Distributed Estimation of Inter-Area Oscillation Modes in Large Power Systems using ExoGENI-WAMS Communication Network

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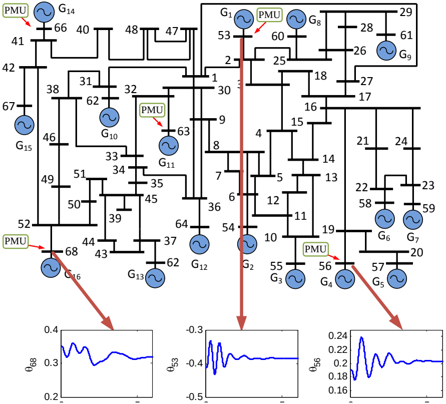
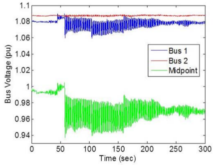
Wide-Area Oscillation Monitoring

Using PMU measurements to estimate the frequency, damping factor and residue of the different electro-mechanical oscillation modes

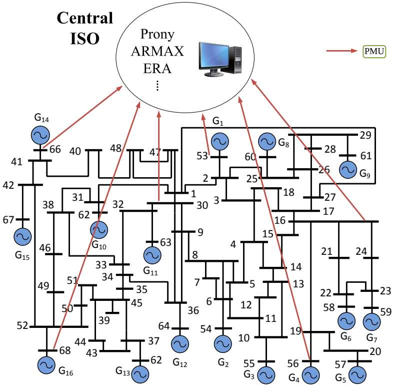
IEEE 68-Bus Model



The WECC Model

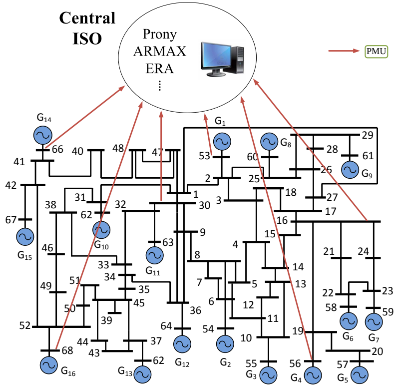


State of the Art Monitoring Architecture

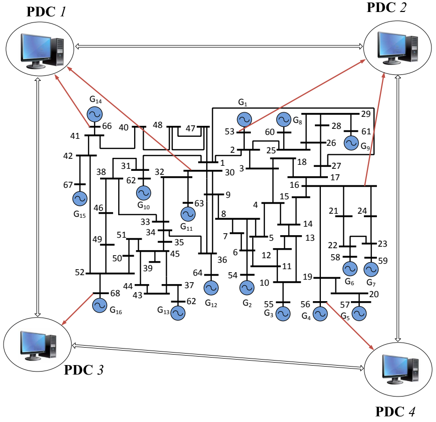


Wide-Area Oscillation Monitoring

State of the Art Monitoring Architecture



Proposed Distributed Monitoring Architecture



Wide-Area Oscillation Monitoring

State of the Art Monitoring Architecture

Pros:

- Less Communication
- Guaranteed data privacy

Cons:

- High risk for security and resiliency
- High computational load for central computer
- Higher computational time for very large data volumes

Proposed Distributed Monitoring Architecture

Pros:

- Reduced computational time
- Privacy still preserved
- More secure and resilient
- More efficient and tractable data handling

Cons:

- Significant increase in communication infrastructure
- Asynchrony between PDCs
- Communication delays

Swing Equation

- Swing equation of the i^{th} machine:

$$\dot{\delta}_i = \omega_s(\omega_i - 1)$$

$$M_i \dot{\omega}_i = P_{m_i} - \sum_k \left(\frac{E_i E_k}{x_{ik}} \sin(\delta_{ik}) \right) - D_i(\omega_i - 1)$$

