ExoGENI-WAMS: A Cyber-Physical Testbed for Wide-Area Monitoring and Control of Power Systems using Distributed Cloud Computing

Jianhua Zhang, Matthew Weiss
Dr. Aranya Chakrabortty, Dr. Yufeng Xin

North Carolina State University
Renaissance Computing Institute (RENCI), UNC

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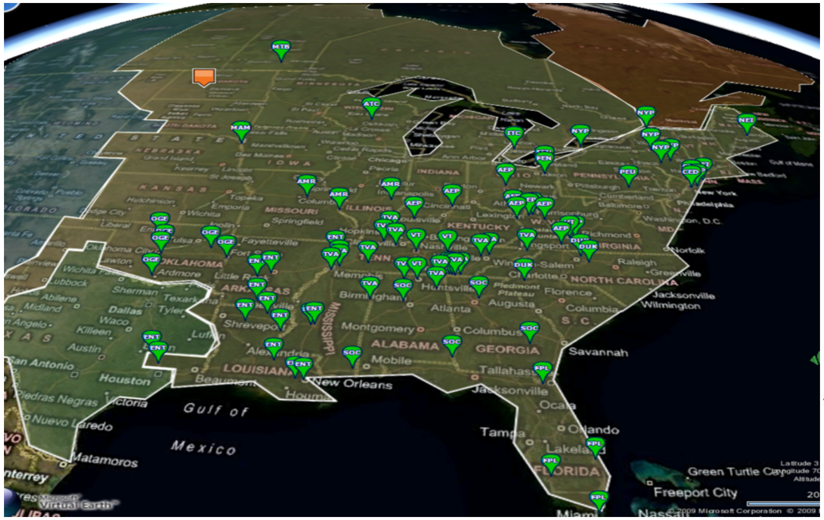
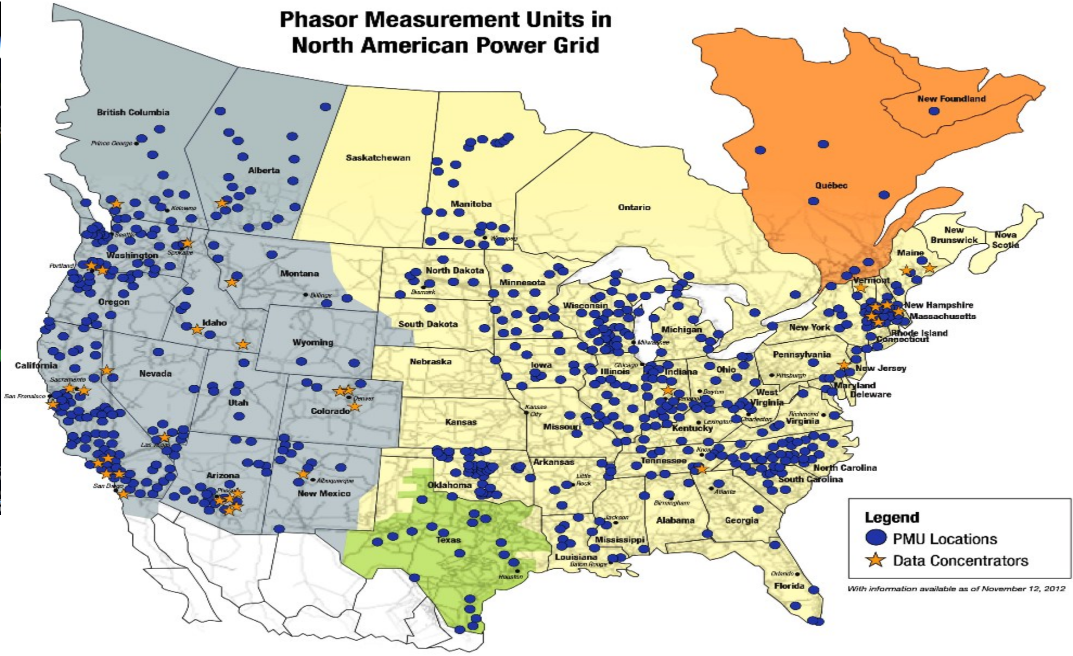
Outline

- Motivations
- Architecture
- Components
- Integration
- Validation of Distributed PMU based Applications
  - Visualization of Power Grid
  - Distributed Oscillation Monitoring Algorithm
  - Distributed Storage System for Multiple Applications
  - Distributed Control Algorithm
- Conclusions and Future work

Distributed Operations of Power System



2008: Only 40 Sensors in the entire east coast



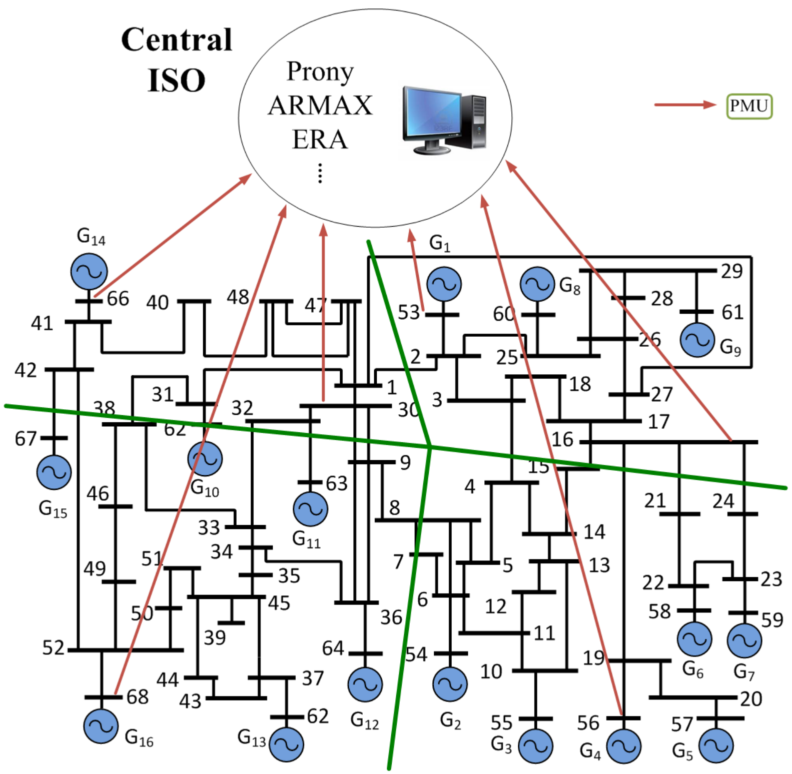
2015: More than 1000 sensors across USA

- Cascade failures and blackouts and high–resolution GPS-synchronized synchrophasors
- Massive volumes of PMU data need to be transported from one part of the grid to another for monitoring and control
- Needs a highly reliable and resilient communication infrastructure
- Centralized processing will not be tenable
- Need combination of distributed monitoring and control spread over the entire system

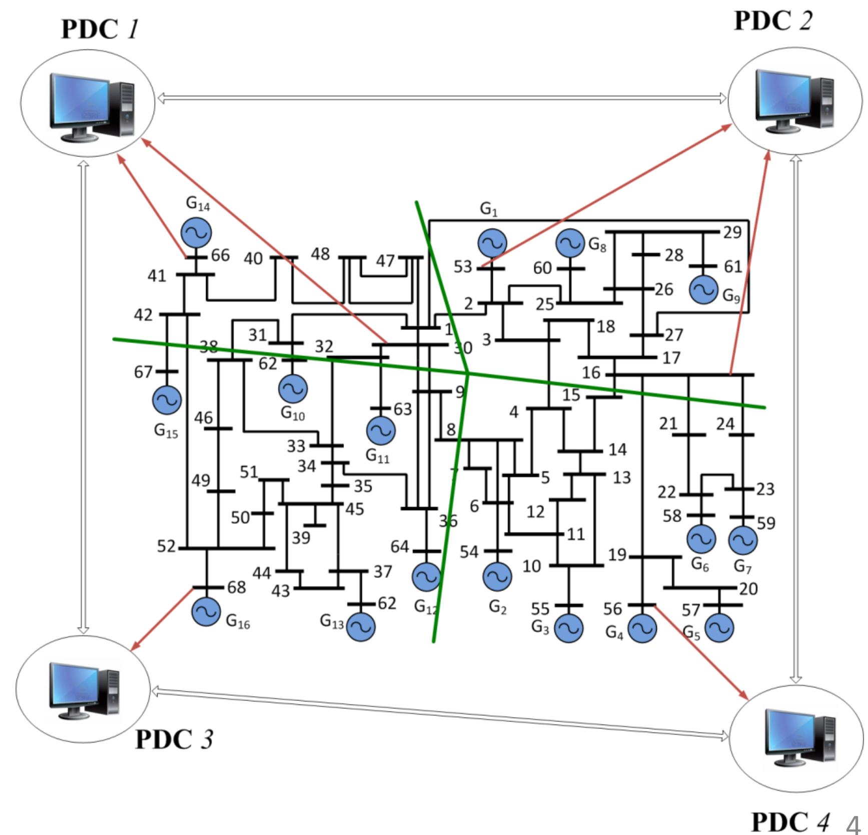
Wide-Area Monitoring and Control

Validate the distributed applications for wide-area monitoring and control through the cyber-physical distributed cloud computing testbed

