
From Centralized to Distributed Architecture

Centralized WAMS

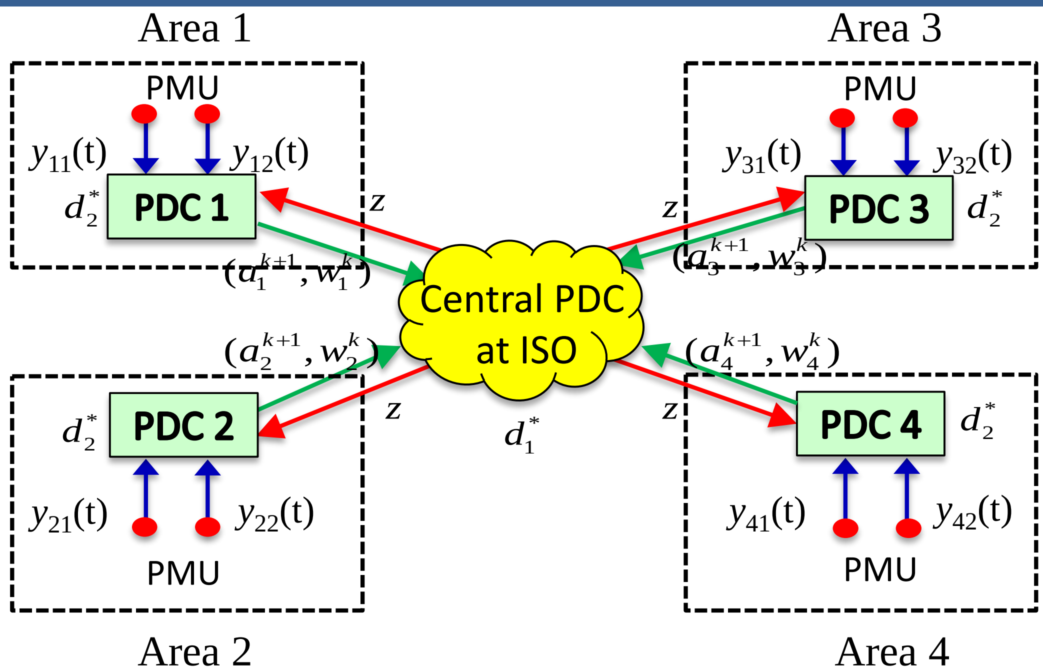


Distributed WAMS



1. Formulation of centralized strategies to distributed algorithms
2. Investigation of cyber-physical issues: delays and cyber-security
3. Validation using cyber-physical networked cloud computing testbed

Distributed Asynchronous Algorithms



Assumption of S-ADMM:
the communication between local PDCs and central PDC is completely synchronized. Practically, it is not always possible.

Proposed method: to counteract asynchrony by defining a set of **flexible deadlines** for message arrival in every PDC, and by modifying the **update rules** based on these deadlines.

Our Objective: Study the impact of asynchronous communication on the convergence of distributed ADMM-based algorithms. Result algorithm is called A-ADMM.

Approach:

Step 1. Consider a probabilistic traffic model for modeling delays in Internet

Step 2. Propose different update strategies to immune asynchrony

Step 3. Analyze the convergence of the A-ADMM algorithm on 1) ***delay distribution parameters*** *2)* ***different update strategies***

Delay Model for Wide-Area Communication

1. Minimum deterministic delay,
2. Internet traffic delay (*alternating renewal process*)
3. Router processing Delay (*Gaussian process*)

Then, the total Probability Density Function (PDF)

$$\phi(t)=\frac{p}{\sigma\sqrt{2\pi}}e^{-\frac{(t-\mu)^2}{2\sigma^2}}+\frac{\lambda(1-p)}{\sigma\sqrt{2\pi}}e^{-\lambda t}\int_0^t e^{\lambda s-\frac{(s-\mu)^2}{2\sigma^2}}ds$$

We derive the Cumulative Distribution Function (CDF)

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

Parameters:

1. μ - mean deterministic delay (5.3ms),
2. σ - derivative value of delay of router processing(0.078ms),
3. λ^{-1} - mean length of the closure period (1/1.39),
4. p - probability of open period of the path with no Internet traffic(0.58),
5. $\tau = P(X \le d^*)$ - cumulative distribution function of d*, d* is the delay threshold.

Security Enhancement of Distributed Optimization

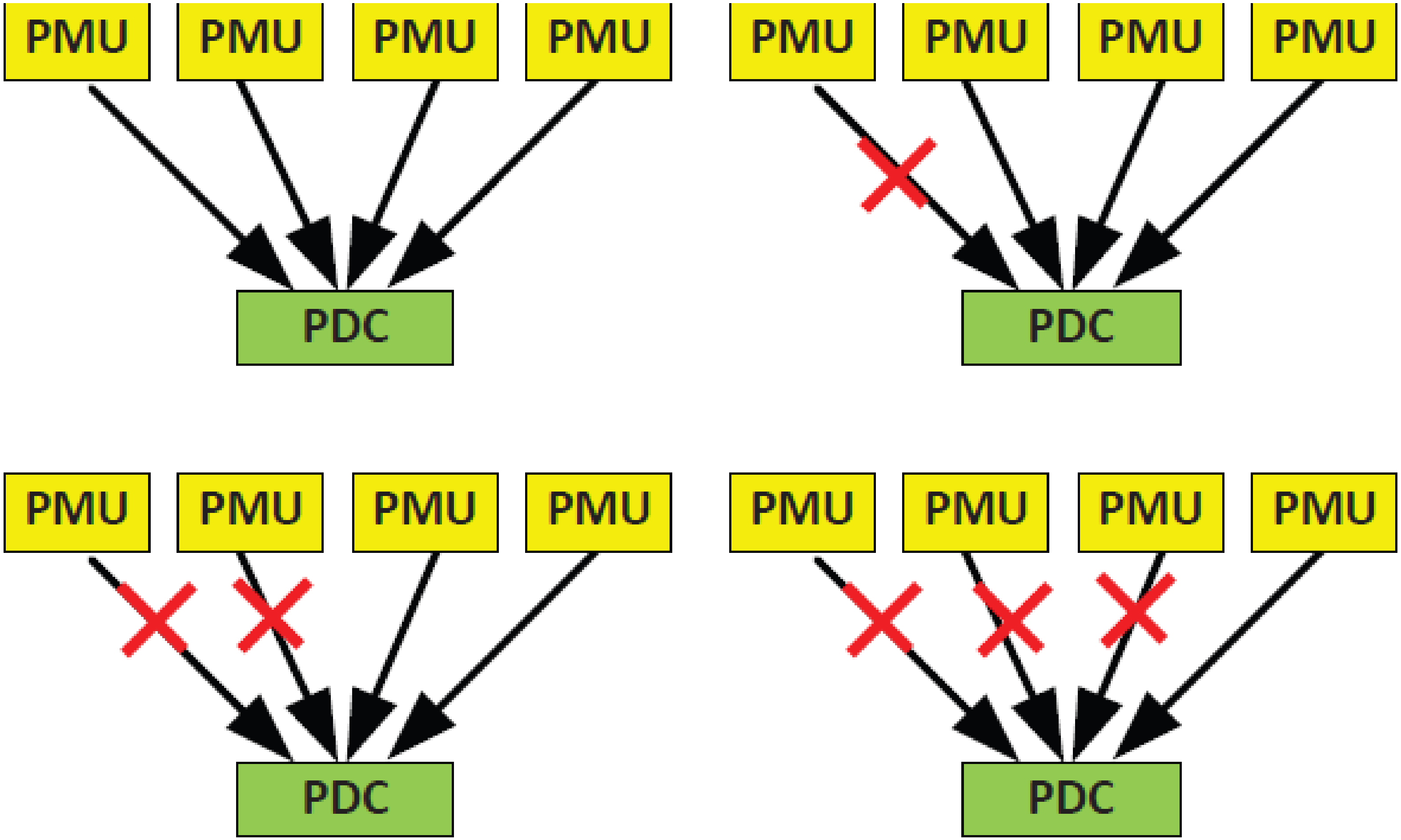
Question: Cyber-physical architectures are prone to failures and attacks on their physical infrastructure, as well as cyber attacks on their data management and communication layer.

