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A US-Wide ExoGENI-WAMS Testbed for Wide-Area Monitoring and Control of Power Systems

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NASPI User Group Meeting,

San Mateo, March 23 2015

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Research Objectives

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

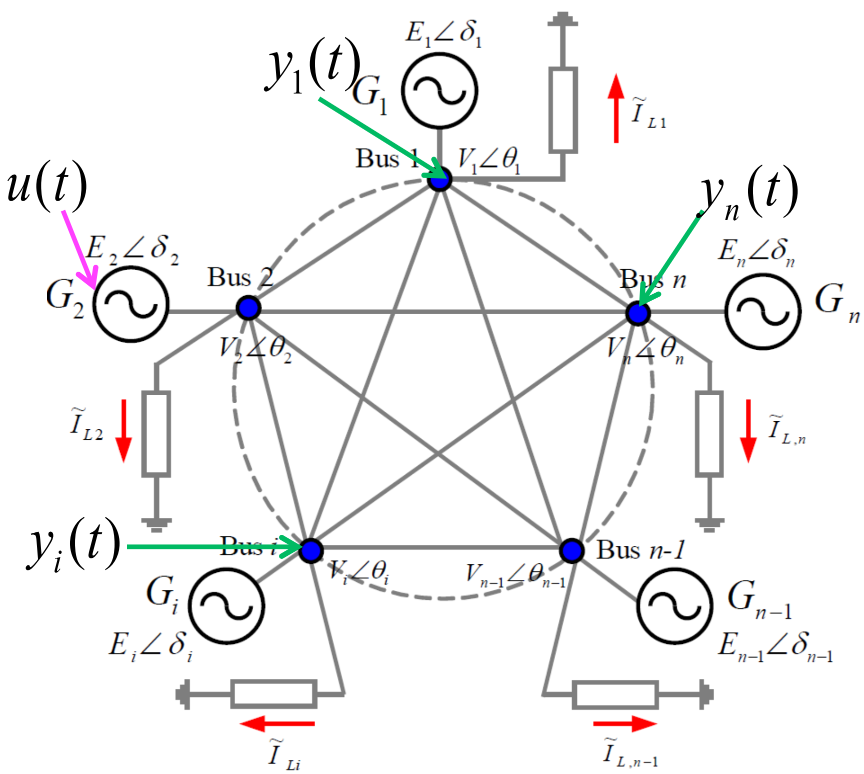
- Develop theoretical distributed optimization algorithms for wide-area monitoring and control of over a secure communication network
  - test stability, convergence and robustness.

- Experimental verify different estimation algorithms using the ExoGENI-WAMS testbed:

  1. Distributed estimation and damping control of wide-area oscillation modes
  2. Distributed estimation of energy function for transient stability assessment.
  3. Distributed estimation of voltage stability metrics

Wide-Area Oscillation Monitoring

Using PMU measurements to estimate frequency and damping factor of different EM oscillation modes , $\lambda_i(A)$, which is equivalent to estimating the characteristic polynomial of its transfer function.



$$G_1(z) = \frac{Y_1(z)}{U(z)} = \frac{a_0 + a_1 z^{-1} + \ldots + a_{m_1} z^{-m_1}}{1 + b_1 z^{-1} + \ldots + b_{2n} z^{-2n}}$$

$$\vdots$$

$$G_i(z) = \frac{Y_i(z)}{U(z)} = \frac{c_0 + c_1 z^{-1} + \ldots + c_{m_i} z^{-m_i}}{1 + b_1 z^{-1} + \ldots + b_{2n} z^{-2n}}$$

$$\vdots$$

$$G_n(z) = \frac{Y_n(z)}{U(z)} = \frac{c_0 + c_1 z^{-1} + \ldots + c_{m_n} z^{-m_n}}{1 + b_1 z^{-1} + \ldots + b_{2n} z^{-2n}}$$

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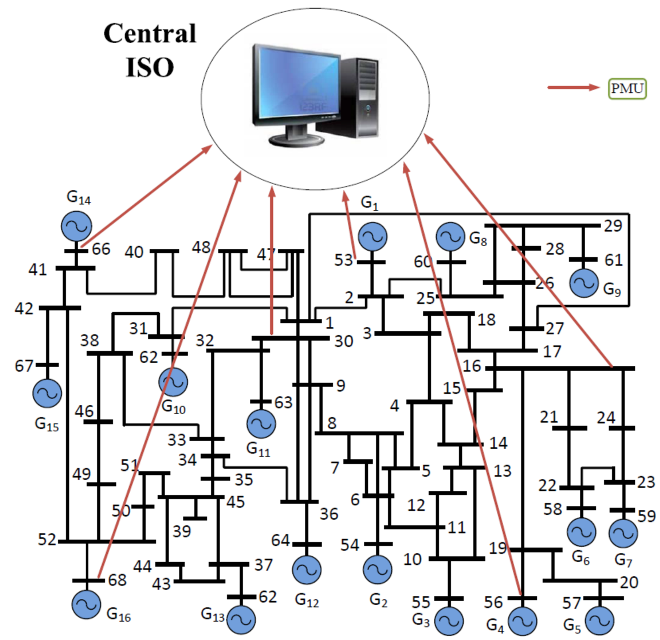
CLS &DLS

Centralized LS (CLS)

$$A = col(y_i(1), y_j(1), y_i(2), y_j(2), \ldots, y_i(K), y_j(K))$$

$$B = \begin{bmatrix} \phi_i(1) & U_i(1) & 0 \\ \phi_j(1) & 0 & U_j(1) \\ \phi_i(2) & U_i(2) & 0 \\ \phi_j(2) & 0 & U_j(2) \\ \vdots & \vdots & \vdots \\ \phi_i(K) & U_j(K) & 0 \\ \phi_i(K) & 0 & U_j(K) \end{bmatrix}_{2K\times(n+m_i+m_j+2)} \Rightarrow \beta = -\left[B^{-1}A\right]^{+n}$$



Decentralized LS (DLS)

$$A_i = col(y_i(1), y_i(2), \ldots, y_i(K))$$

$$B_i = \begin{bmatrix} \phi_i(1) & U_i(1) \\ \phi_i(2) & U_i(2) \\ \vdots & \vdots \\ \phi_i(K) & U_i(K) \end{bmatrix}_{K\times(n+m_i+1)}$$

$$\Rightarrow \quad \beta_i = -\left[B_i^{-1}A_i\right]^{+n} \qquad \beta_j = -\left[B_j^{-1}A_j\right]^{+n}$$

$$\overline{\beta} = \frac{\beta_i + \beta_j}{2}$$

Recursive Least-Square (RLS)

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A **real-time** parameter estimation method

1. For each measurement, the discrete-domain equation is generalized as below

$$y_i(k) = \begin{bmatrix} \phi_i(k) & U_i(k) \end{bmatrix} \begin{bmatrix} \beta \\ \gamma_i \end{bmatrix} \Rightarrow y_k = \phi_k^T \theta$$

2. To estimate θ_K , we follow the standard least-squares algorithm

$$\min_{\theta_K} \sum_{k=0}^{K-1} (y_k - \phi_k^T \theta_K)^2 \Rightarrow \theta_K = (\sum_{k=0}^{K-1} \phi_k \phi_k^T)^{-1} (\sum_{k=0}^{K-1} y_k \phi_k)$$