State-of-the-Art Monitoring & Control Architecture



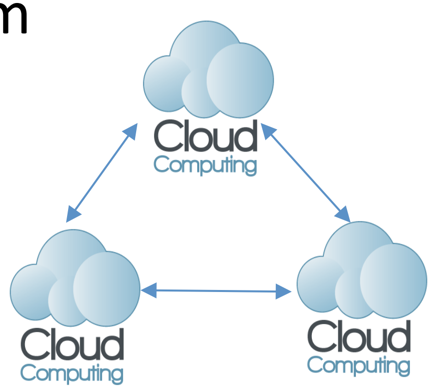
Distributed Monitoring & Control Architecture



Cyber-Physical System & Cloud Computing

- Growing Interest of

  - Adding physical hardware to "cyberspace" will increase the levels of system monitoring and control.
  - **Time-critical** system



- Popularization of
  - Dedicated network infrastructure which connects dispersed physical assets like PMUs is costly.
  - Existing commodity Internet

ExoGENI-WAMS Testbed

Bring Concepts of Cloud Computing and Software Defined Network into Research on Distributed Architecture of Wide-Area Monitoring and Control using PMU data

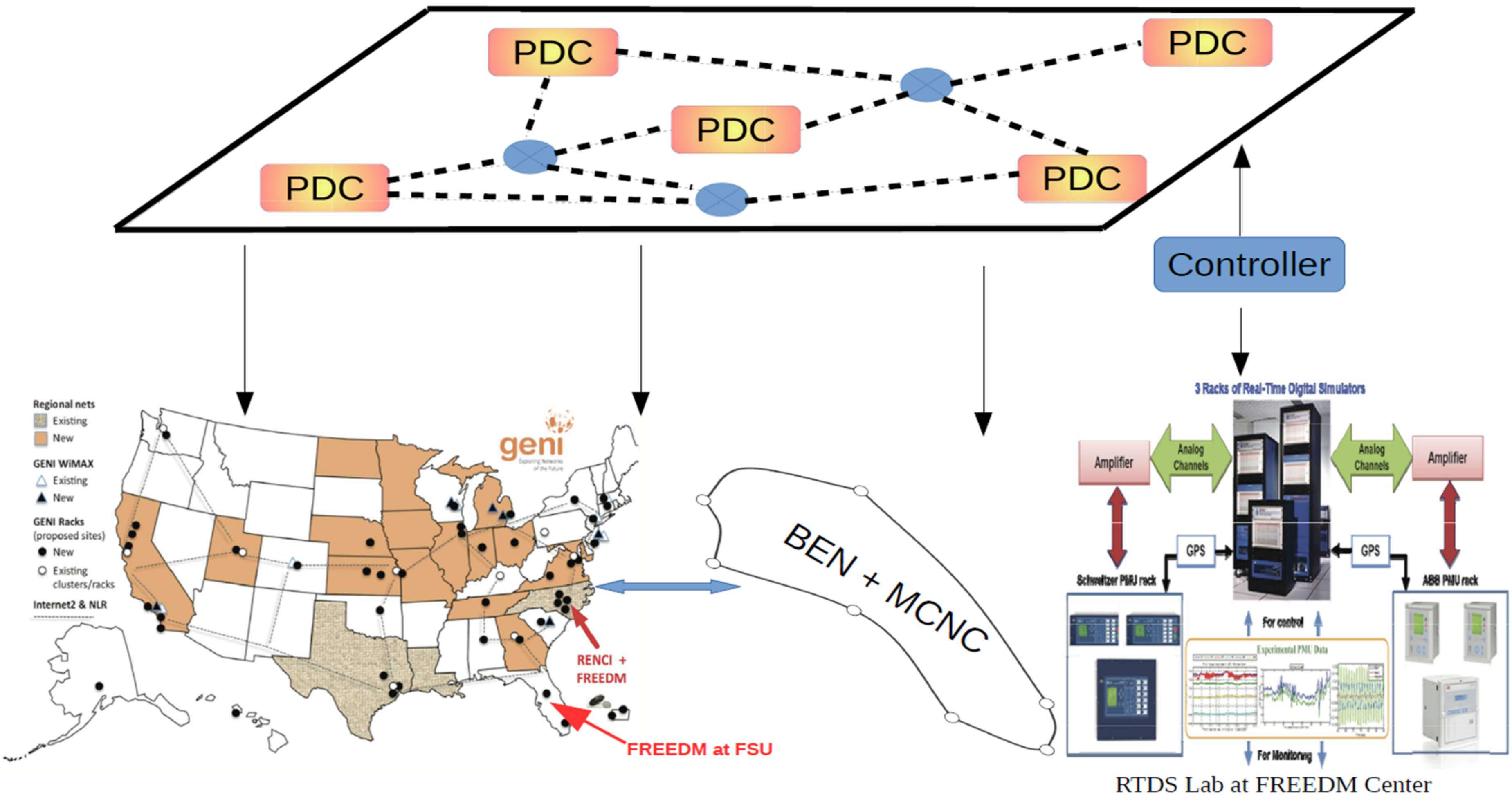
- **Wide-Area Monitoring and Control is a typical cyber-physical system**
- **Problems of the physical subsystem**
  1. Accessing of real PMU measurements due to privacy and non-disclosure issues
  2. Not sufficient for studying dynamics of the entire system due to limited coverage
- **Requirements of 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 WAMC 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