- Linearized dynamic model (after Kron reduction)

$$\left[\begin{array}{c} \Delta\dot{\delta}(t) \\ \hline \Delta\dot{\omega}(t) \end{array}\right] = \underbrace{\left[\begin{array}{c|c} 0 & \omega_s I_n \\ \hline \mathcal{M}^{-1} L & -\mathcal{M}^{-1}\mathcal{D} \end{array}\right]}_{A} \left[\begin{array}{c} \Delta\delta(t) \\ \hline \Delta\omega(t) \end{array}\right] + \underbrace{\left[\begin{array}{c} 0 \\ \hline \mathcal{M}^{-1}\mathbf{e}_j \end{array}\right]}_{B} u(t),$$

$$\mathbf{y}(t) = \mathrm{col}(\Delta\theta), \quad \text{for} \;\; i \in S$$

$$\mathcal{L}_{ii} = -\sum_{k \in \mathcal{N}_i} \frac{E_i E_k}{x_{ik}} \cos(\delta_{i0} - \delta_{k0}), \;\; \mathcal{L}_{ij} = \frac{E_i E_j}{x_{ij}} \cos(\delta_{i0} - \delta_{j0})$$

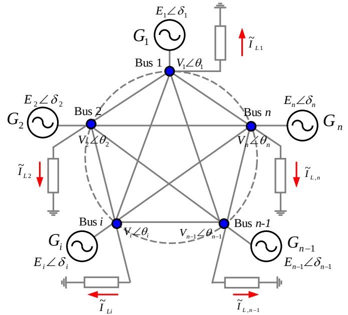


Figure: A power system with both PV buses (differential bus) and PQ buses (algebraic bus)

Oscillation Monitoring

$$y_j(t) = \Delta\theta_j(t) = \sum_{i=1}^{n} \left(r_{j,i} e^{(-\sigma_i + j\Omega_i)t} + r_{j,i}^{*} e^{(-\sigma_i - j\Omega_i)t} \right)$$

$$\mathbf{y}(t) = \begin{bmatrix} \Delta\theta_1(t) \\ \vdots \\ \Delta\theta_p(t) \end{bmatrix} = \sum_{i=1}^{n} \left(\begin{bmatrix} r_{1,i} \\ \vdots \\ r_{p,i} \end{bmatrix} e^{(-\sigma_i + j\Omega_i)t} + \begin{bmatrix} r_{1,i}^{*} \\ \vdots \\ r_{p,i}^{*} \end{bmatrix} e^{(-\sigma_i - j\Omega_i)t} \right)$$

- Our objective is to use PMU measurements $\mathbf{y}(t)$ to estimate Ω_i, σ_i and $\text{col}(r_{1,i}, \ldots, r_{p,i})$ for $i = 1, \cdots, n$
- We use Prony algorithm for this.
- Let us consider the discrete-time transfer function of $\Delta\theta_i$ from a single input disturbance:

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

Centralized Prony Method

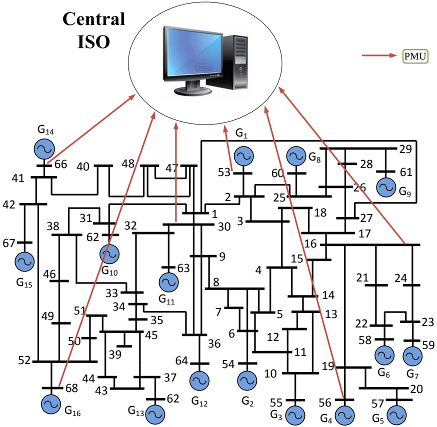
Step 1. Find a_1 through a_{2n}

$$\underbrace{\begin{bmatrix} \Delta\theta_i(2n) \\ \Delta\theta_i(2n+1) \\ \vdots \\ \Delta\theta_i(2n+\ell) \end{bmatrix}}_{\mathbf{c}_i} = \underbrace{\begin{bmatrix} \Delta\theta_i(2n-1) & \cdots & \Delta\theta_i(0) \\ \Delta\theta_i(2n) & \cdots & \Delta\theta_i(1) \\ \vdots & & \vdots \\ \Delta\theta_i(2n+\ell-1) & \cdots & \Delta\theta_i(\ell) \end{bmatrix}}_{H_i} \underbrace{\begin{bmatrix} -a_1 \\ -a_2 \\ \vdots \\ -a_{2n} \end{bmatrix}}_{\mathbf{a}}$$