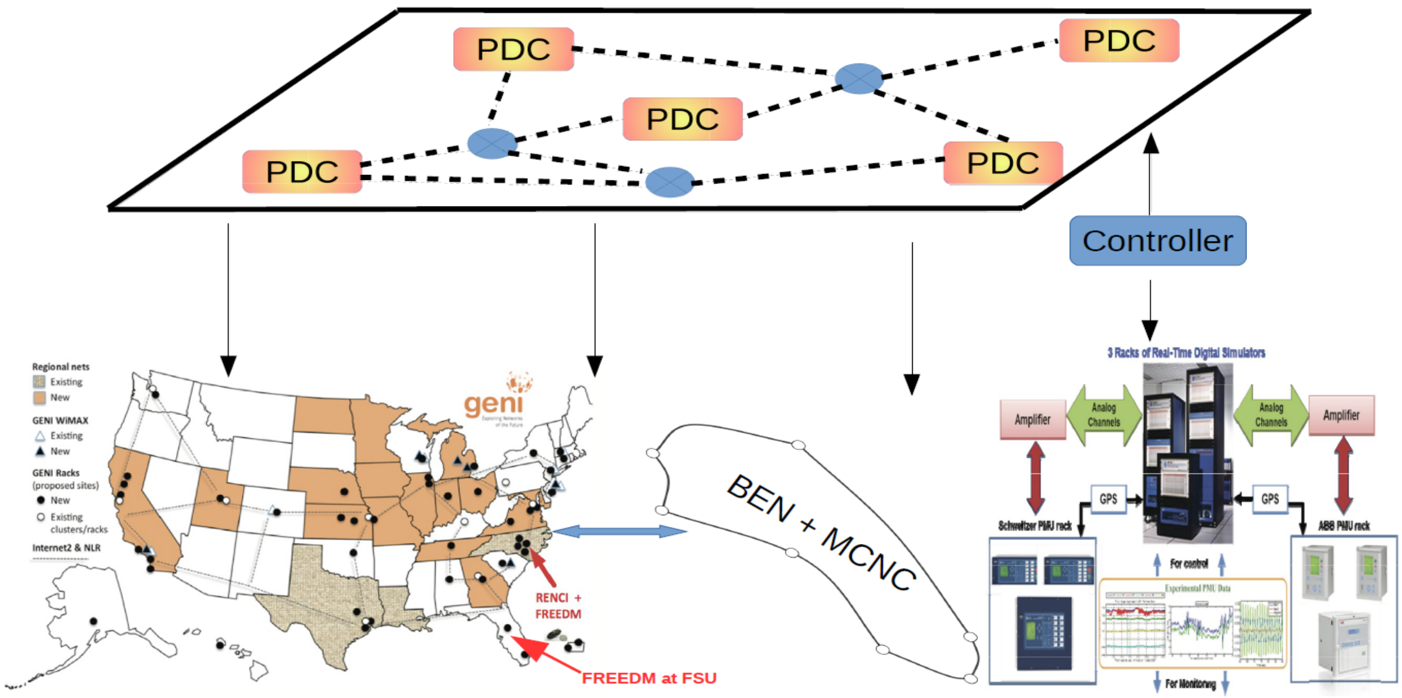
3. Define another cost function

$$\min_{\theta_K} (\sum_{k=0}^{K-1} (y_k - \phi_k^T \theta_K)^2 + (\theta_K - \theta_0)^T R_0 (\theta_K - \theta_0)) \Rightarrow$$

$$\theta_K = (R_0 + \sum_{k=0}^{K-1} \phi_k \phi_k^T)^{-1} (R_0 \theta_0 \sum_{k=0}^{K-1} y_k \phi_k)$$

ExoGENI Testbed for Wide-Area Monitoring

- RTDS: Simulate high fidelity detailed models of large power systems
- ExoGENI: Widely distributed networked IaaS platform for experimentation and computational tasks.
- WAMS: Multi-ventor PMU-based hardware-in-loop simulation testbed.
- PDCs connected to ExoGENI network through 10 Gbps Breakable Experimental Network (BEN).



RTDS Lab at FREEDM Center

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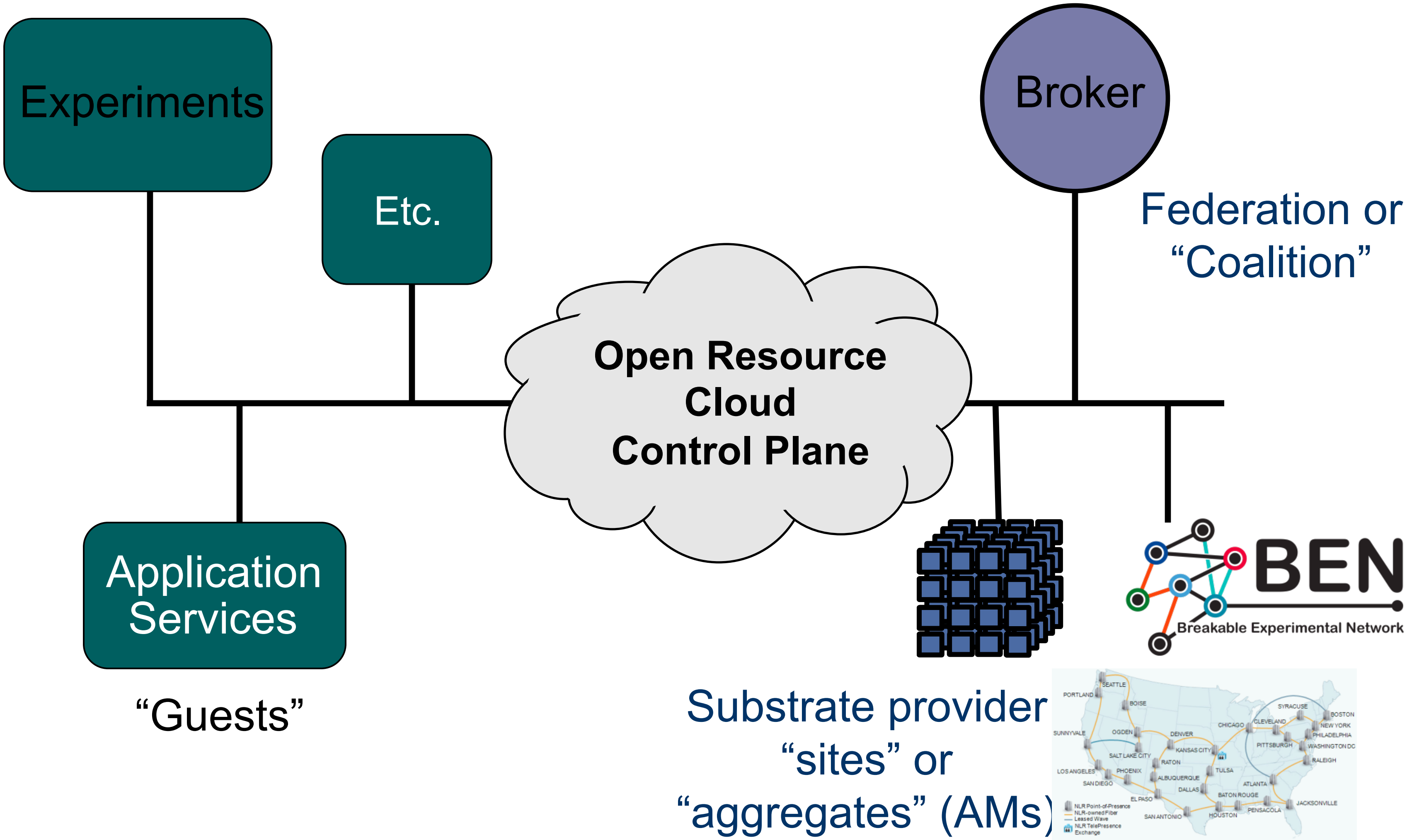
BEN Breakable Experimental Network

- BEN: Breakable Experimental Network
  - Dark fiber interconnecting RENCI, UNC, Duke and NCSU campuses
  - **Unique testbed for developing disruptive distributed technologies**
  - Managed by RENCI for Triangle Universities
- Multi-layered, high-performance (multiple 10Gbps), dedicated to research
- Controlled by ORCA software
  - Open Resource Control Architecture (ORCA)
  - A framework for distributed computational, network substrate orchestration


ORCA
c whale-images.com


Experiments
Etc.
Application Services
"Guests"
Open Resource Cloud Control Plane
Broker
Federation or "Coalition"
BEN
Breakable Experimental Network
Substrate provider "sites" or "aggregates" (AMs)