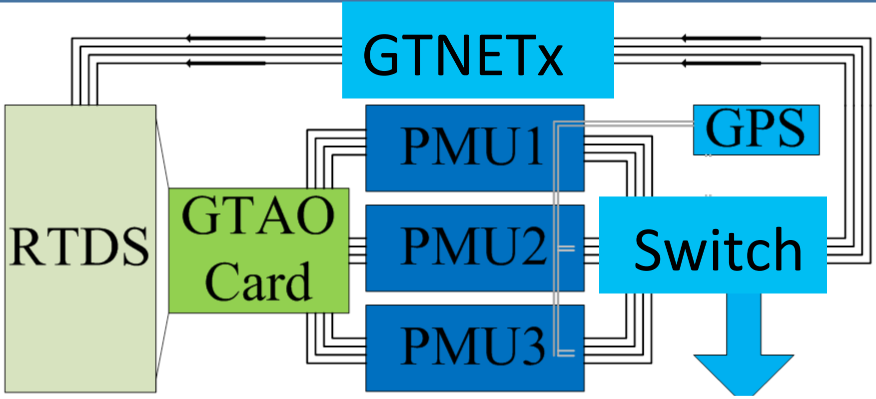
Components: RTDS-PMU based WAMS

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

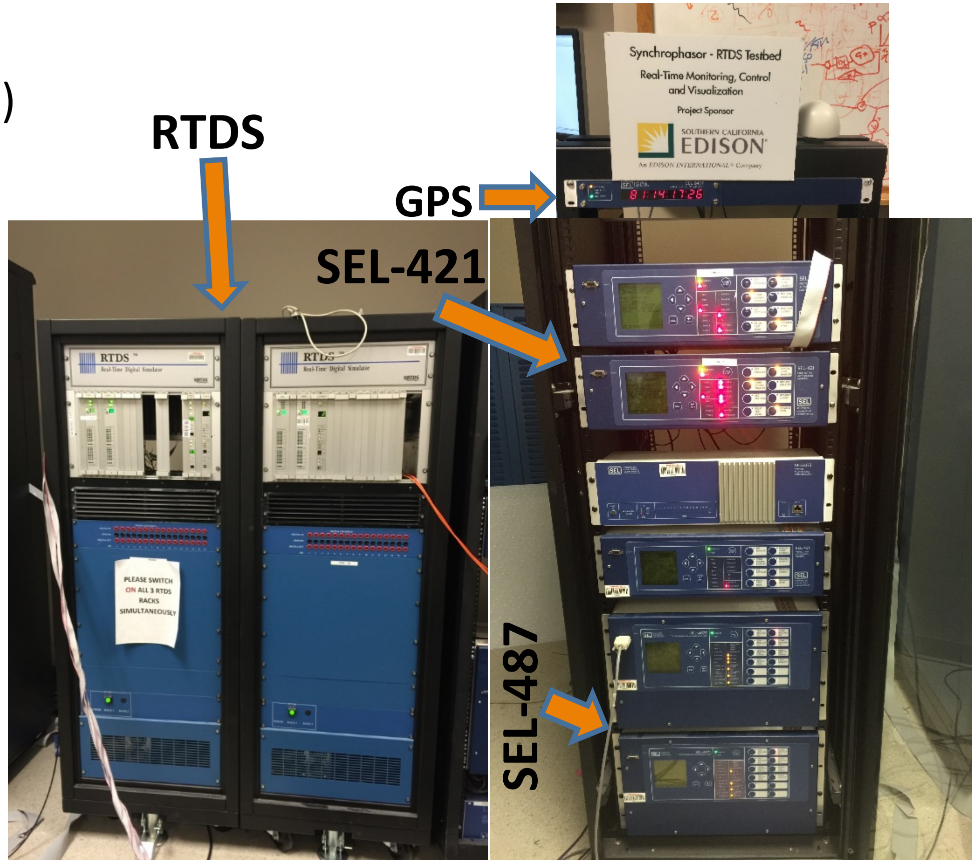
GTNETx2 – Gigabit Transceiver Network interface card to communicate with remote station. Multiple protocols (TCP socket, DNP, …) IEEE 754 floating-point and integer type.



PMU – 5 units: 3 SEL-421 & 2 SEL-487

Functions: accepting IRIG-B signal for satellite synchronization

GPS – SEL-2407 Satellite-Synchronized Clock



Components: ExoGENI

GENI – Global Environment for Network Innovation project (Distributed IaaS)

1. Develop and deploy integrated network testbeds
2. Support research and innovation in networking, operating systems, distributed systems, future Internet architectures, and **deeply networked, data-intensive cloud computing**.

ExoGENI – links GENI to two advances in virtual IaaS services

1. open cloud computing 2. dynamic circuit fabrics

It orchestrates a federation **of independent cloud sites** and **circuit providers** through **native IaaS interfaces**

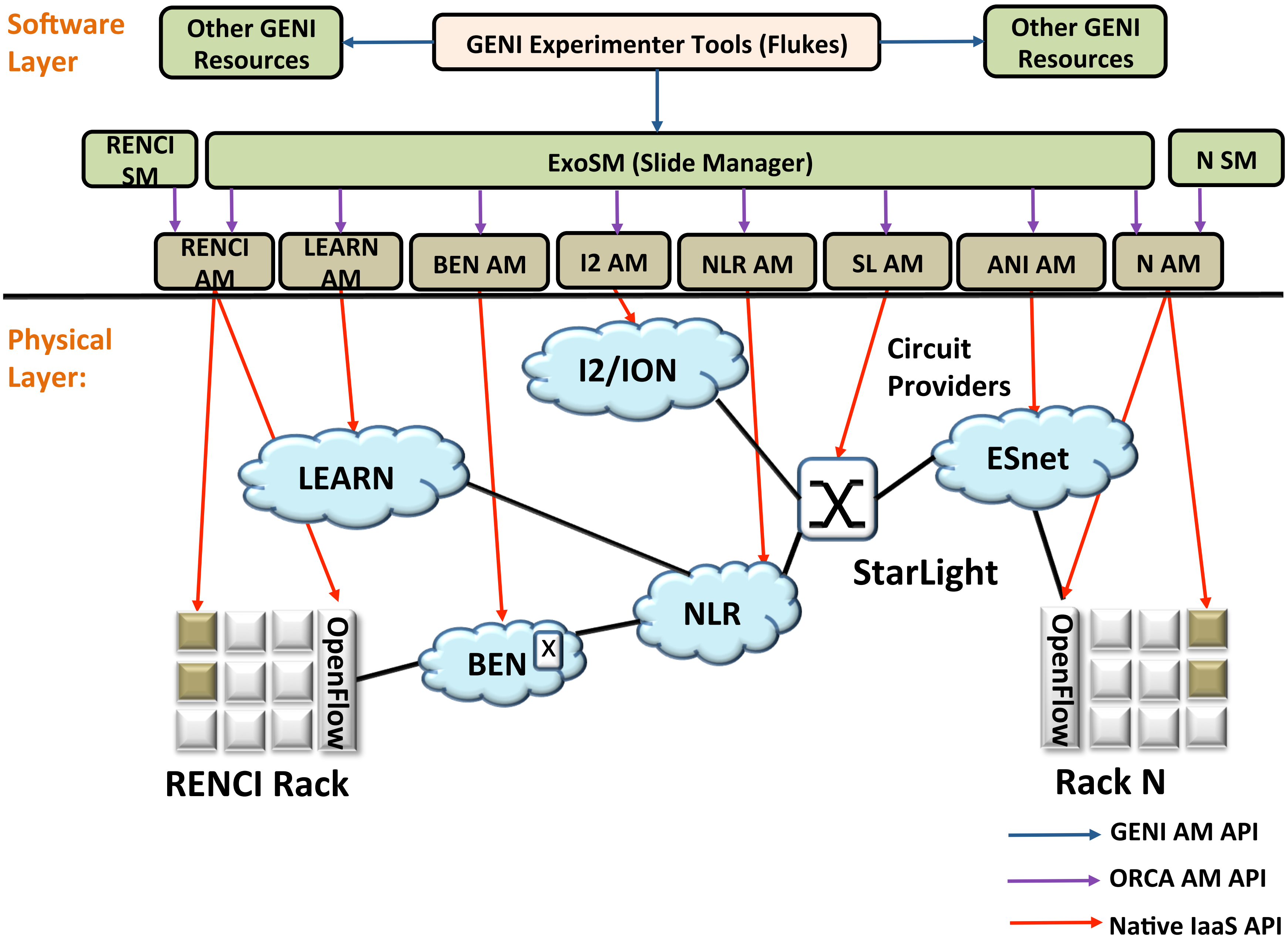
→ **ExoGENI is a networked cloud computing platform for innovative research on distributed applications of Wide-Area Monitoring and Control. (14 rack sites at uni. & labs over U.S.)**

Components of ExoGENI:

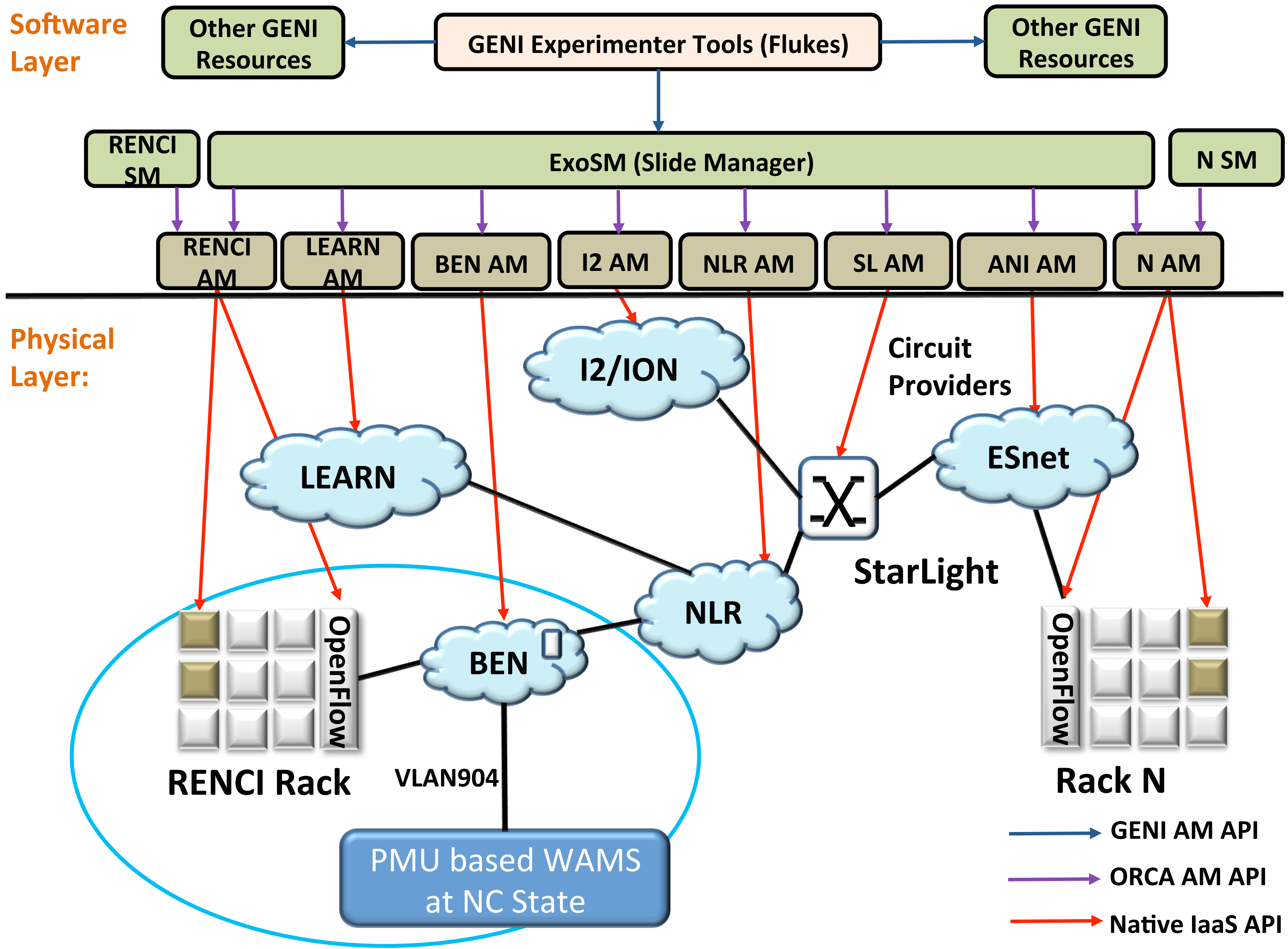
- **Physical layer: rack sites and circuit providers**
- **Software layer:**

ORCA Aggregate Manager (AM) (Open Resource Control Architecture)	**Each site has an ORCA AM including 1. a cloud handler plugin to invoke OpenStack APIs (cloud service) 2. an ImangeProxy server to obtain node imanges named by a URL in the request**
ORCA Slice Manager (SM)	designate an OpenFlow controller to manage traffic, manage each slice

Components: ExoGENI

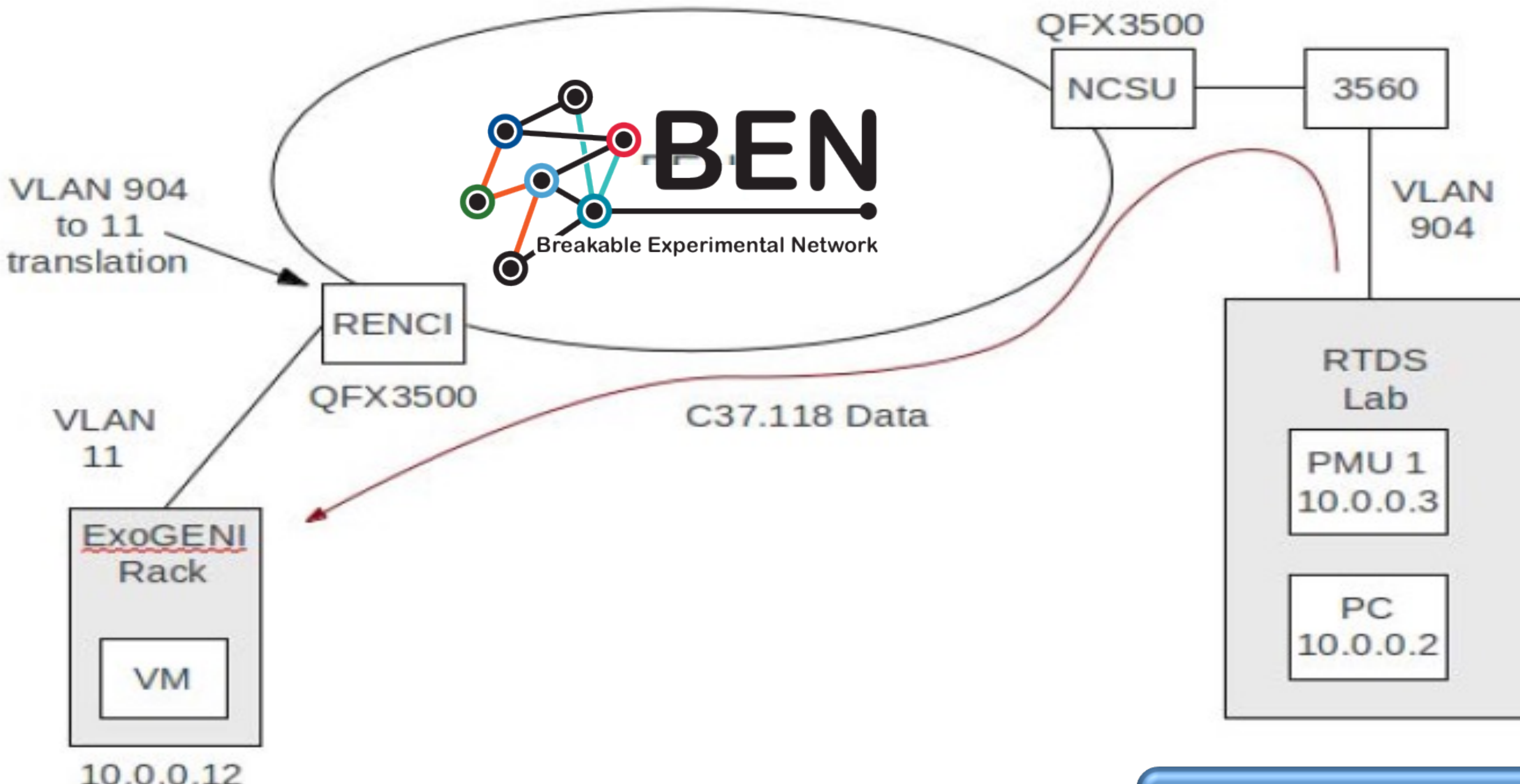


Integration through BEN



Integration through BEN

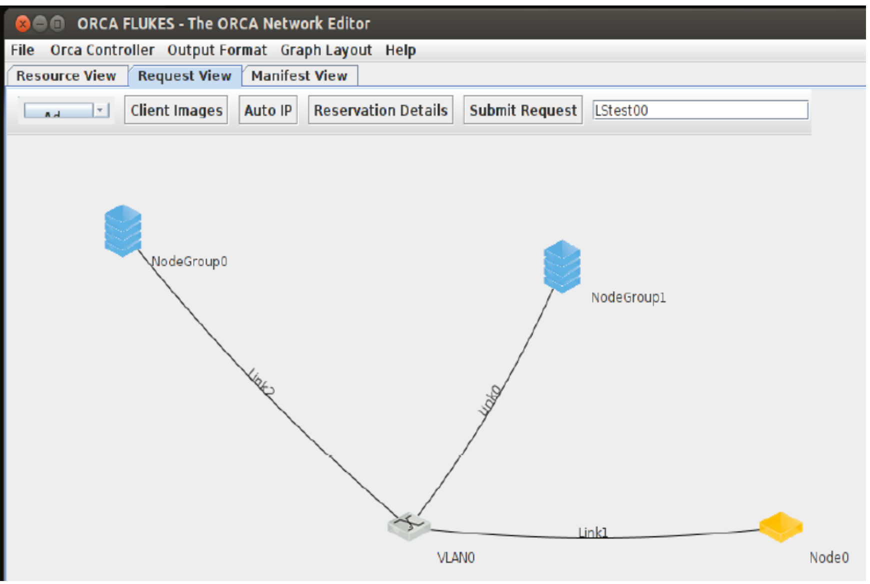
- BEN: Breakable Experimental Network
  - 10Gbps Dark fiber interconnecting RENCI, UNC, Duke and NCSU campuses