Objective: To investigate how distributing a monitoring functionality over multiple estimators can guarantee significantly more resiliency against extreme events.

Attack Scenarios:

1. Malware attack that disrupts the normal execution of monitoring algorithms
2. Flooding attack by generating malicious traffic to delay messages
3. Malfunction of physical infrastructure due to natural calamities such as storms and earthquakes

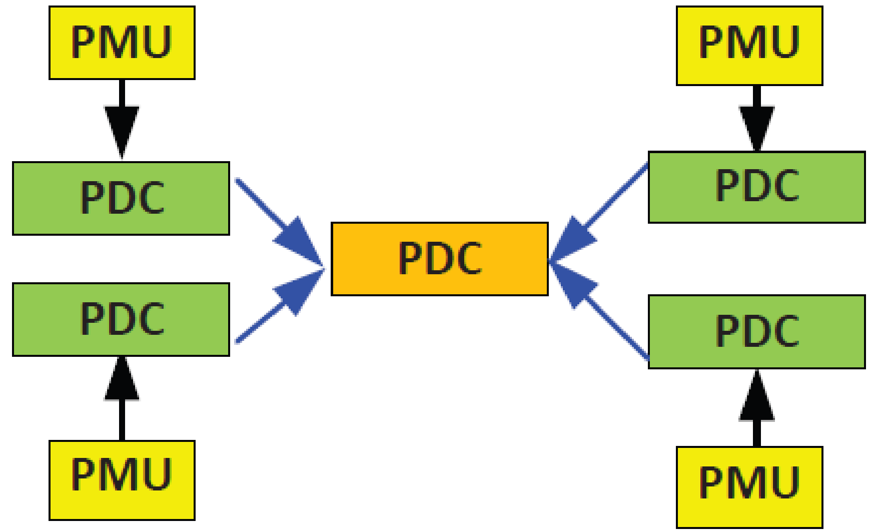
Resilient Strategy for Centralized RLS

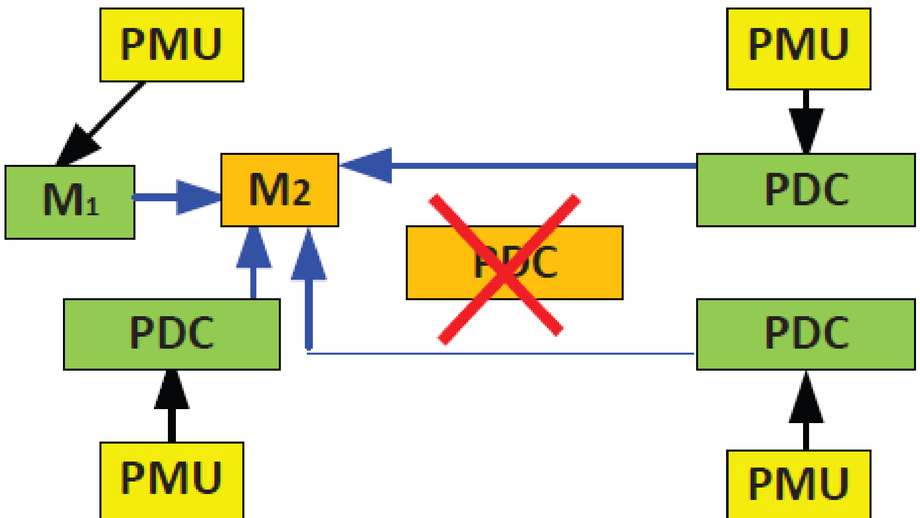


Resilient Strategies for Distributed S-ADMM

Redundancy-based Strategy

Local PDC runs as dual roles
of local estimator and central estimator

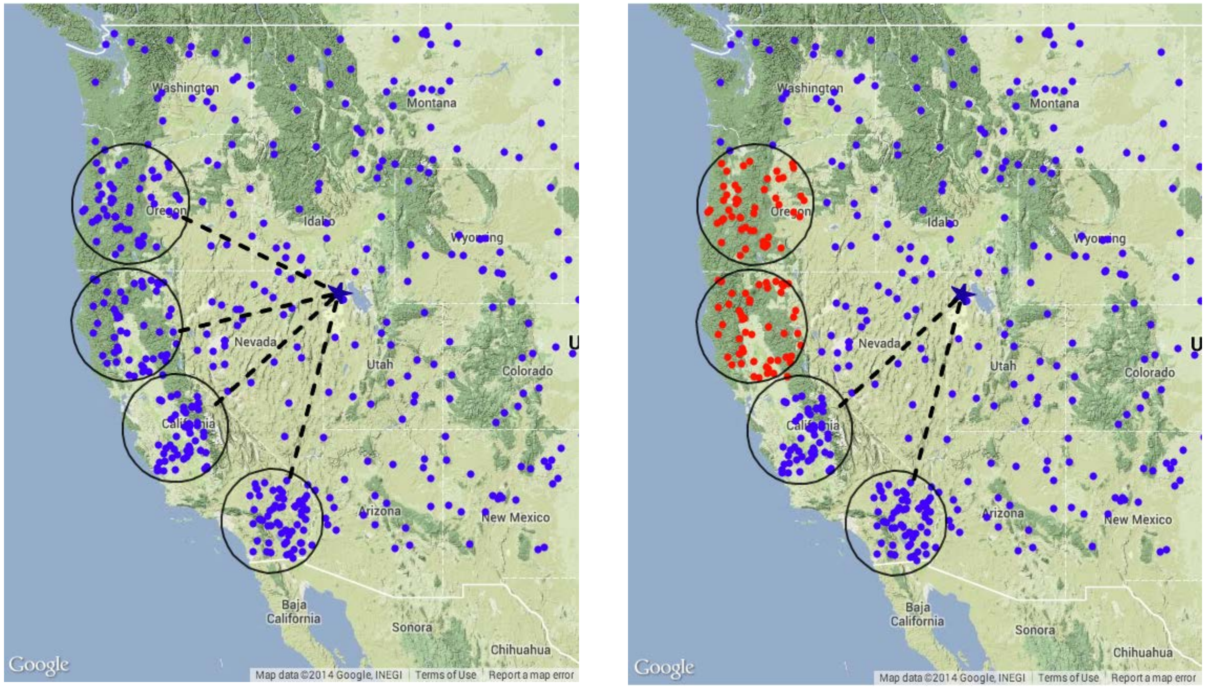


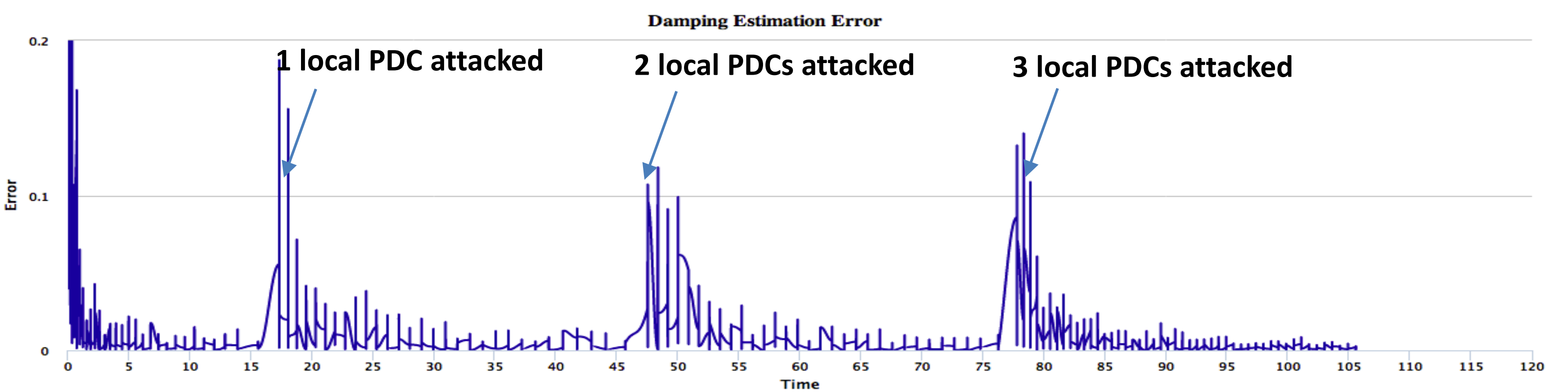


Experimental Validation on Federated Testbeds

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