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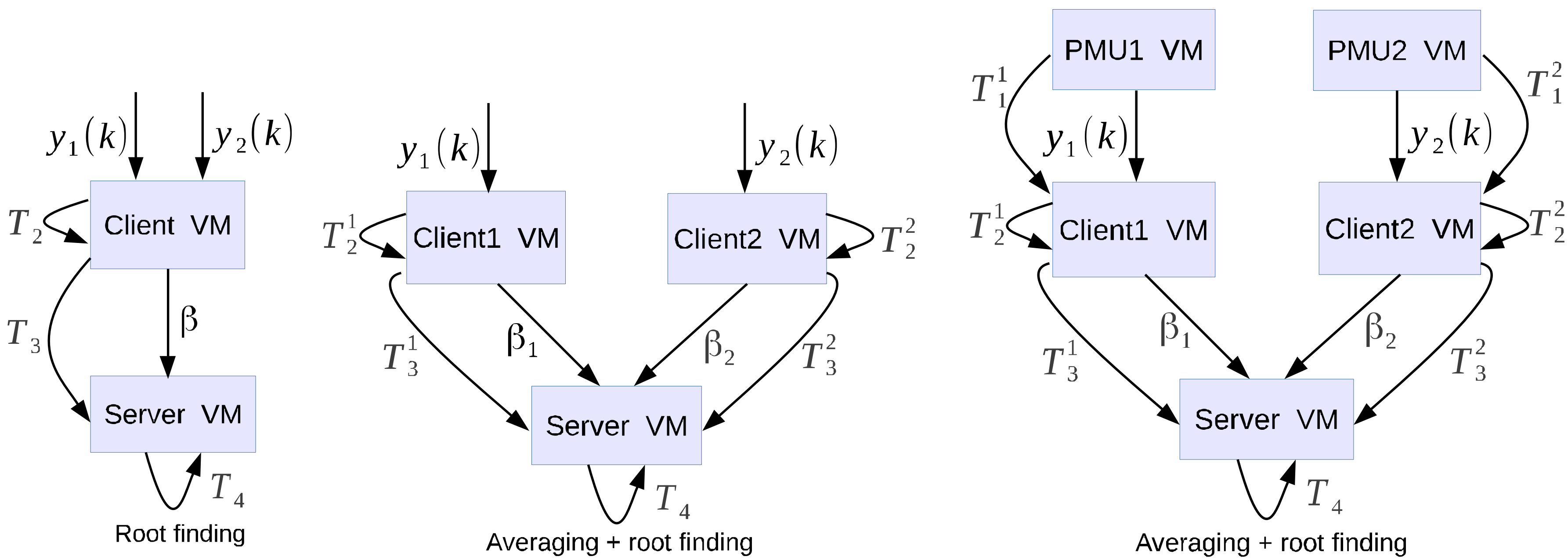
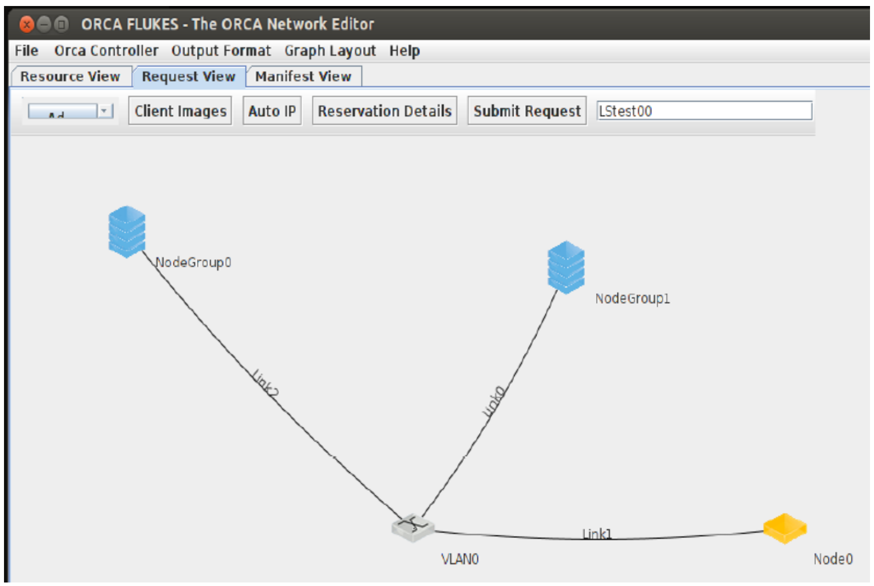
Design Network Topologies

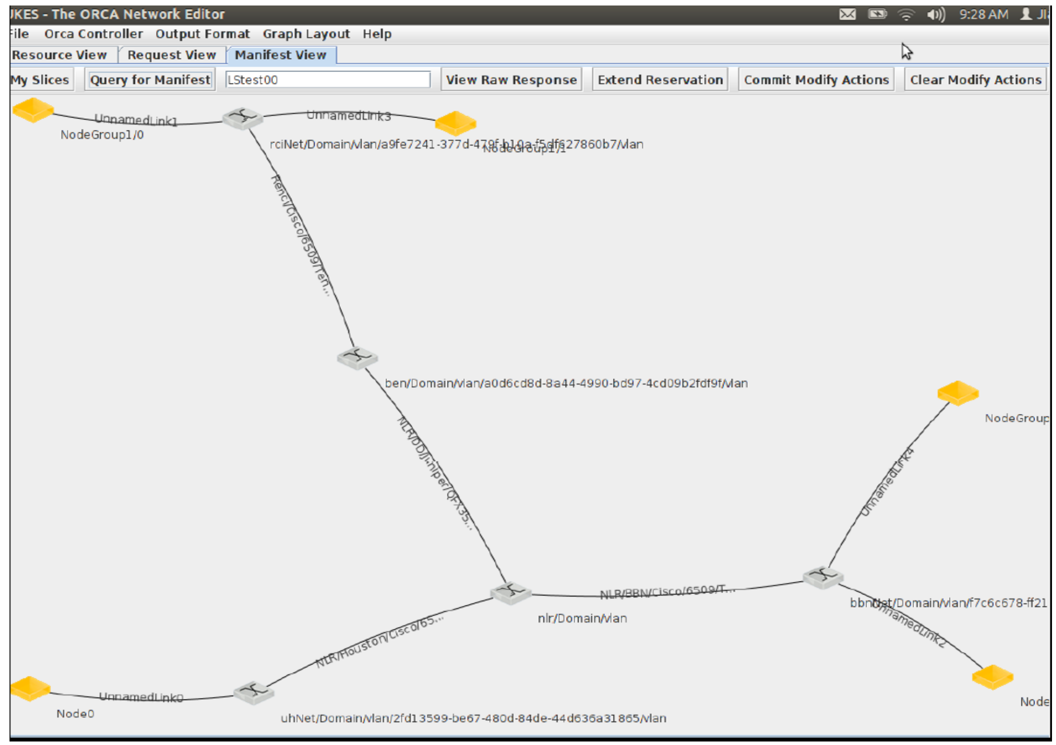


(a) Centralized LS **(b) Decentralized LS** **(c) Decentralized LS v.s. RLS**

Experimental Process in ExoGENI

- Create customized OS image for Virtual Machines and C source code for algorithms.
- Create network topologies on ExoGENI using a web-start app Flukes.