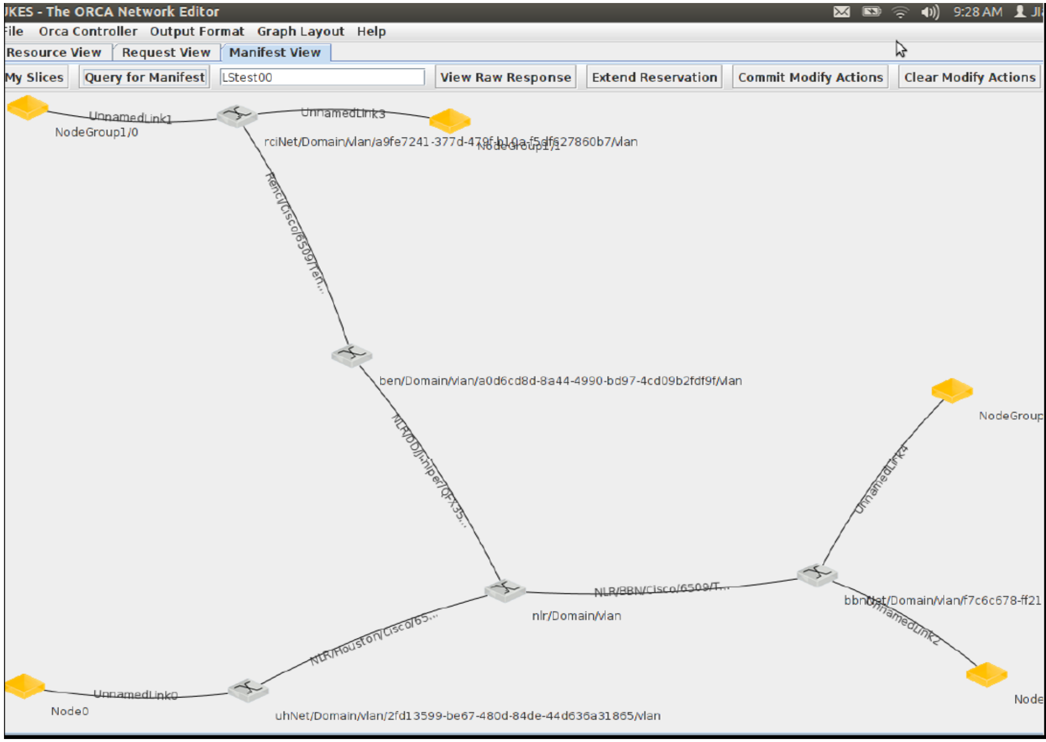


PMU based WAMS at NC State

Experimental Process on ExoGENI testbed

- Create customized OS image for Virtual Machines and C/C++ source code for algorithms.
- Run experiments using a web-start app Flukes through 1. creating network topologies on ExoGENI; 2. executing distributed applications on networked VMs





Validation of ExoGENI-WAMS testbed

- **Visualization of Power Grid**
- **Distributed Oscillation Monitoring Algorithm**
- **Distributed Storage System (DSS) for Multiple Applications**

Features of DSS:

1. support multiple WAMC applications with different resolutions of PMU data;