Finding the global $\mathbf{a}$ using all available measurements by solving:

$$\underbrace{\begin{bmatrix} \mathbf{c}_1 \\ \vdots \\ \mathbf{c}_p \end{bmatrix} = \begin{bmatrix} H_1 \\ \vdots \\ H_p \end{bmatrix} \mathbf{a}}_{\text{Solve this using Batch Least Squares - Centralized Prony Method}}$$

Centralized Prony Method

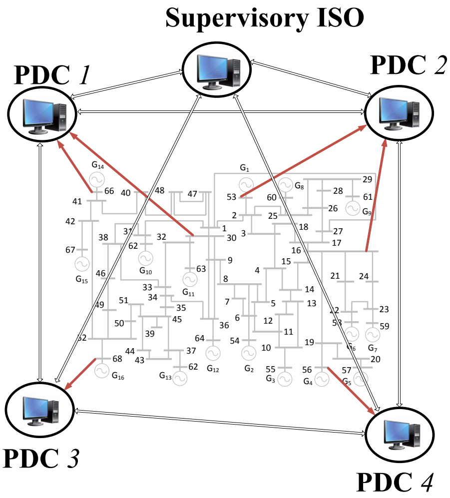


$$\theta_i \;\rightarrow\; (H_i, \mathbf{c}_i), \quad i = 1, \ldots, p$$

$$\Rightarrow \begin{bmatrix} H_1 \\ \vdots \\ H_p \end{bmatrix} \mathbf{a} = \begin{bmatrix} \mathbf{c}_1 \\ \vdots \\ \mathbf{c}_p \end{bmatrix}$$

$$\Rightarrow \mathbf{a} = \arg\min_{\mathbf{a}} \frac{1}{2} \left\| \begin{bmatrix} H_1 \\ \vdots \\ H_p \end{bmatrix} \mathbf{a} - \begin{bmatrix} \mathbf{c}_1 \\ \vdots \\ \mathbf{c}_p \end{bmatrix} \right\|_2^2$$

Distributing the Prony Method



Multiple Computational Areas

$$\hat{\theta}_1 \triangleq \{\theta_{30}, \theta_{66}\} \rightarrow (\hat{H}_1 \triangleq \begin{bmatrix} H_{30} \\ H_{66} \end{bmatrix}, \hat{\mathbf{c}}_1 \triangleq \begin{bmatrix} \mathbf{c}_{30} \\ \mathbf{c}_{66} \end{bmatrix})$$

$$\hat{\theta}_2 \triangleq \{\theta_{16}, \theta_{53}\} \rightarrow (\hat{H}_2 \triangleq \begin{bmatrix} H_{16} \\ H_{53} \end{bmatrix}, \hat{\mathbf{c}}_2 \triangleq \begin{bmatrix} \mathbf{c}_{16} \\ \mathbf{c}_{53} \end{bmatrix})$$

$$\hat{\theta}_3 \triangleq \{\theta_{68}\} \rightarrow (\hat{H}_3 \triangleq H_{68}, \hat{\mathbf{c}}_3 \triangleq \mathbf{c}_{68})$$

$$\hat{\theta}_4 \triangleq \{\theta_{56}\} \rightarrow (\hat{H}_4 \triangleq H_{56}, \hat{\mathbf{c}}_4 \triangleq \mathbf{c}_{56})$$

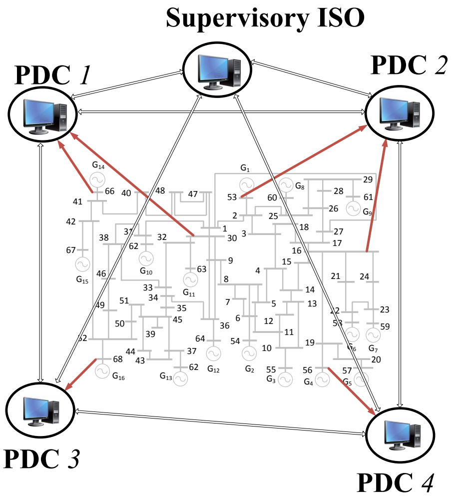
Global Consensus Problem:

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

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

Distributed Optimization Algorithms

- Gradient-Based Methods
  - Distributed Subgradient Method (DSM)
  - Nesterov Method
- Dual Decomposition Based Methods
  - Alternating Direction Method of Multipliers (ADMM)