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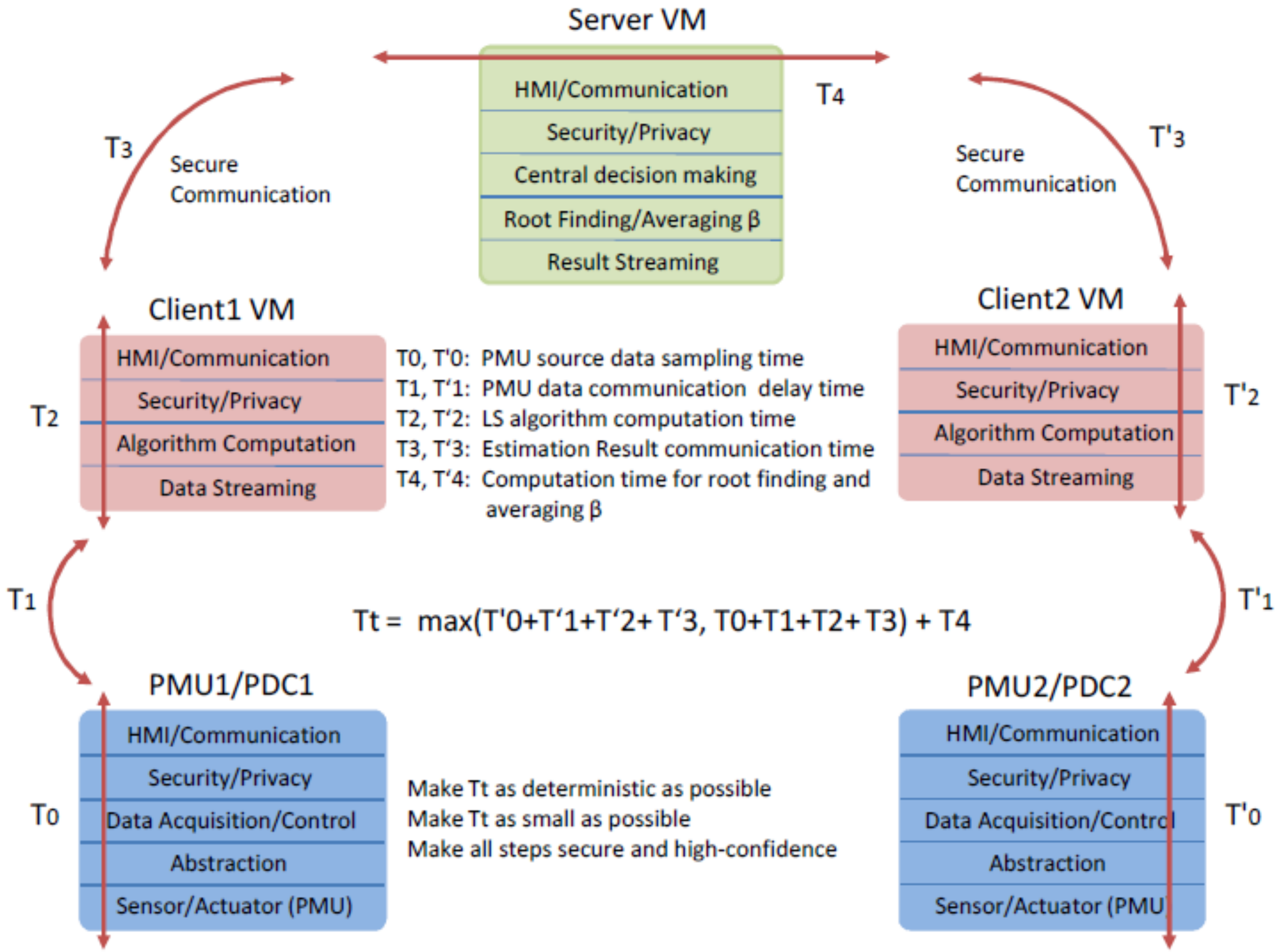
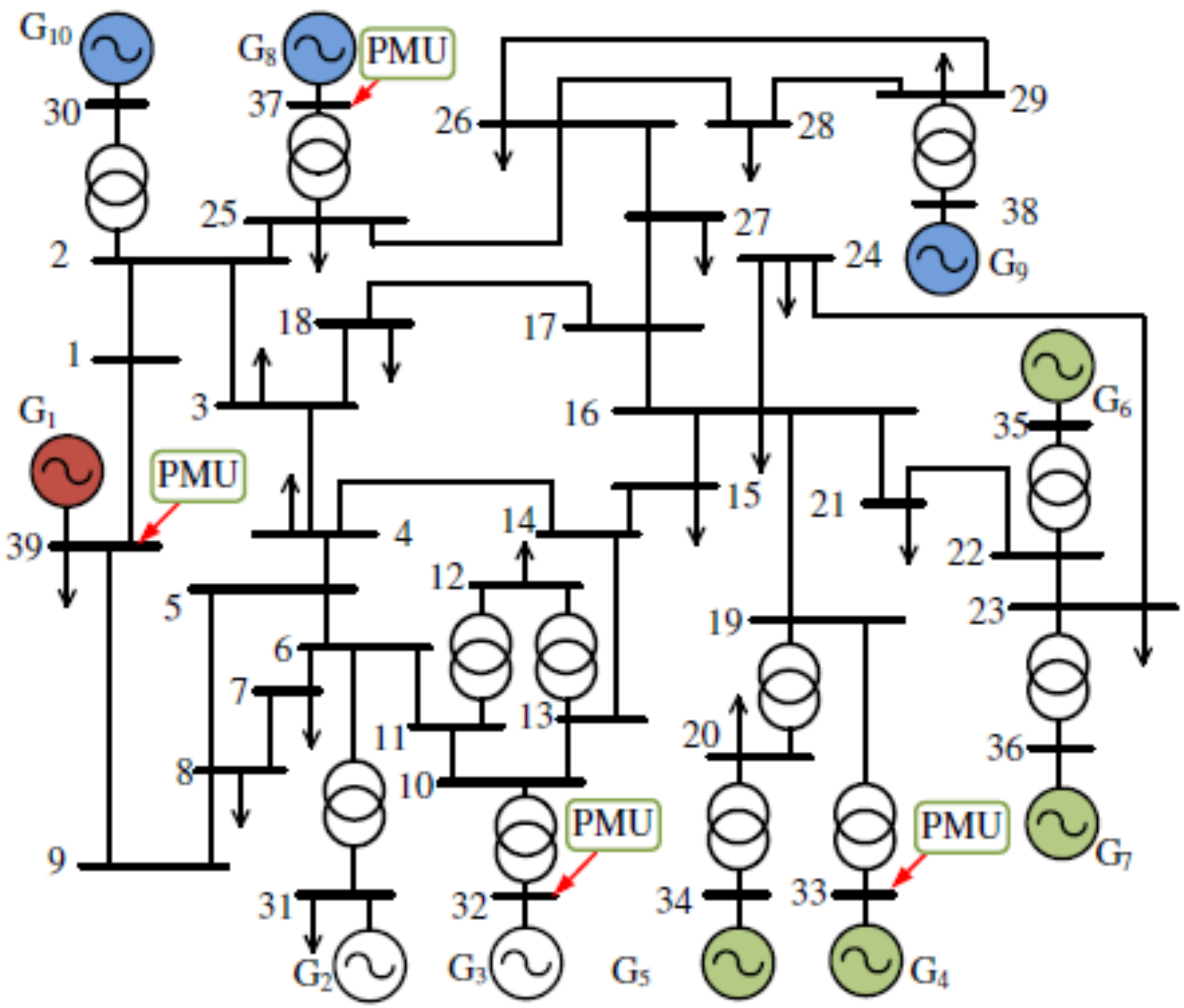
Delay Components



IEEE 39-bus Model



Power System Information:

- 10 machines
- 4 areas
- 4 measurements

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Evaluation Results

1. Accuracy

- DLS and CLS have same accuracy
- RLS loses accuracy to certain extent

2. End-to-end delay

- RLS have less total end-to-end delay
- communication distance and type of PMU data vary total end-to-end delay of RLS

ACCURACY OF CLS, DLS, RLS ESTIMATES

Algorithm	b_1	b_2	b_3	b_4
CLS	-2.2272	0.7047	1.2757	-0.7533
DLS	-2.2273	0.7049	1.2756	-0.7532
RLS	-2.4171	0.7870	1.4393	-0.8136