2. guarantee Quality of Service in network delay

3. network failure tolerance – each PMU storages data to 2 storage nodes

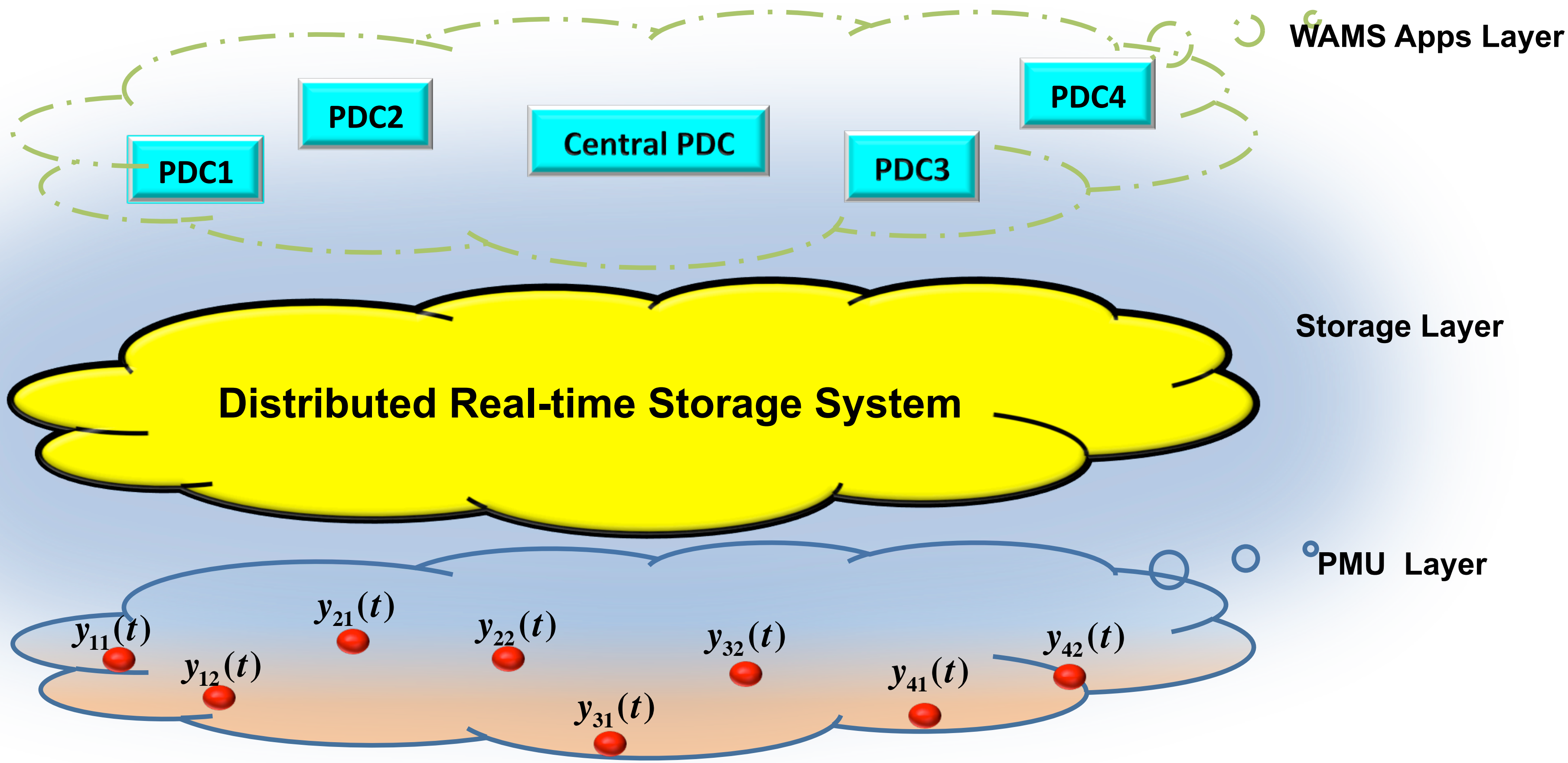
4. self-recoverability

- **Distributed Control Algorithm**

Distributed Storage System with S-ADMM

Storage System + Synchronized ADMM

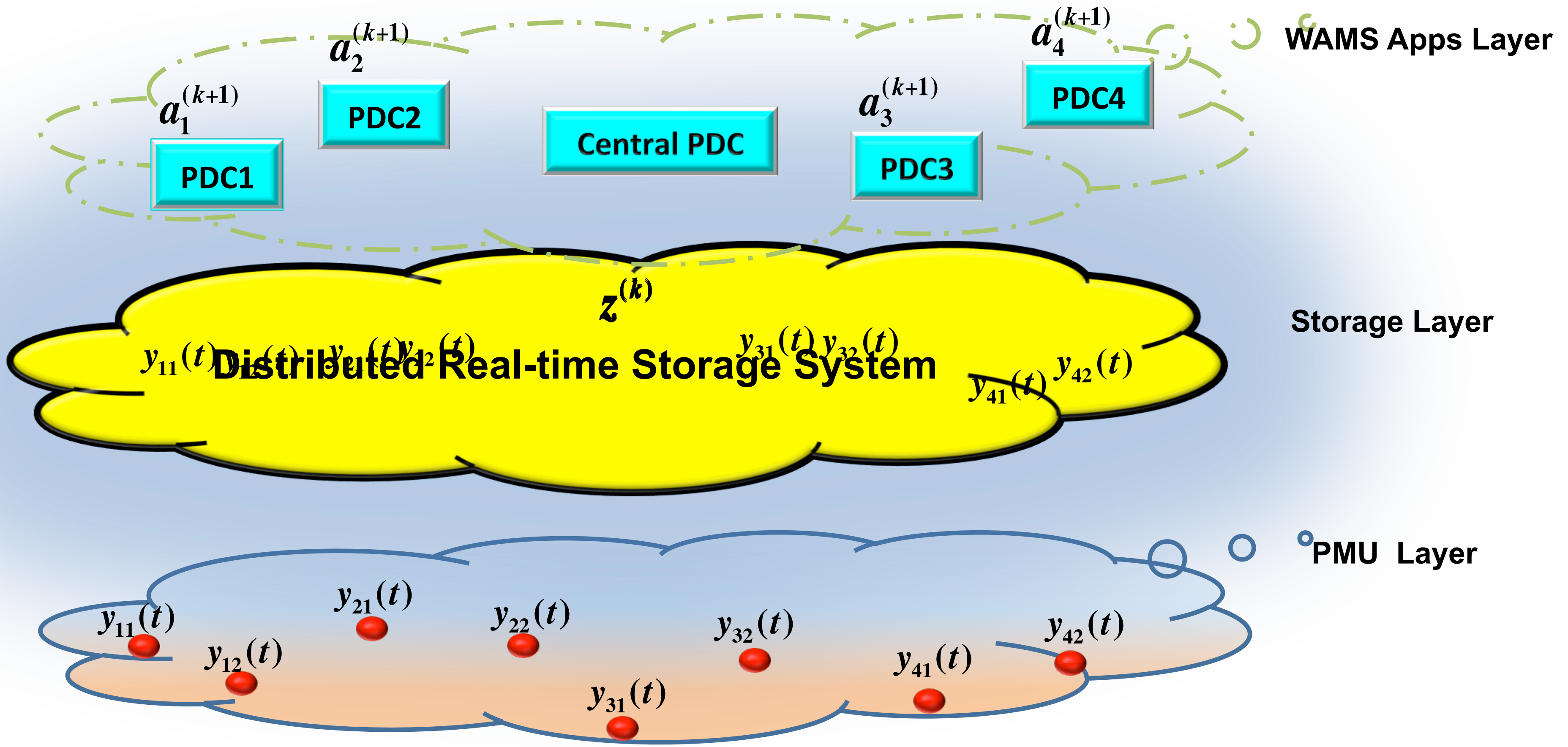
Step 1: PMUs keep storing data into Storage System



Distributed Storage System with S-ADMM

Storage System + Synchronized ADMM

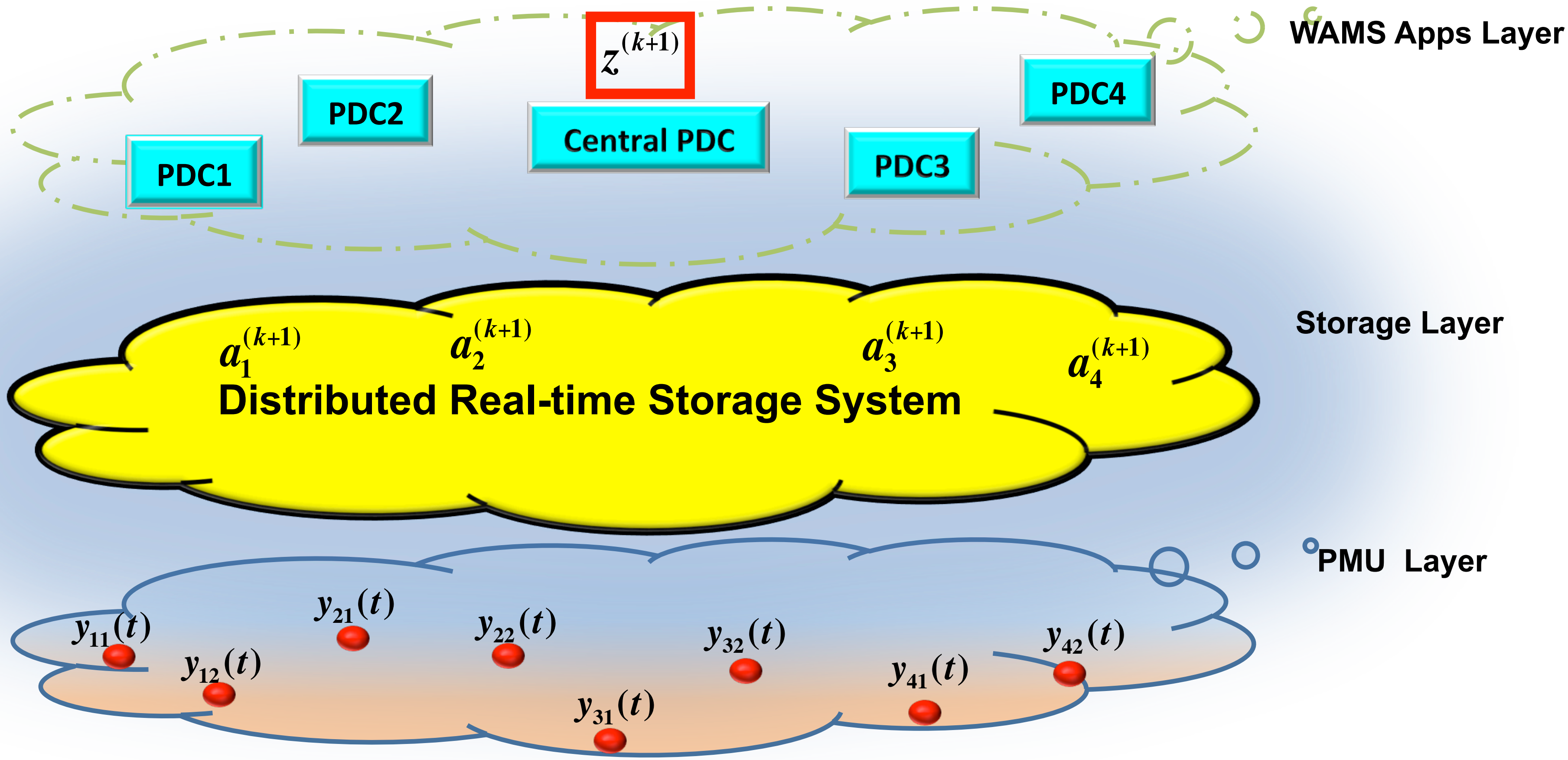
Step 2: Local PDCs request PMU data, locally estimate, and send results back