Alternating Direction Method of Multipliers (ADMM)

Iteration k

Step 1 Update $\mathbf{w}_i$ and $\mathbf{a}_i$ locally at PDC i

$$\mathbf{a}_i^{(k+1)} = ((H_i^{(k)})^T H_i^{(k)} + \rho I)^{-1}((H_i^{(k)})^T \mathbf{c}_i^{(k)} - \mathbf{w}_i^{(k)} + \rho \bar{\mathbf{a}}^{(k)})$$

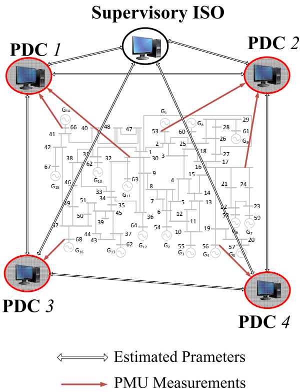
$$\mathbf{w}_i^{(k+1)} = \mathbf{w}_i^{(k)} + \rho(\mathbf{a}_i^{(k+1)} - \bar{\mathbf{a}}^{(k+1)})$$

Step 2 Gather the values of $\mathbf{a}_i^{(k+1)}$ at the central PDC

Step 3 Take the average of $\mathbf{a}_i^{(k+1)}$

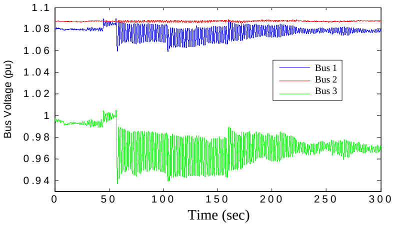
Step 4 Broadcast the average value ($\bar{\mathbf{a}}^{(k+1)}$) to local PDCs

Step 5 Finding the frequency Ω_i and damping factors σ_i at each local PDC using $\bar{a}^{(k)}$ from the characteristic equation

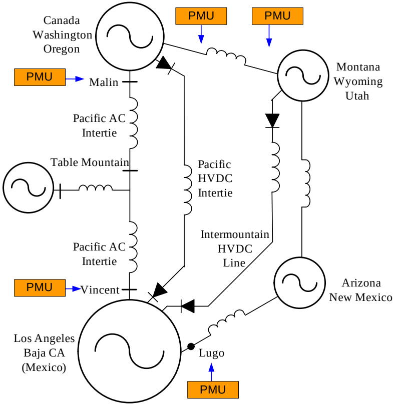


Targeted Estimation of Inter-Area Modes

Given PMU data $\mathbf{y}(t) = \mathrm{col}(\Delta V_i, \Delta\theta_i)$, we can estimate modes of the aggregated model.



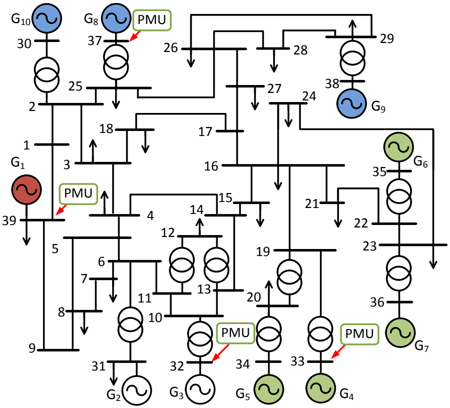
WECC 500 (kV)



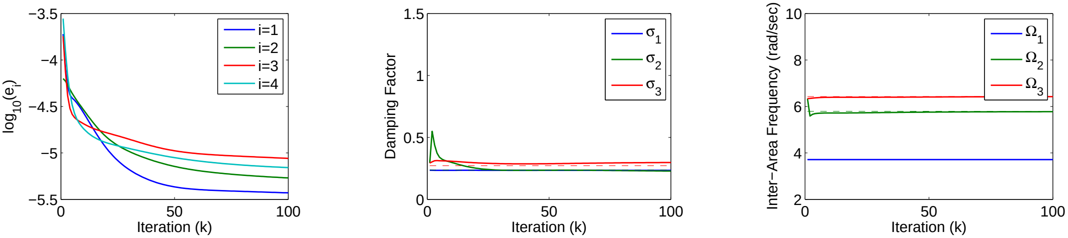
- Massive volumes of PMU data from various buses
- Assuming inter-area modes to lie between 0.1 Hz and 1 Hz, apply band-pass filtering
- Use filtered data to estimate oscillations between aggregate clusters