END-TO-END DELAY OF EXPERIMENT I: CLS VS DLS

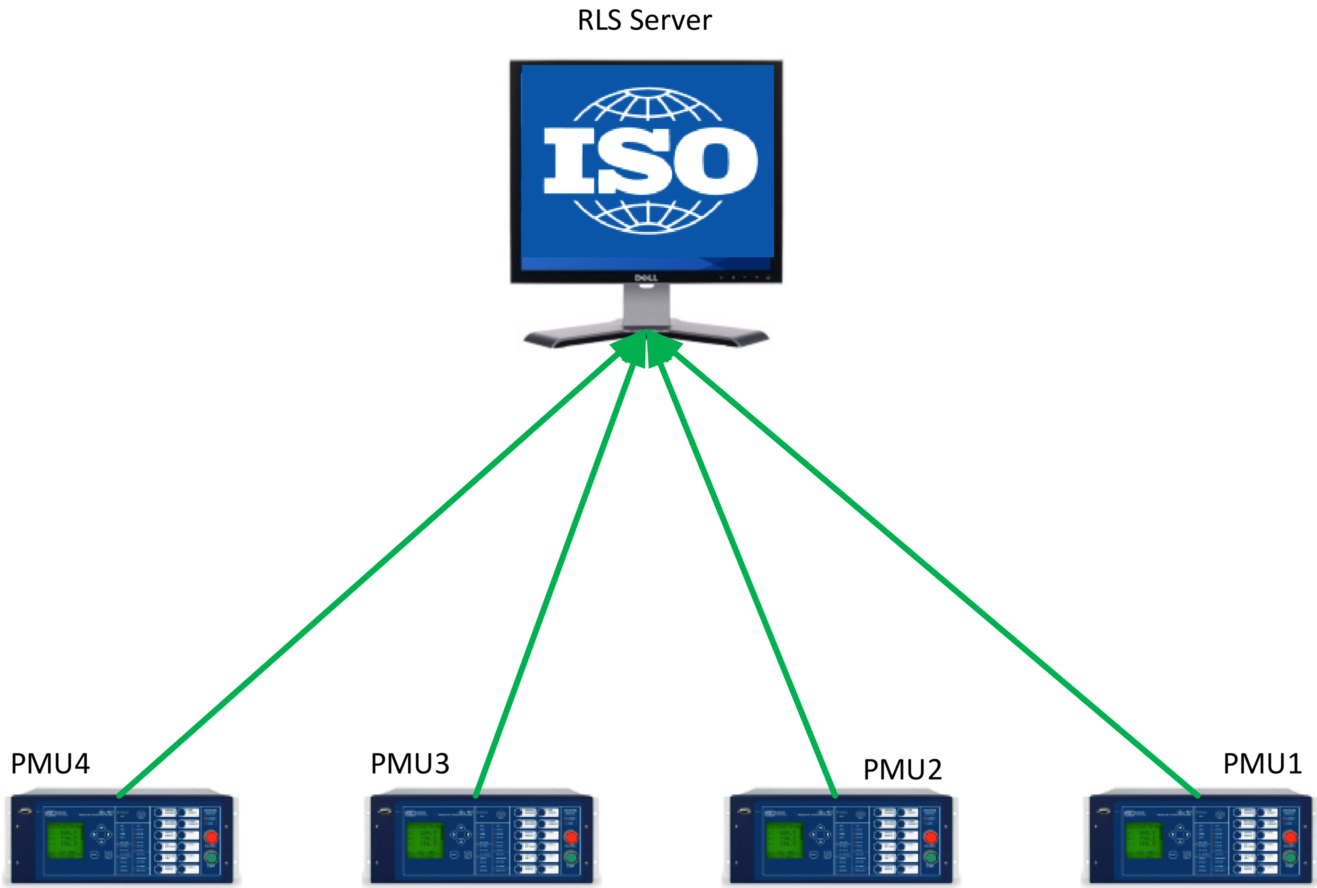
Algorithm	$T_2(us)$	$T_3(us)$	Total (us)
Scenario 1: 3 VMs at RENCI rack			
CLS	134,466	13,054	147,520
DLS	22,088	19,763	54,150
Scenario 2: 2 Clients at RENCI, Server at UvA			
CLS	169,301	3,178,939	3,348,240
DLS	23,752	3,187,137	3,229,170
Scenario 3: Client1 at RENCI, Client2 at Houston, Server at UvA			
CLS	179,913	3,267,583	3,447,497
DLS	26,079	3,191,082	3,274,337

END-TO-END DELAY OF EXPERIMENT II: DLS VS RLS

Algorithm	$T_1 + T_2(us)$	$T_3(us)$	Total (us)
Scenario 1: PMU1 at Boston, Client1 at RENCI, Server at Houston			
DLS	56,417	65,975	122,392
RLS with pmu1	53,517	59,858	113,375
RLS with pmu2	47,665	60,376	108,041
Scenario 2: 2 PMUs at Boston, 2 Client at RENCI, Server at Houston			
DLS	55,974	60,765	121,608
RLS	52,854	61,066	114,924

Malicious Denial-of-Service Attack on Links

Normal Operation



Malicious Denial-of-Service Attack on Links

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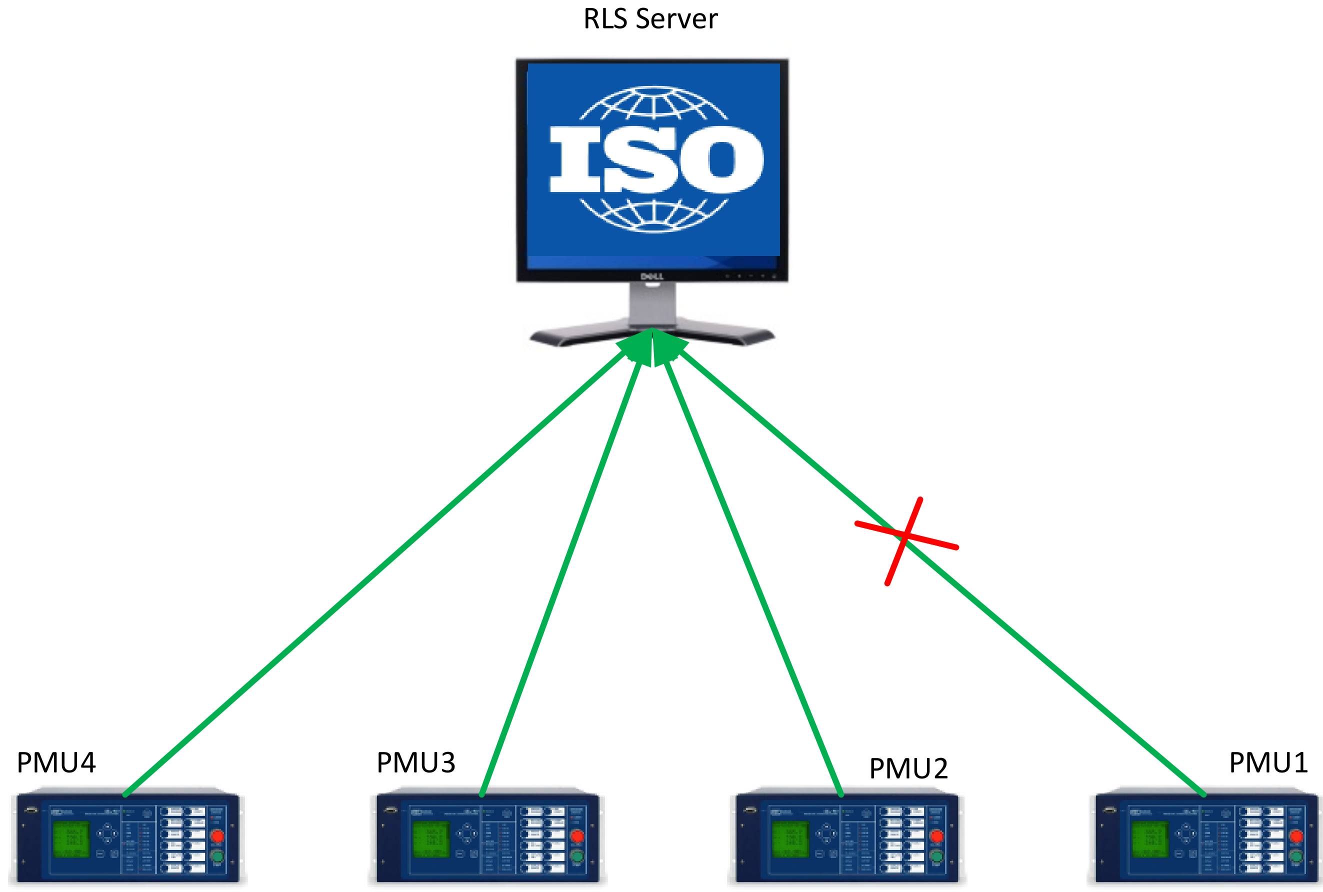
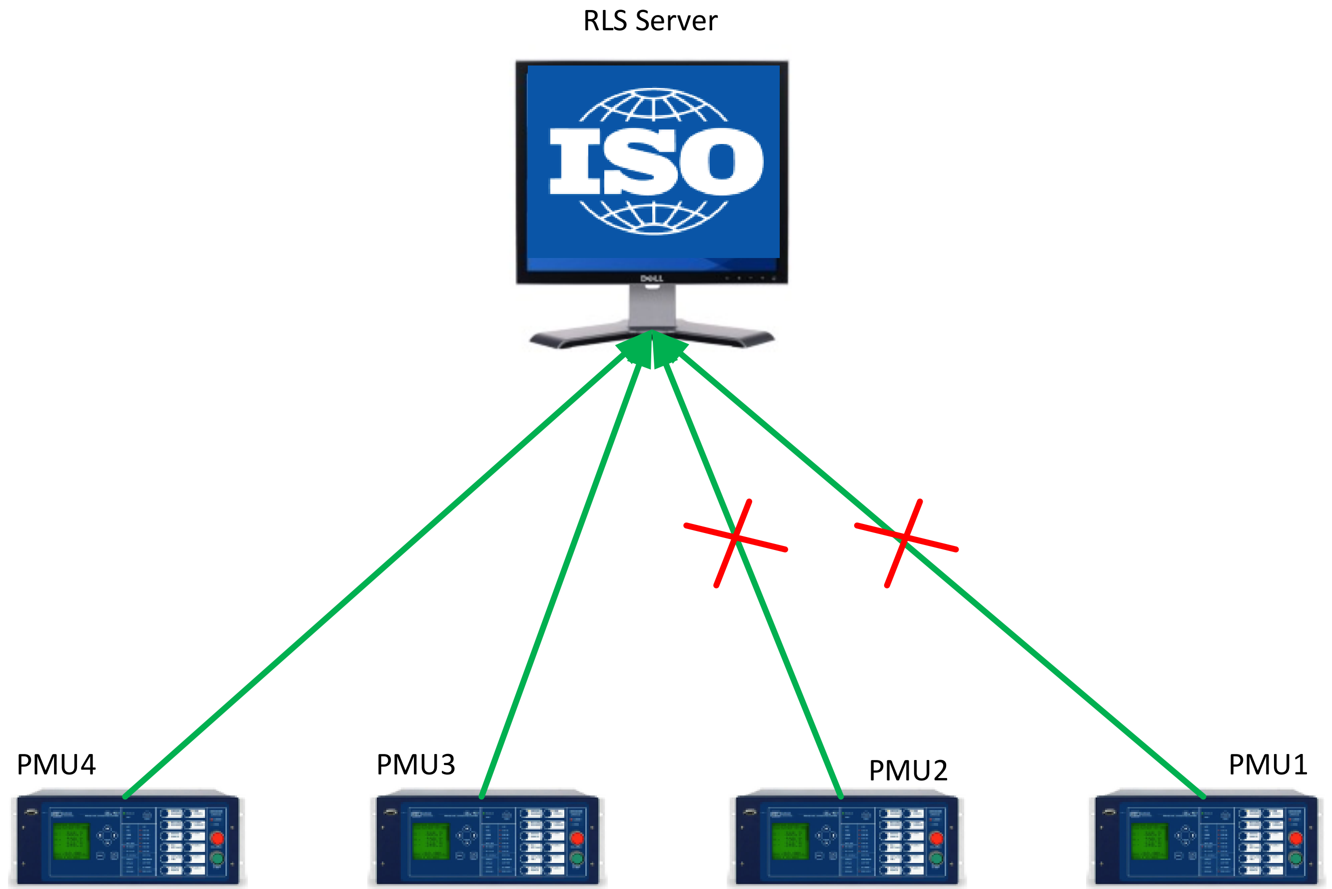
Attack-Strategy 0