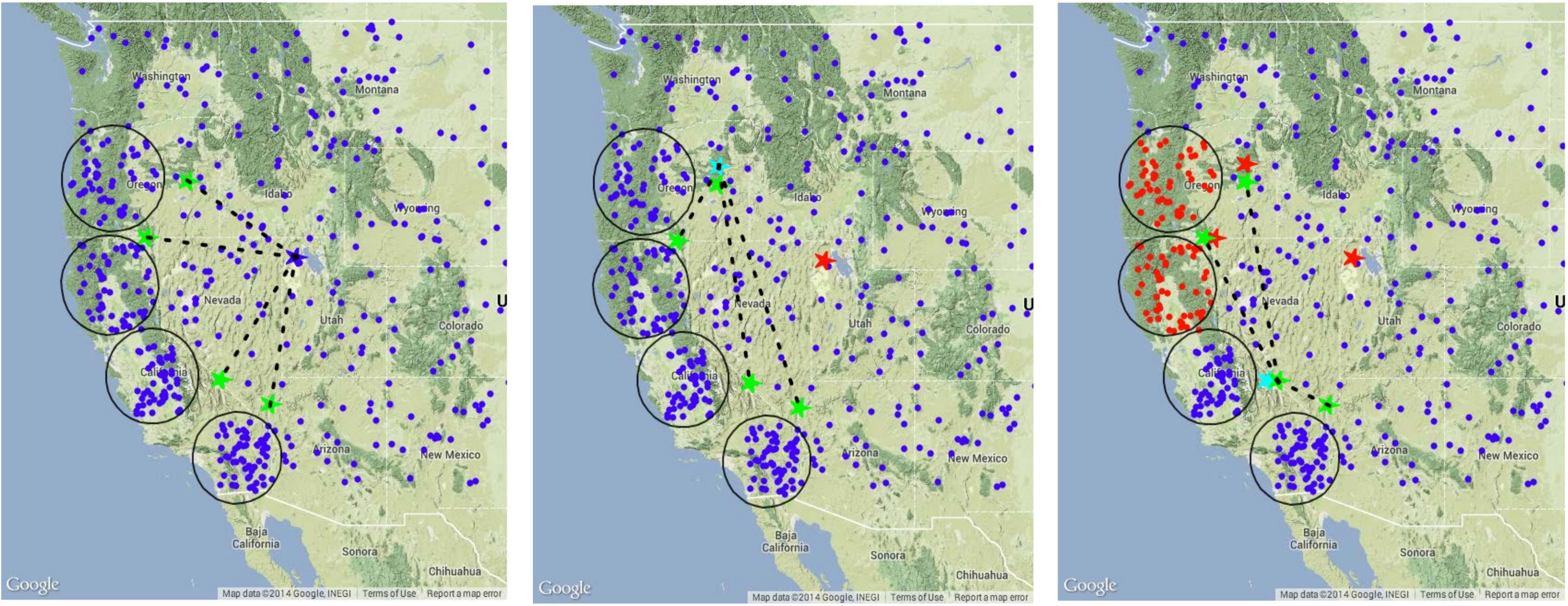
Centralized Architecture

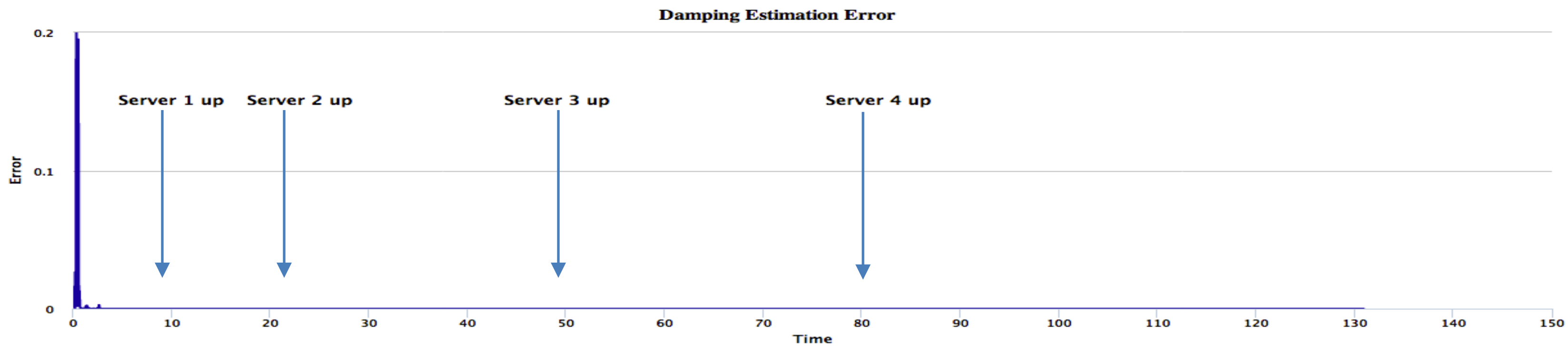




Experimental Validation on Federated Testbeds

Distributed Architecture

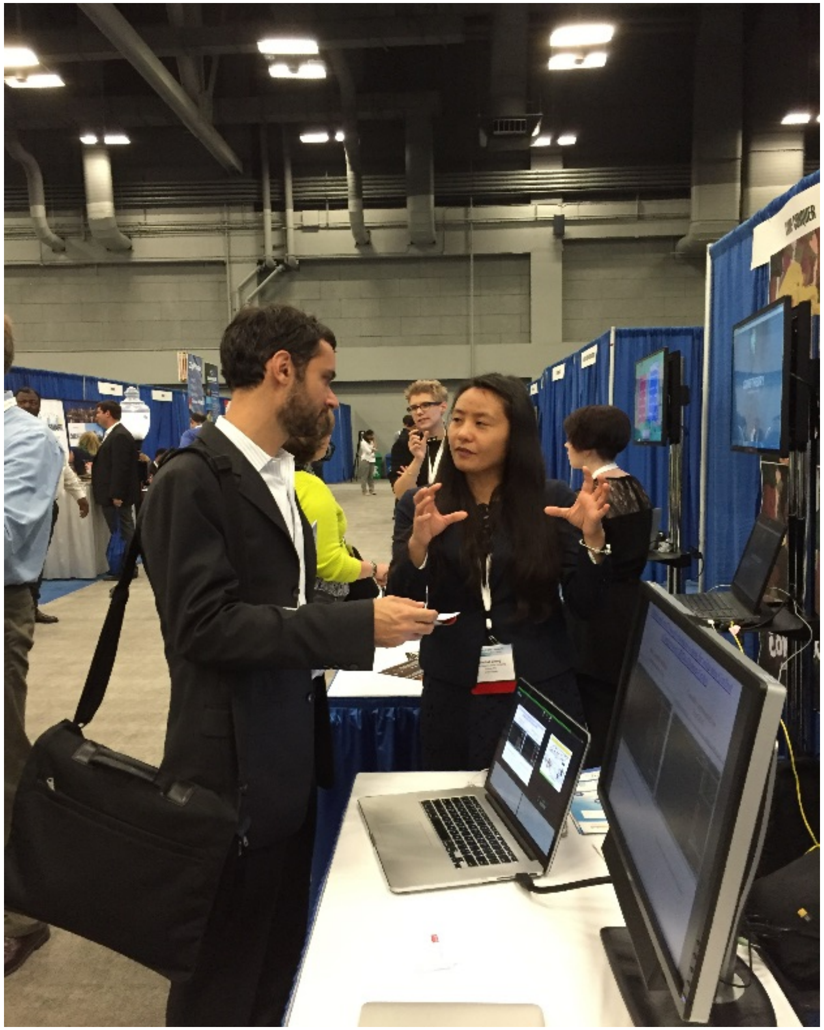




Project Demos:

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

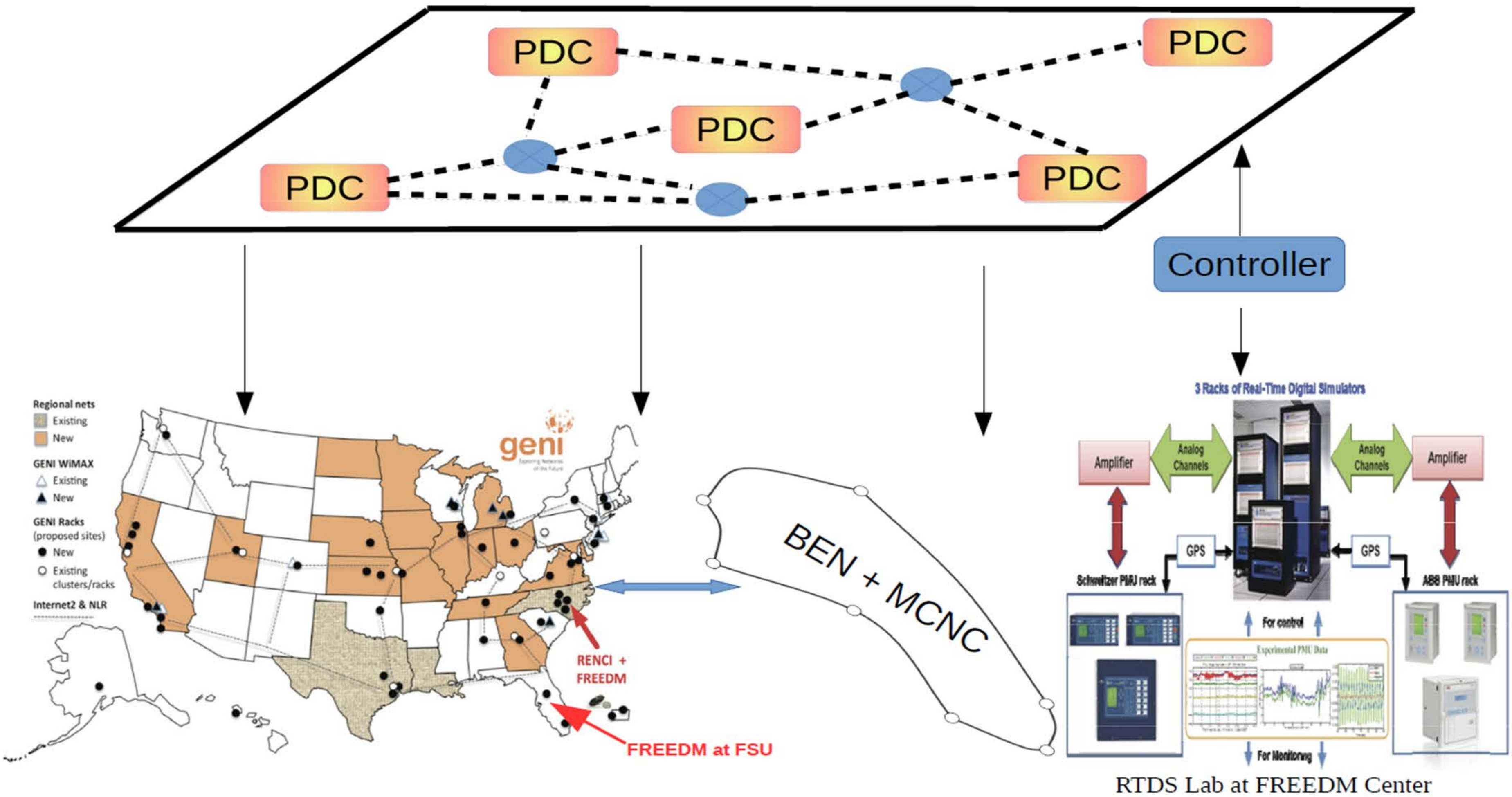
Objective: ***build up a perfect cyber-physical testbed for WAMS research***