Simulation Results

Simulation results for the IEEE-39 bus model,



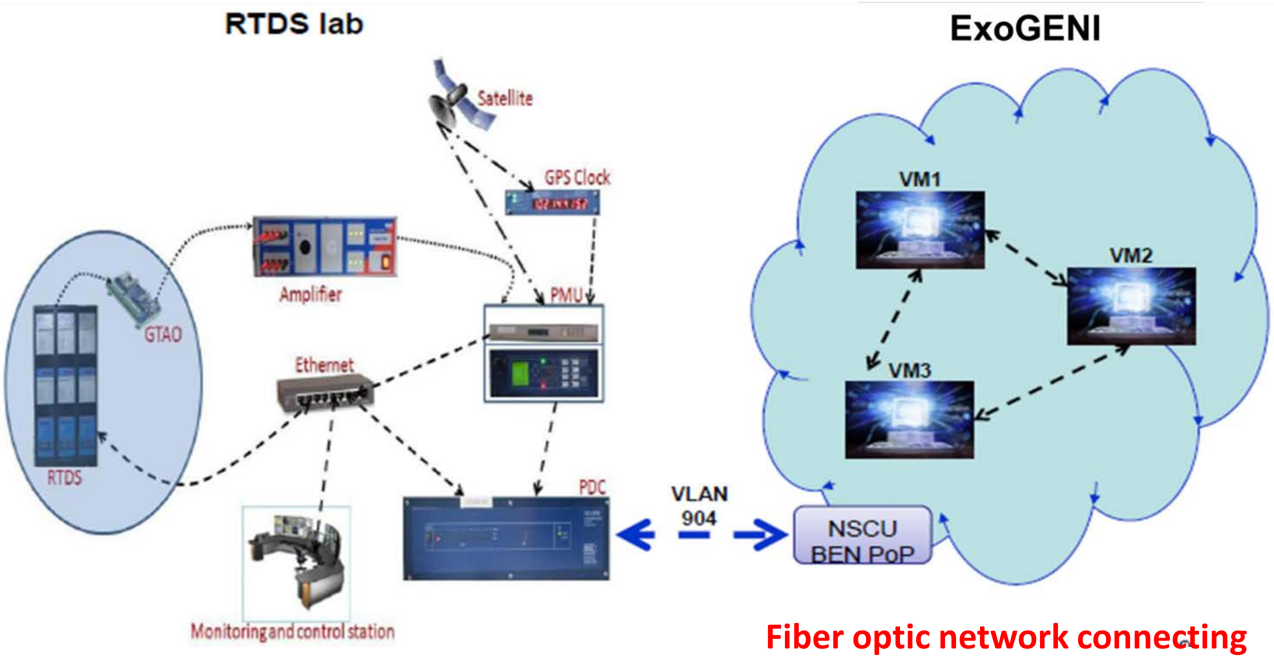
- Simplified model of the New-England power system
- 39 Bus, 10 Generators
- 4 Coherent Areas (shown in different colors)
- Simulations are performed in Power System Toolbox (PST)
- A three-phase fault occurred at line connecting buses 4 and 5, started at $t = 1.0$ (sec), cleared at near end at $t = 1.01$ (sec), and cleared at far end at $t = 1.03$ (sec).