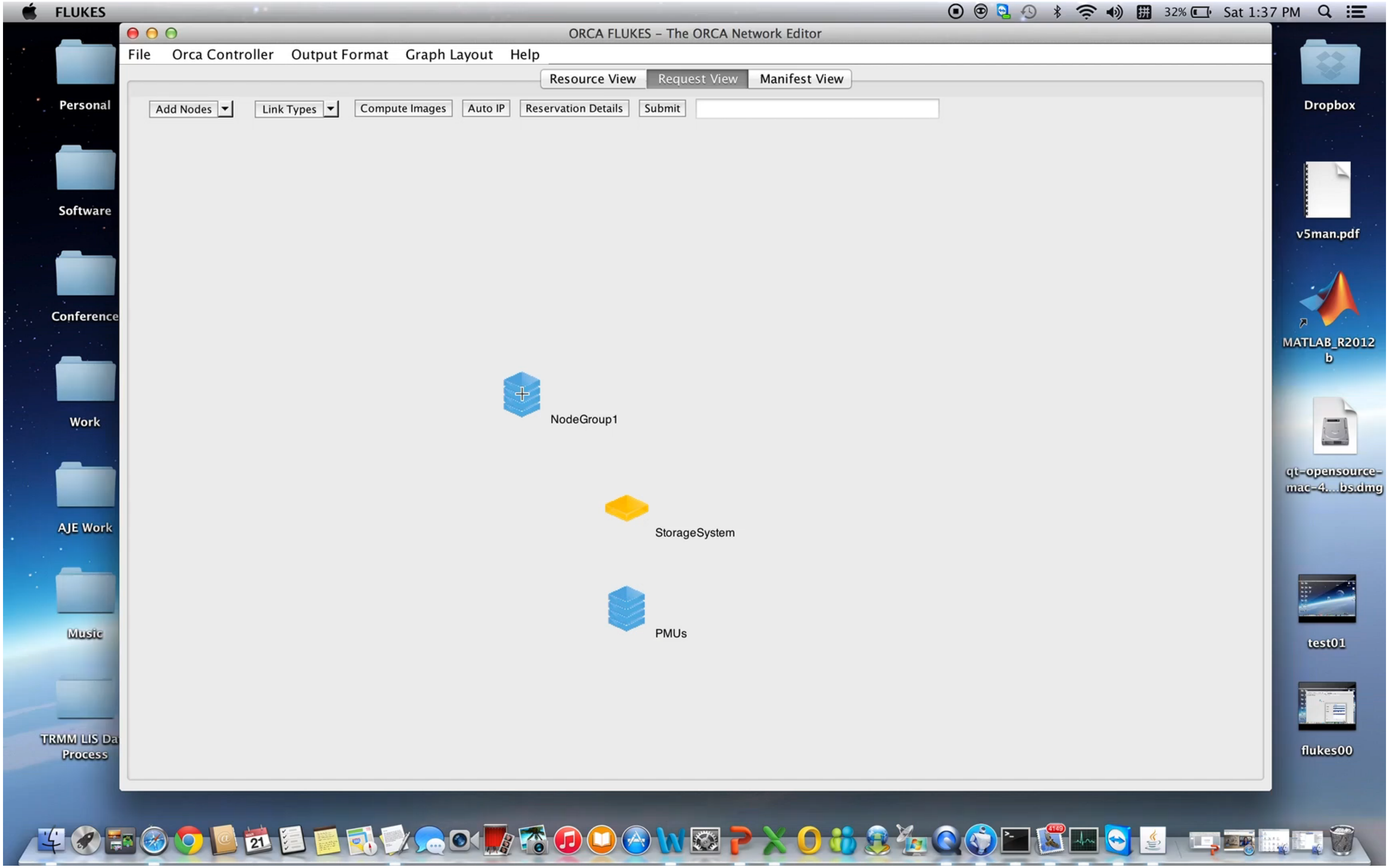
Distributed Storage System with S-ADMM

Storage System + Synchronized ADMM

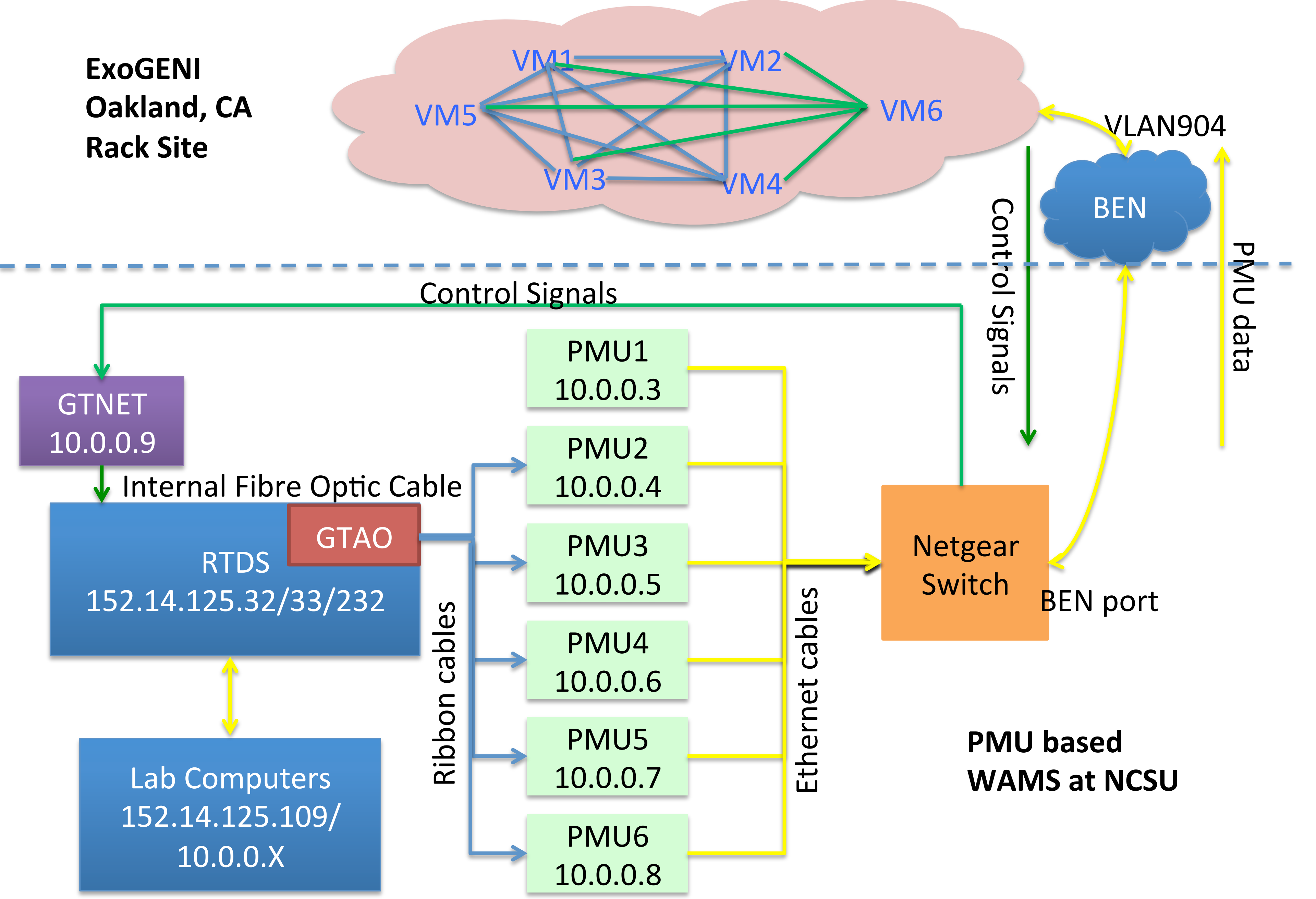
Step 3: Central PDC receives all local estimate, and compute consensus value, then send it back SS



Implementation of Distributed Storage System

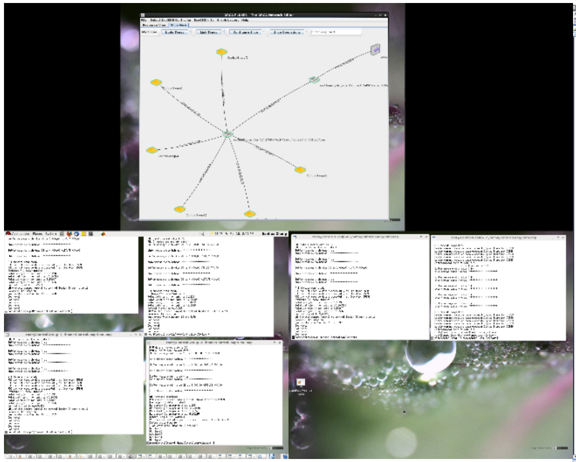


Implementation of Distributed Control Alogrithm

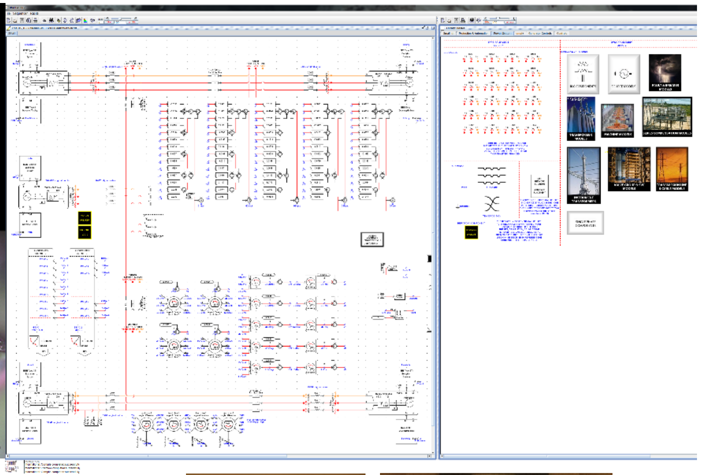


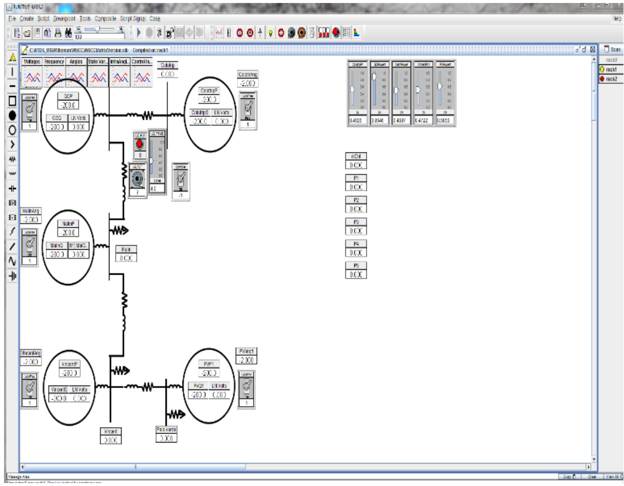
Implementation of Distributed Control Alogrithm