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

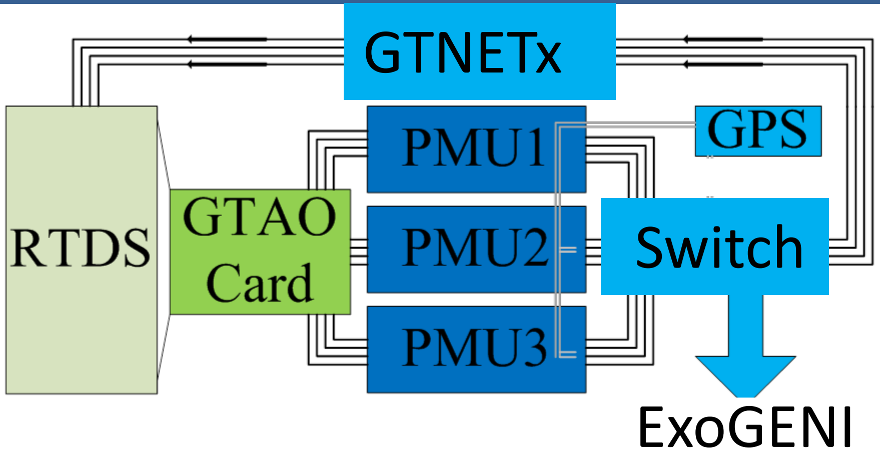
Components: RTDS-PMU based WAMS

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

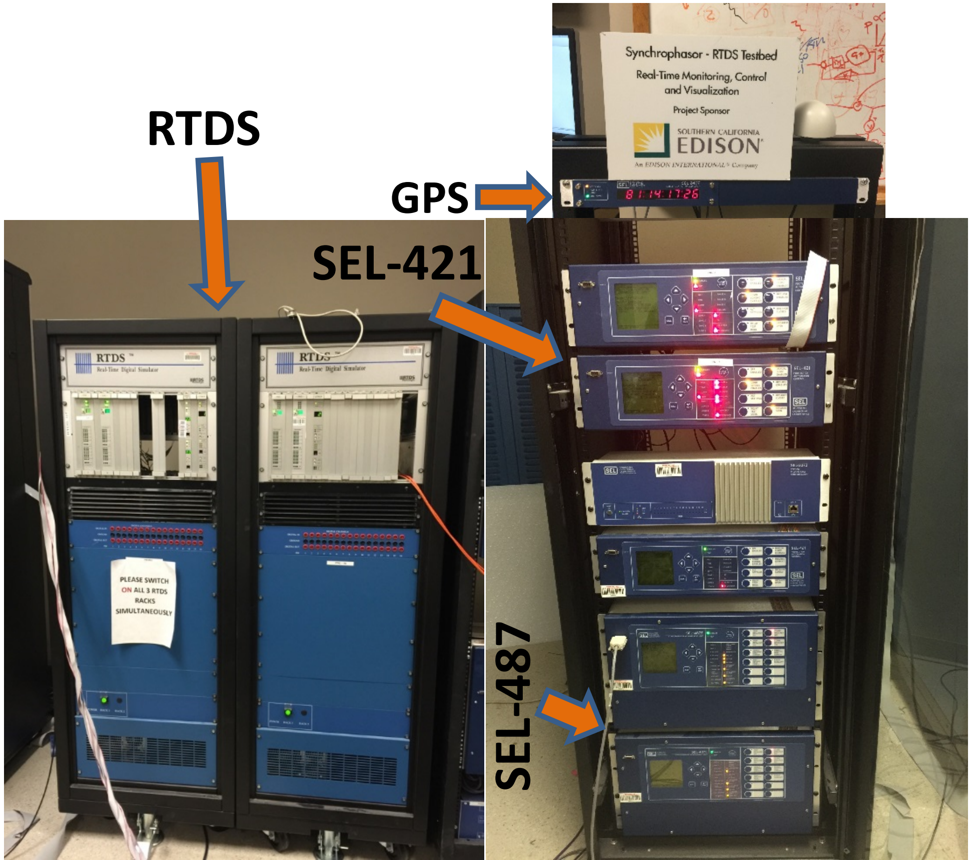
GTNETx2 – Gigabit Transceiver Network interface card to communicate with remote station. Multiple protocols (TCP socket, DNP, …) IEEE 754 floating-point and integer type.



PMU – 5 units: 3 SEL-421 & 2 SEL-487

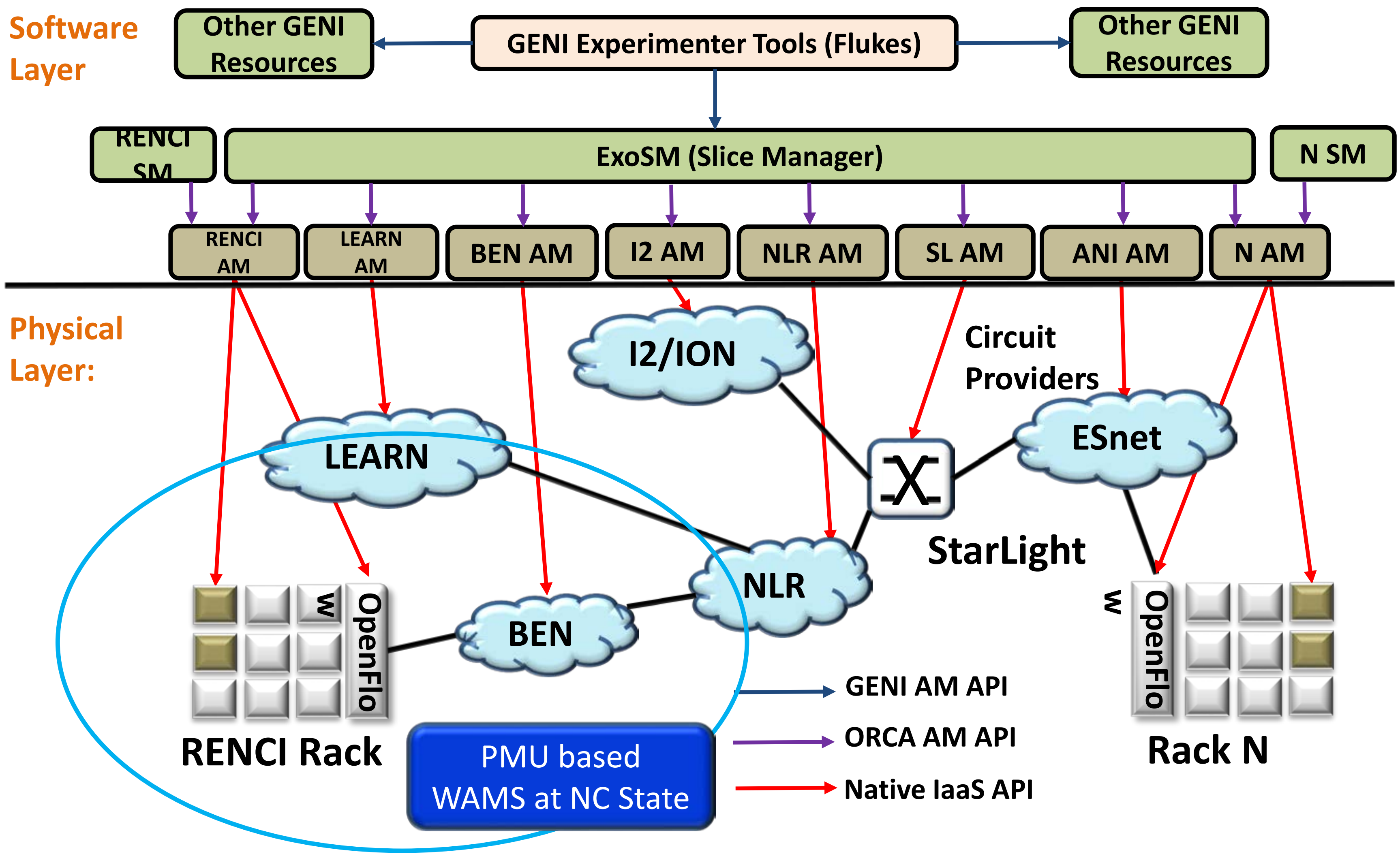
Functions: accepting IRIG-B signal for satellite synchronization