Actual Eigenvalues	Centralized Prony	Decentralized Prony	Distributed Prony
$-0.2333 \pm 3.7128j$	$-0.2341 \pm 3.7127j$	$-0.2339 \pm 3.7142j$	$-0.2339 \pm 3.7124j$
$-0.2375 \pm 5.7914j$	$-0.2323 \pm 5.7638j$	$-0.3818 \pm 5.5658j$	$-0.2199 \pm 5.7673j$
$-0.2718 \pm 6.4277j$	$-0.3014 \pm 6.4228j$	$-0.2928 \pm 6.3887j$	$-0.3003 \pm 6.4224j$

Implementation via Distributed Exo-GENI Communication Network

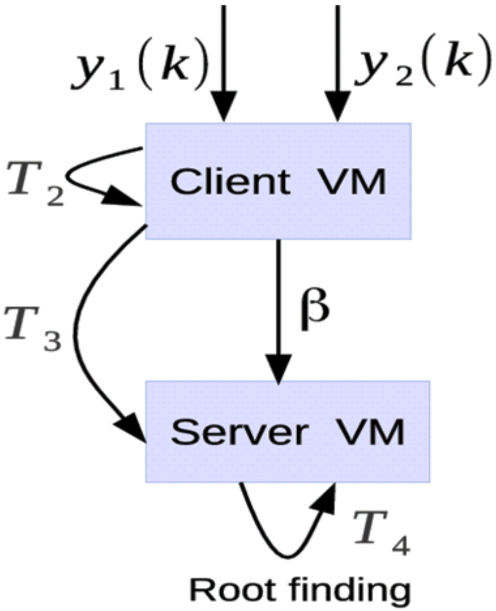
RTDS-PMU Lab at NCSU



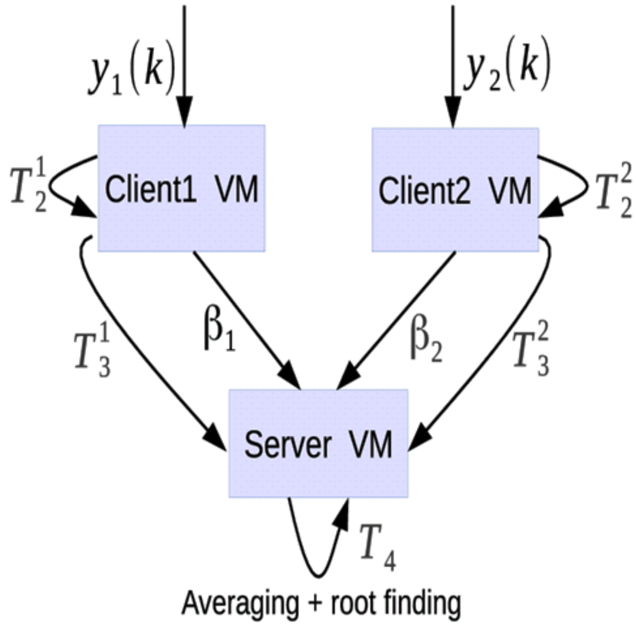
Fiber optic network connecting campuses of NC State, Duke University & UNC Chapel Hill