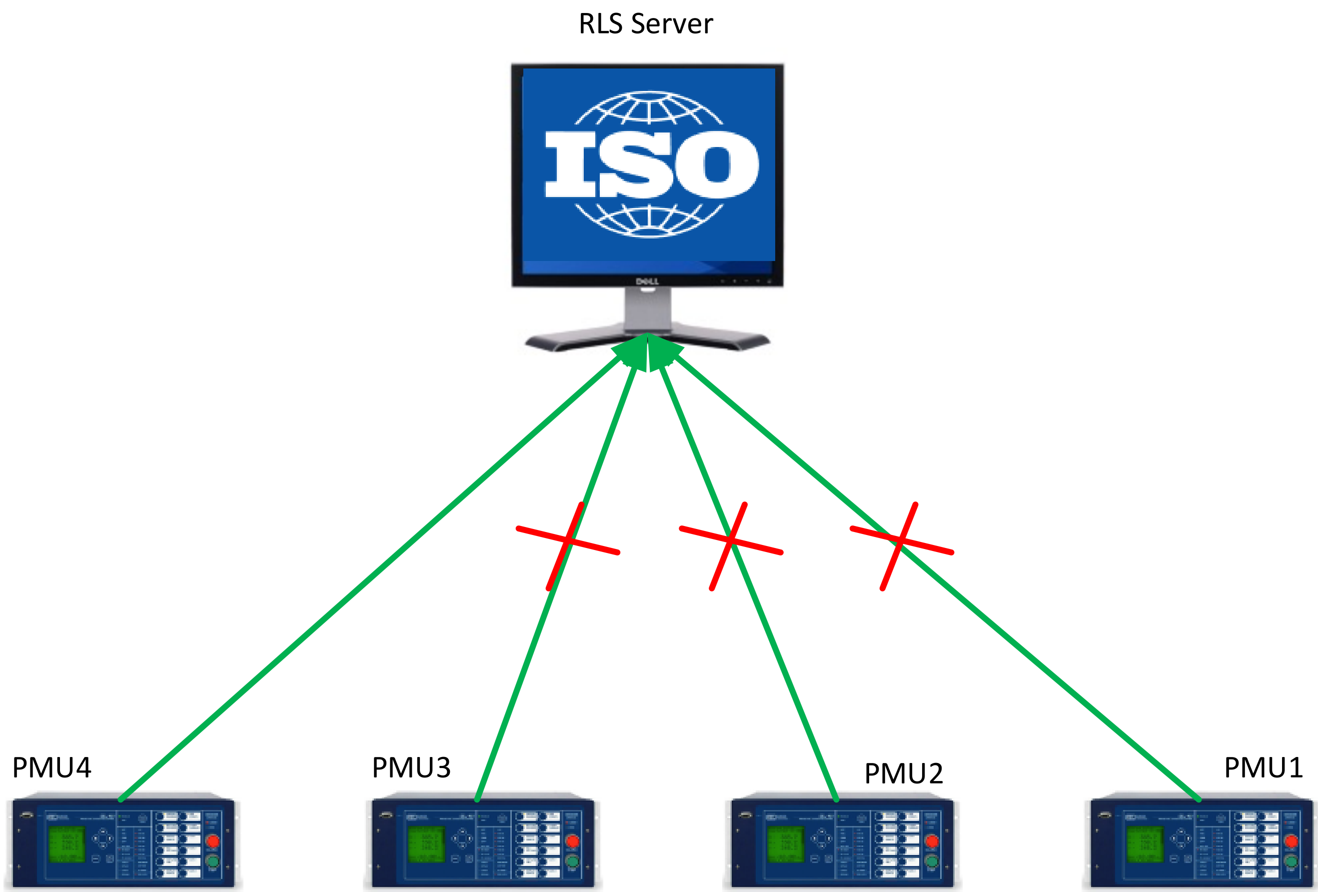
Case Study – RLS (3)

Attack-Strategy 1



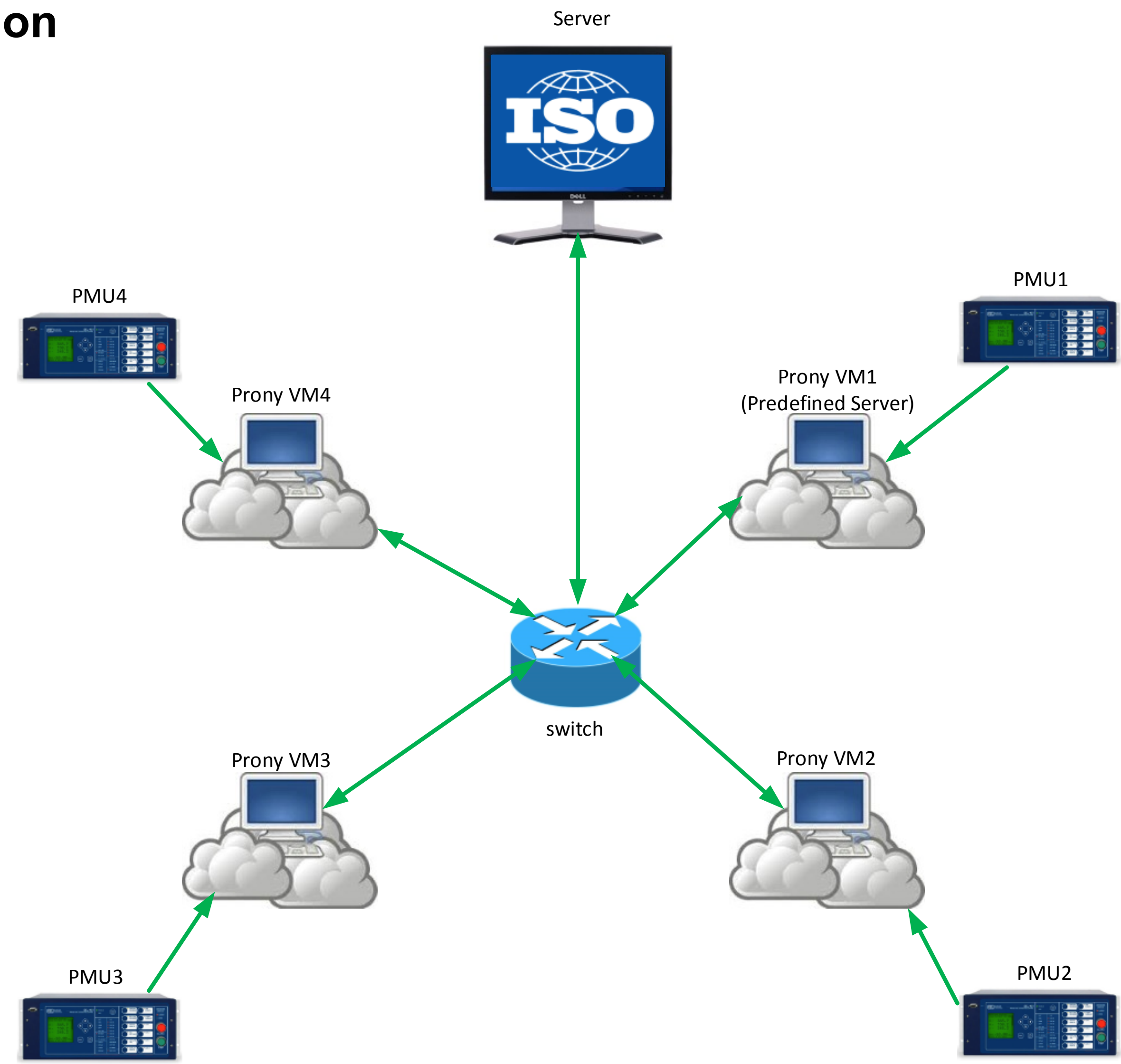
Case Study – RLS (4)