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)



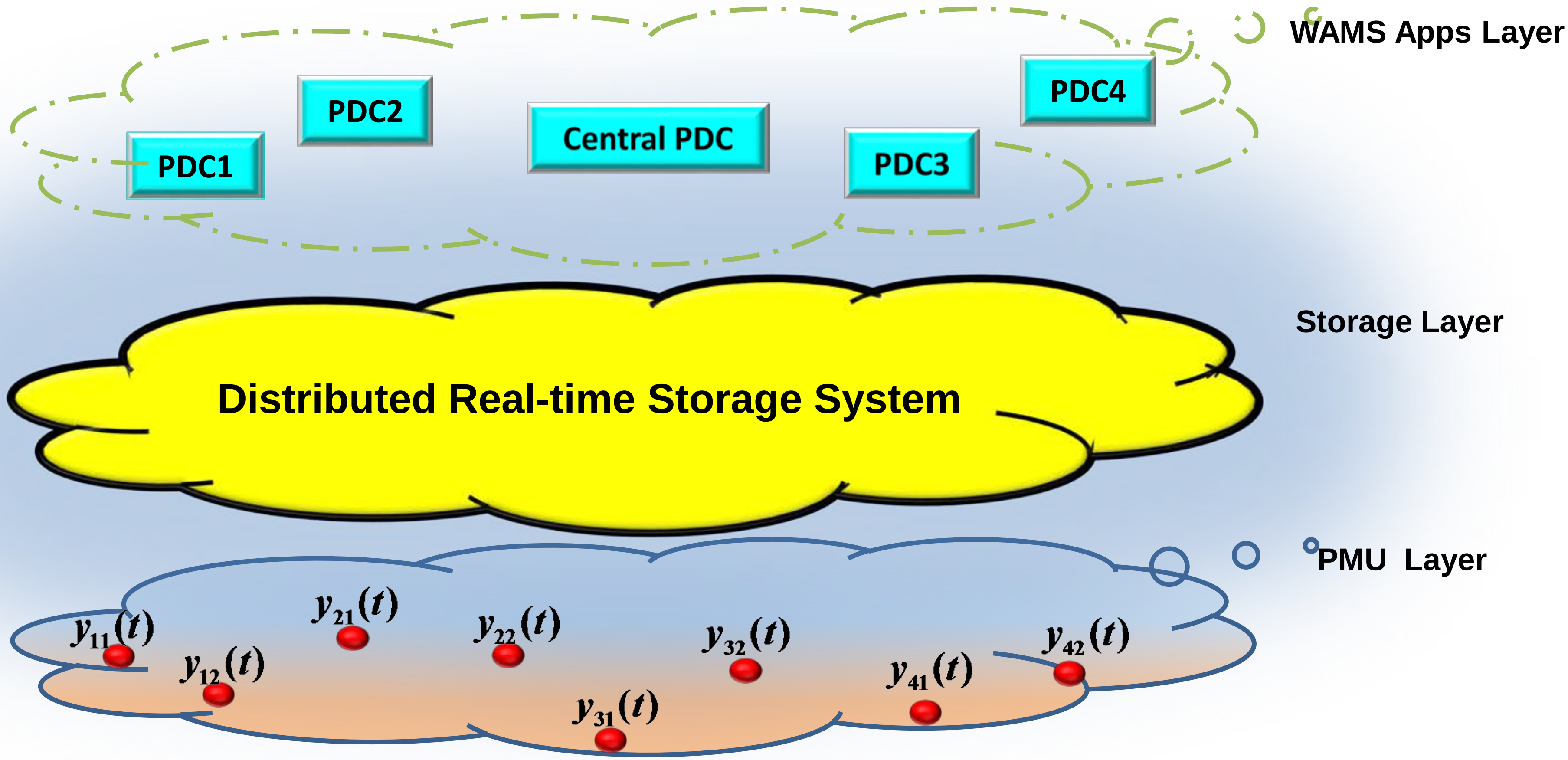
Validations of ExoGENI-WAMS testbed

- **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**