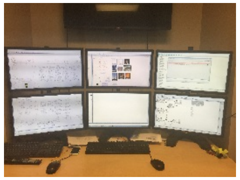
ExoGENI screens



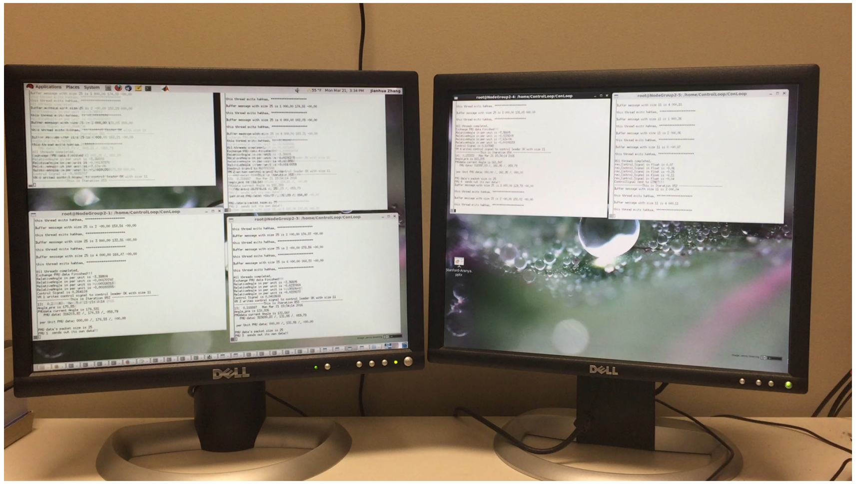
RTDS screens

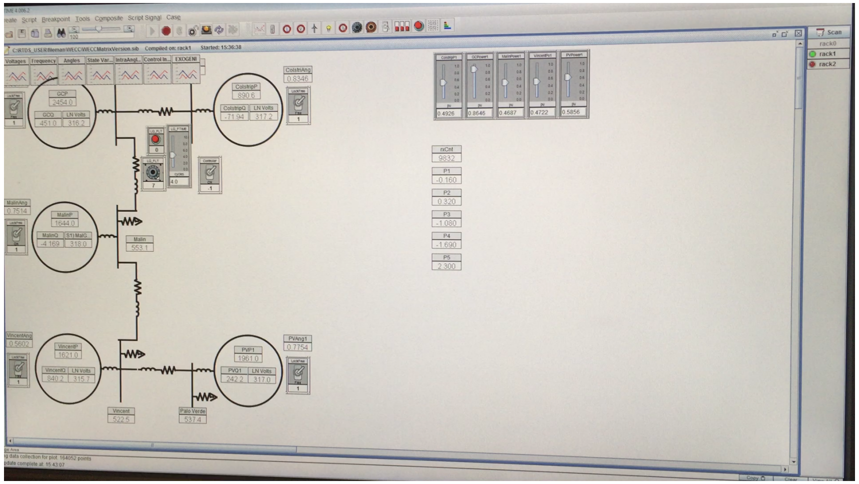






Videos for Experimental Running

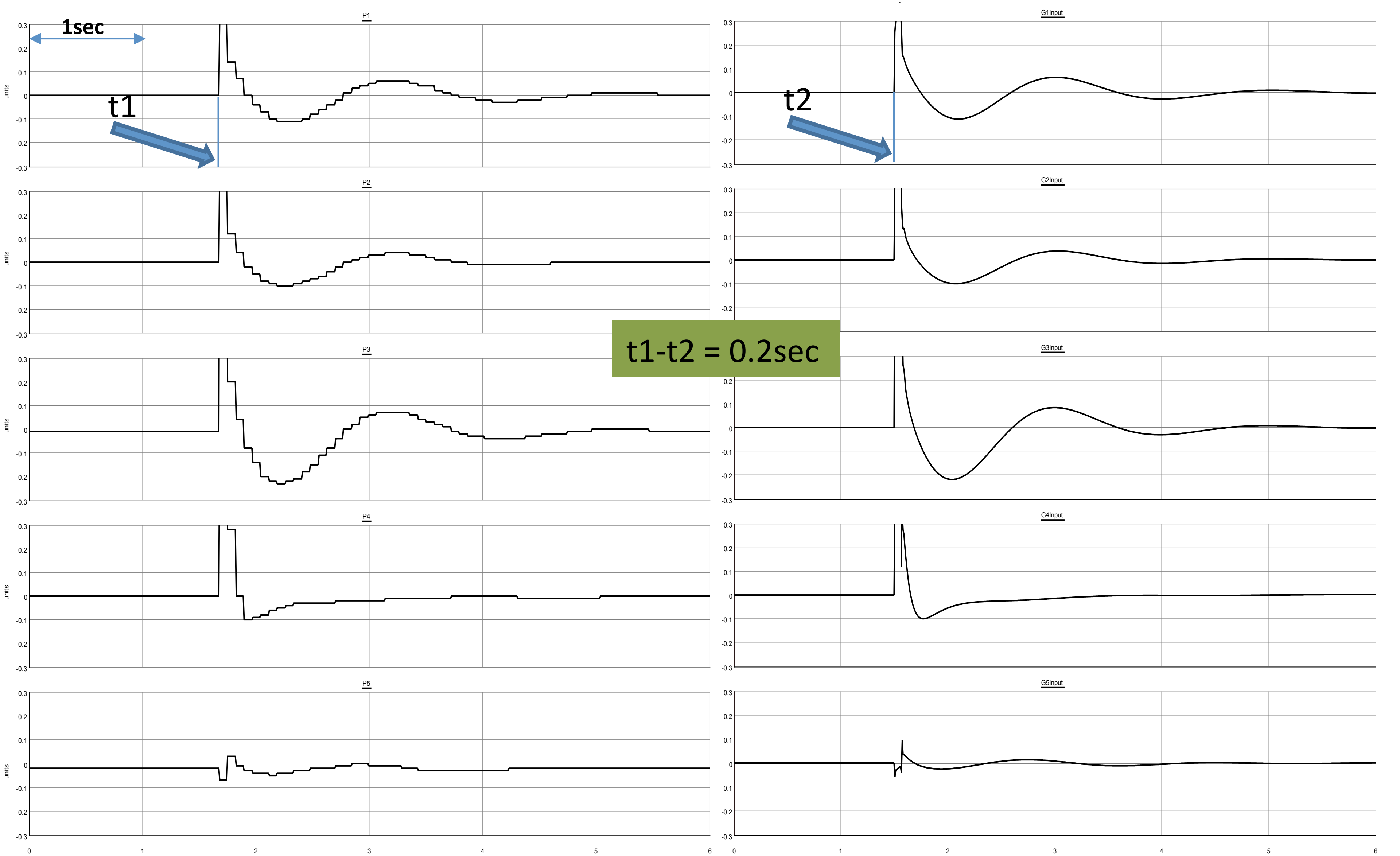




Implementation of Distributed Control Alogrithm

Control Signals from ExoGENI

Control Signals from RSCAD



Conclusion and Future Work

Conclusions

- Introduce ExoGENI-WAMS cyber-physical networkd cloud computing testbeds including architecture, components and integrations
- Demonstrate multiple applications of Wide-Area Monitoring and Control through ExoGENI-WAMS testbed

Future work

- Investigate two of the most important and typical cyber-physical challenges: 1) end-to-end delay 2) attack-resiliency, by implementing these cyber-physical algorithms on the ExoGENI-WAMS testbed