Attack-Strategy 2



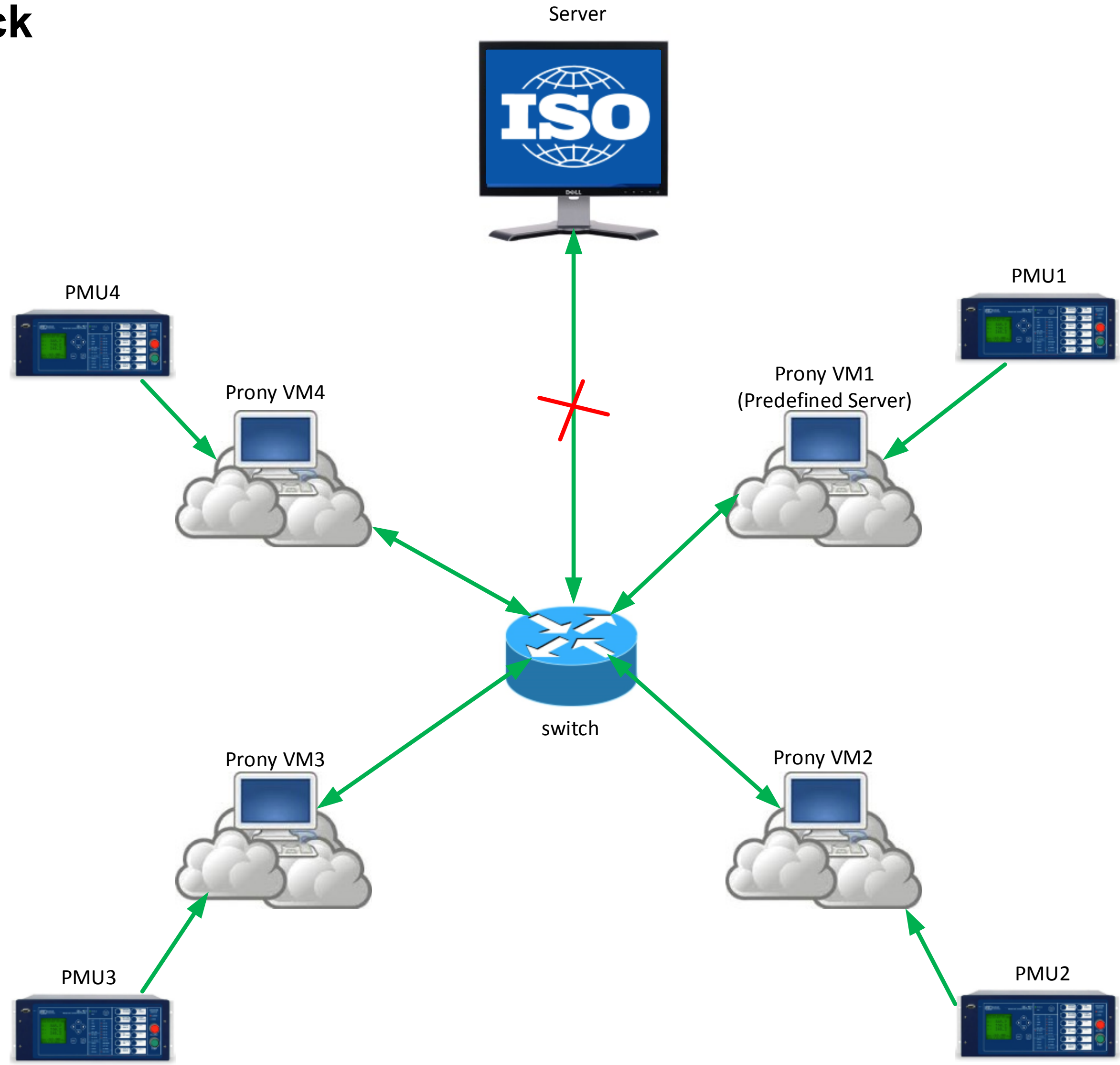
Link-Attack on Distributed Prony Algorithm

Step1-Normal Operation



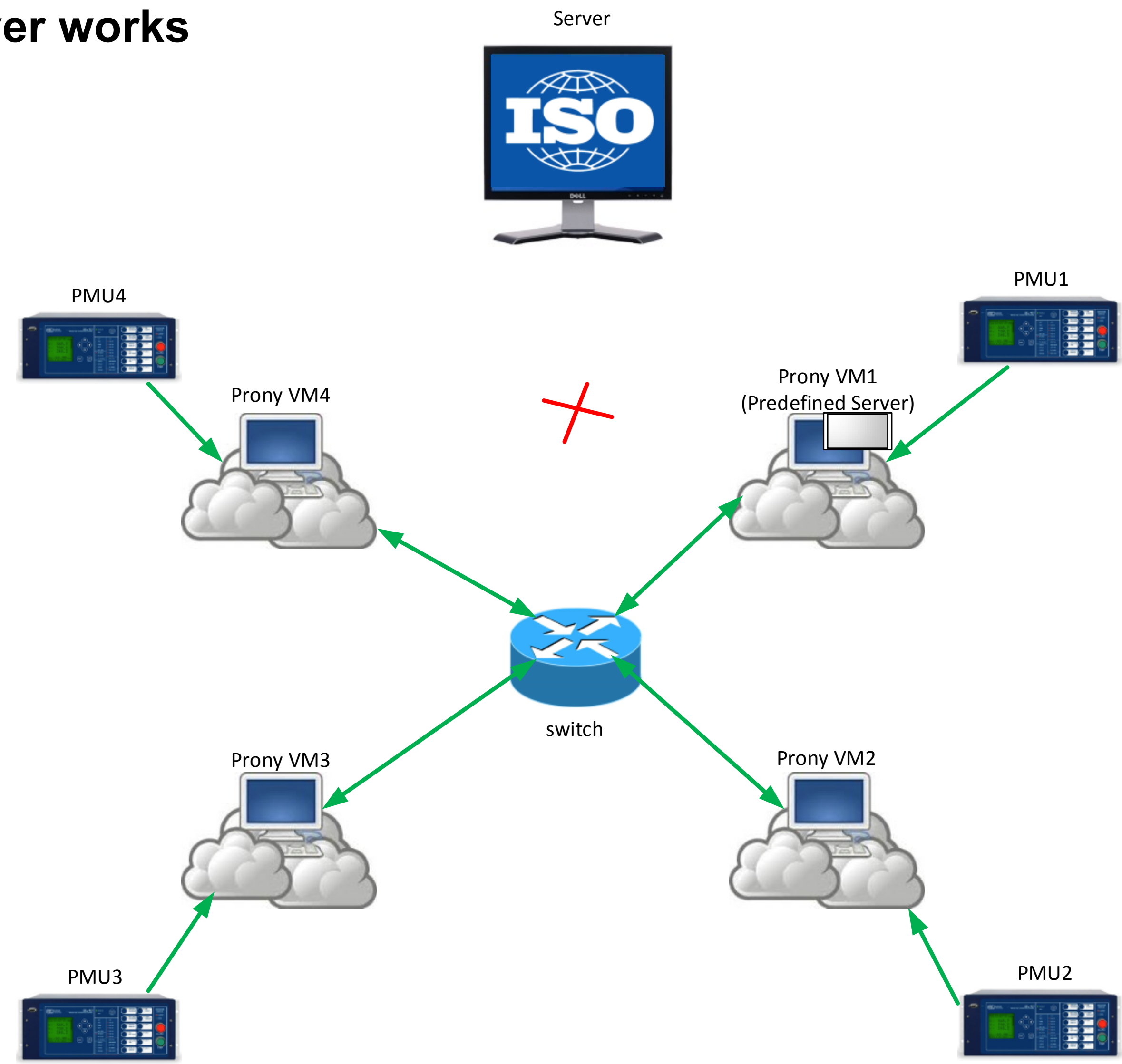
Link-Attack on Distributed Prony Algorithm