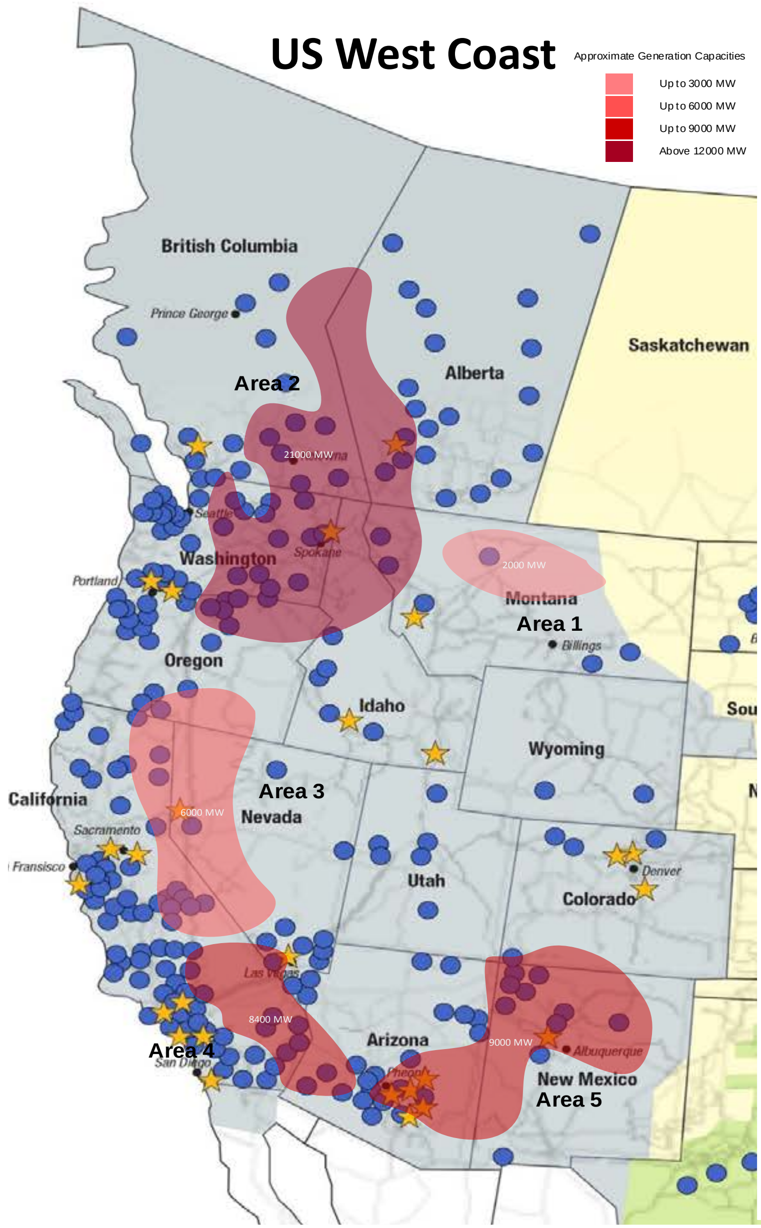
Case Study I —Distributed Storage System with S-ADMM

Synchronized ADMM + Storage System

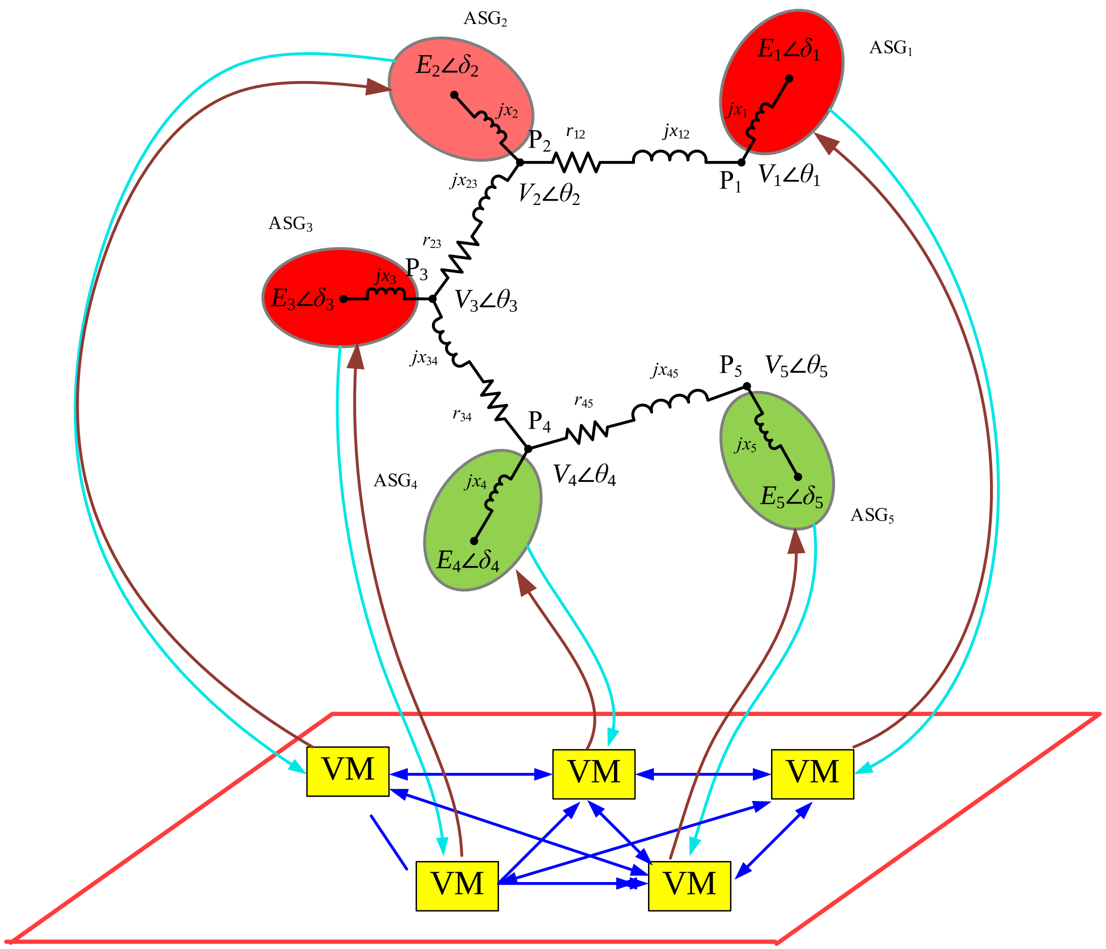
Step 1: PMUs keep storing data into Storage System