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

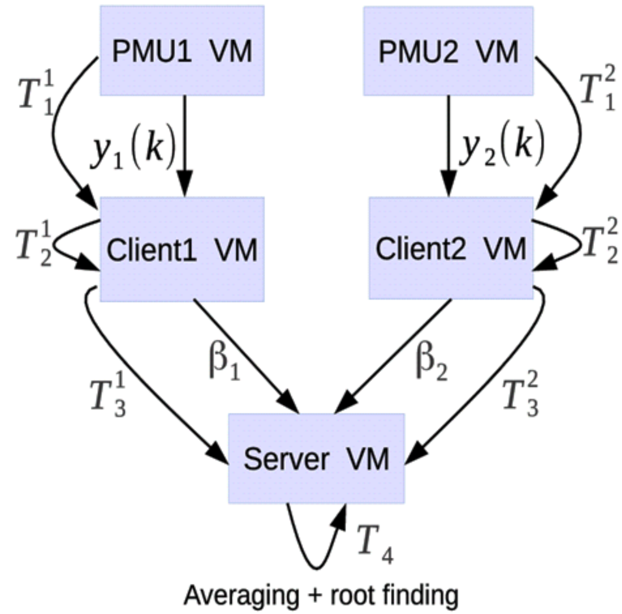
Experimental Network Topologies



Centralized

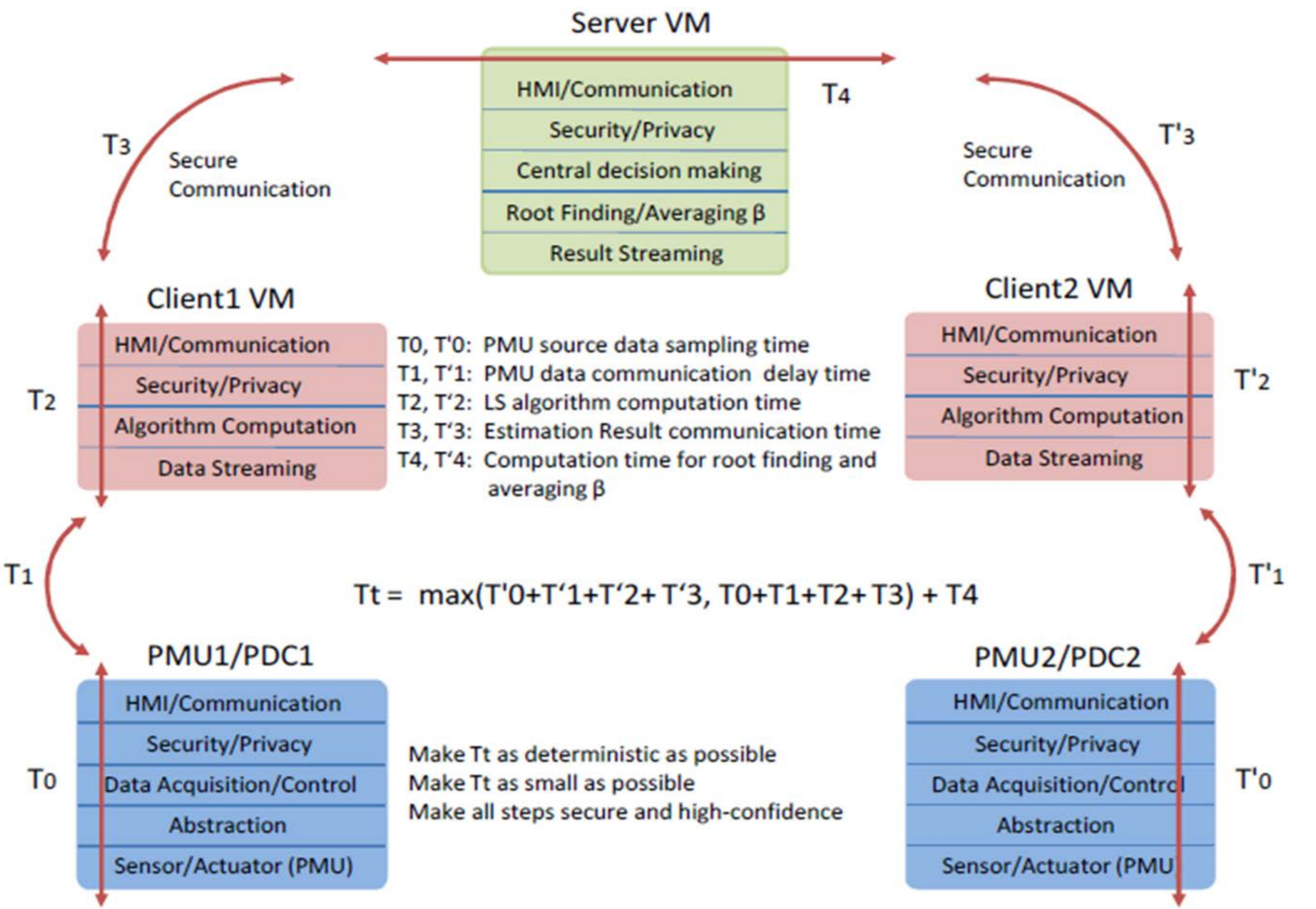


Decentralized (independent)
Followed by
averaging of estimates



Decentralized
but recursive

Calculating End-to-End Network Delays



Calculating End-to-End Network Delays

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

Choice of VM location decided by network traffic

Conclusions

- Development of distributed algorithms is imperative considering the increasing number of PMUs.
- We consider the problem of estimating the frequencies and damping factors of oscillation modes using Prony method in a distributed way.
- The results of ADMM verify that the global values of the inter-area modes can be achieved after a number of iterations.