Step2-Server got attack

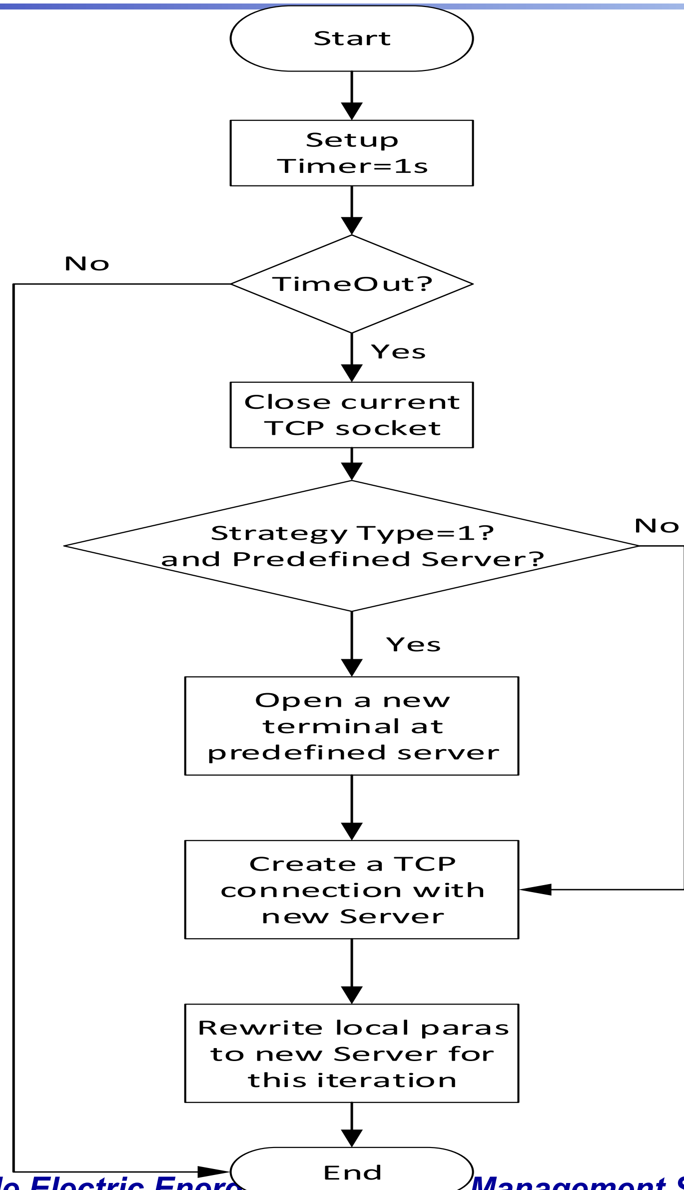


Link-Attack on Distributed Prony Algorithm

Step3-Predefined Server works



Resiliency Implementation - Prony



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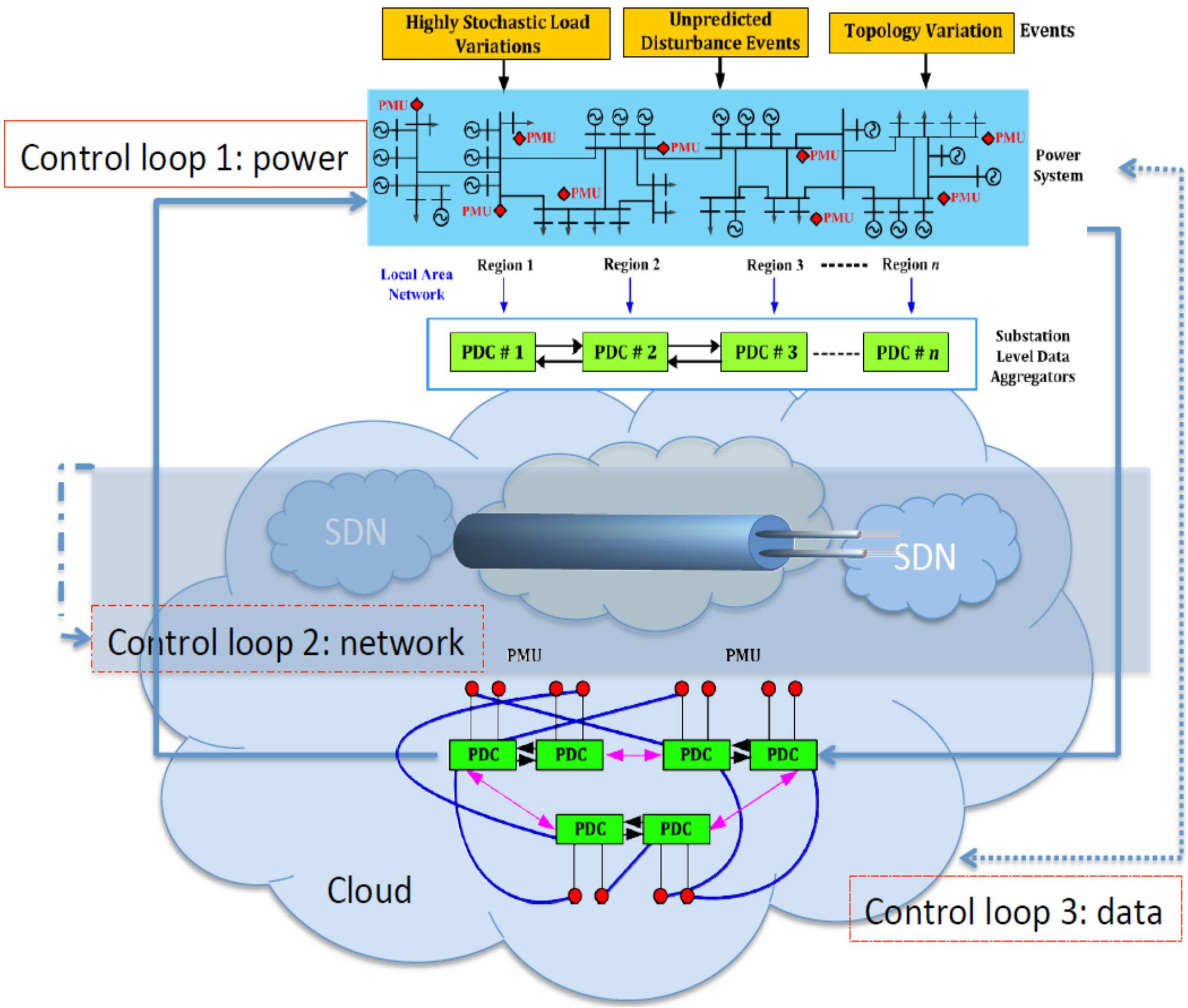
Ongoing Work – ExoGENI Testbed for Wide-Area Control



Control Loop 1:
Physical control of the grid using power system stabilizers and FACTS

Control Loop 2:
Delay control in ExoGENI using Software Defined Networking (SDN)

Control Loop 3:
Event-driven decision-making for data rerouting in case of network failures, contingencies and cyber-attacks

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Conclusions

1. Motivated by need of Wide-Area Monitoring and popularization of CPS and Could Computing – transfer centralized architecture to distributed architecture;

2. Formulate oscillation modes estimation problem arising from the swing dynamic models of large power systems;

3. Review three modal estimation algorithms: LS, RLS, Prony;

4. End-to-end delay on ExoGENI IaaS Clouds for LS v.s. RLS in decentralized way;

5. Implement attack-resiliency mechanisms for real-time centralized RLS v.s. distributed Prony.

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NSF

Thank you!

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