Case Study II - Distributed Control Algorithm



Close the loop from cloud to grid

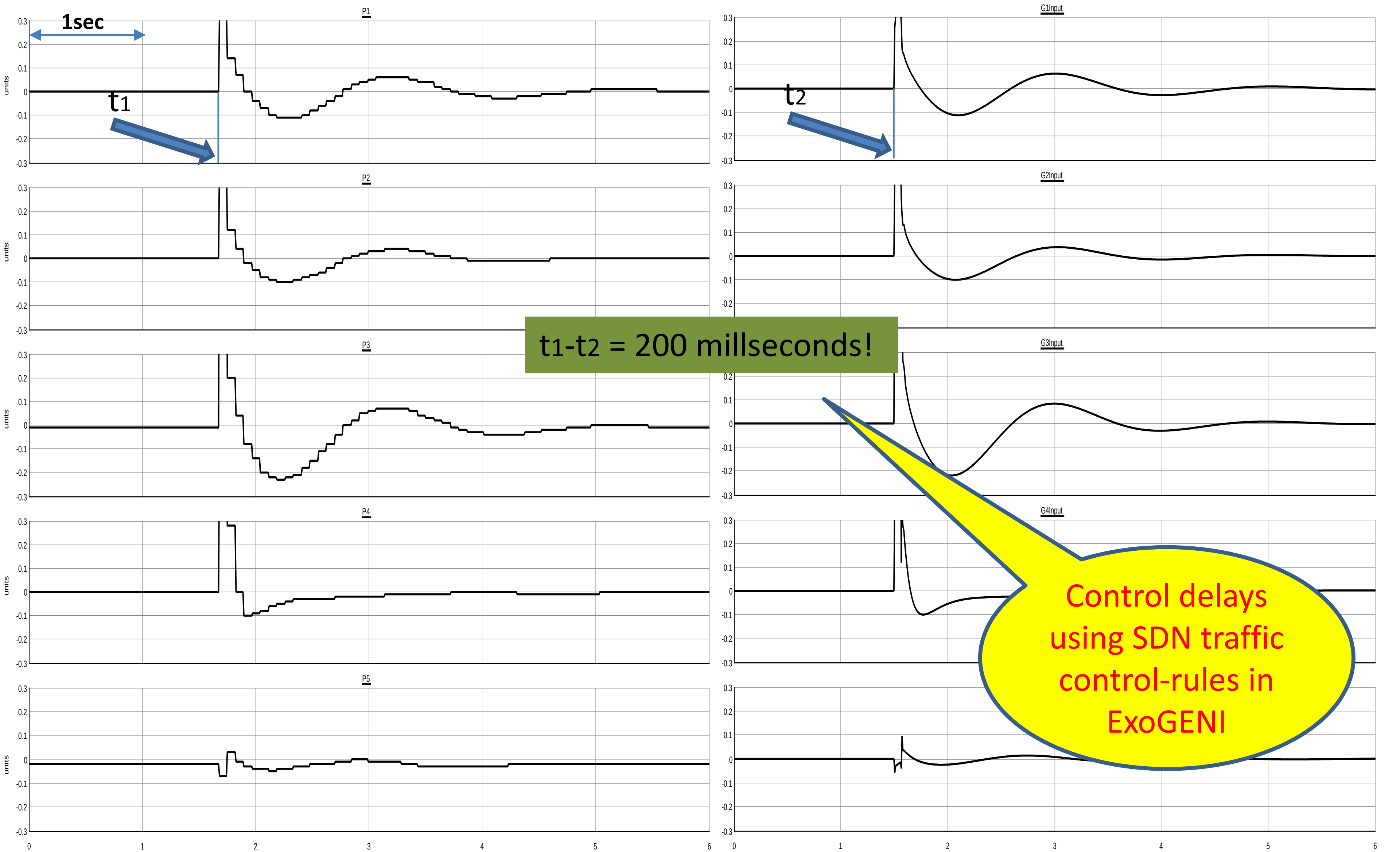


Third-Party Private Cloud
+ Controllable Network

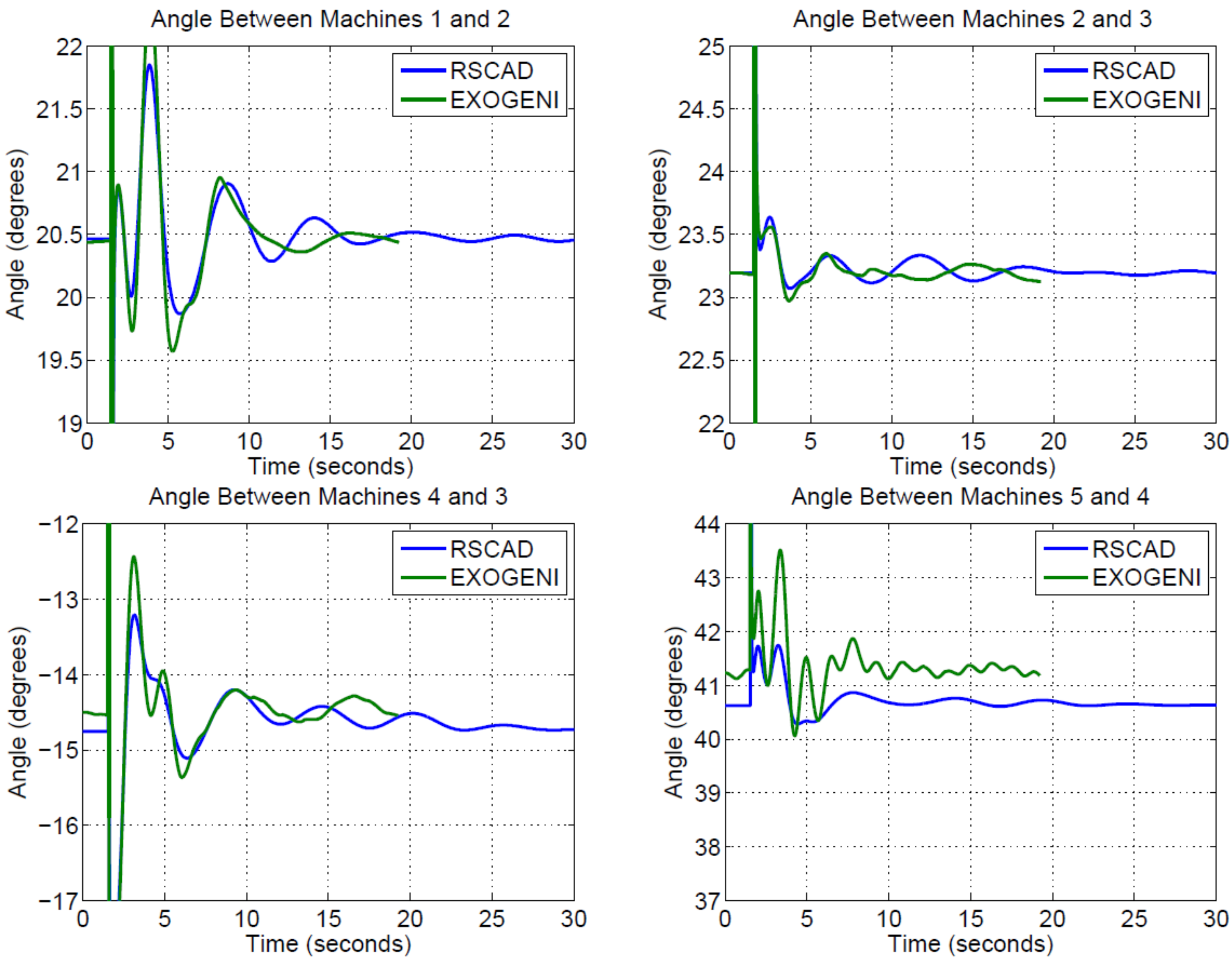
Implementation of Distributed Control Algorithm

Control Signals from ExoGENI

Control Signals from RSCAD



Comparison of LQR Controller Performance



Performance of RSCAD-based LQR-WAC compared against a cloud-computing implementation using the ExoGENI Network.

Conclusions and Future Work

Conclusions

- 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
- Validations of these distributed architecture using distributed cloud computing

Future Work

- Investigate the scalability problem of distributed algorithms
- Resilience of ExoGENI using SDN principles
- Delay management in ExoGENI using SDN principles

Thank You

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