Power Systems/Communication System Co-Simulation and Experimental Evaluation of Cyber Security of Power Grid

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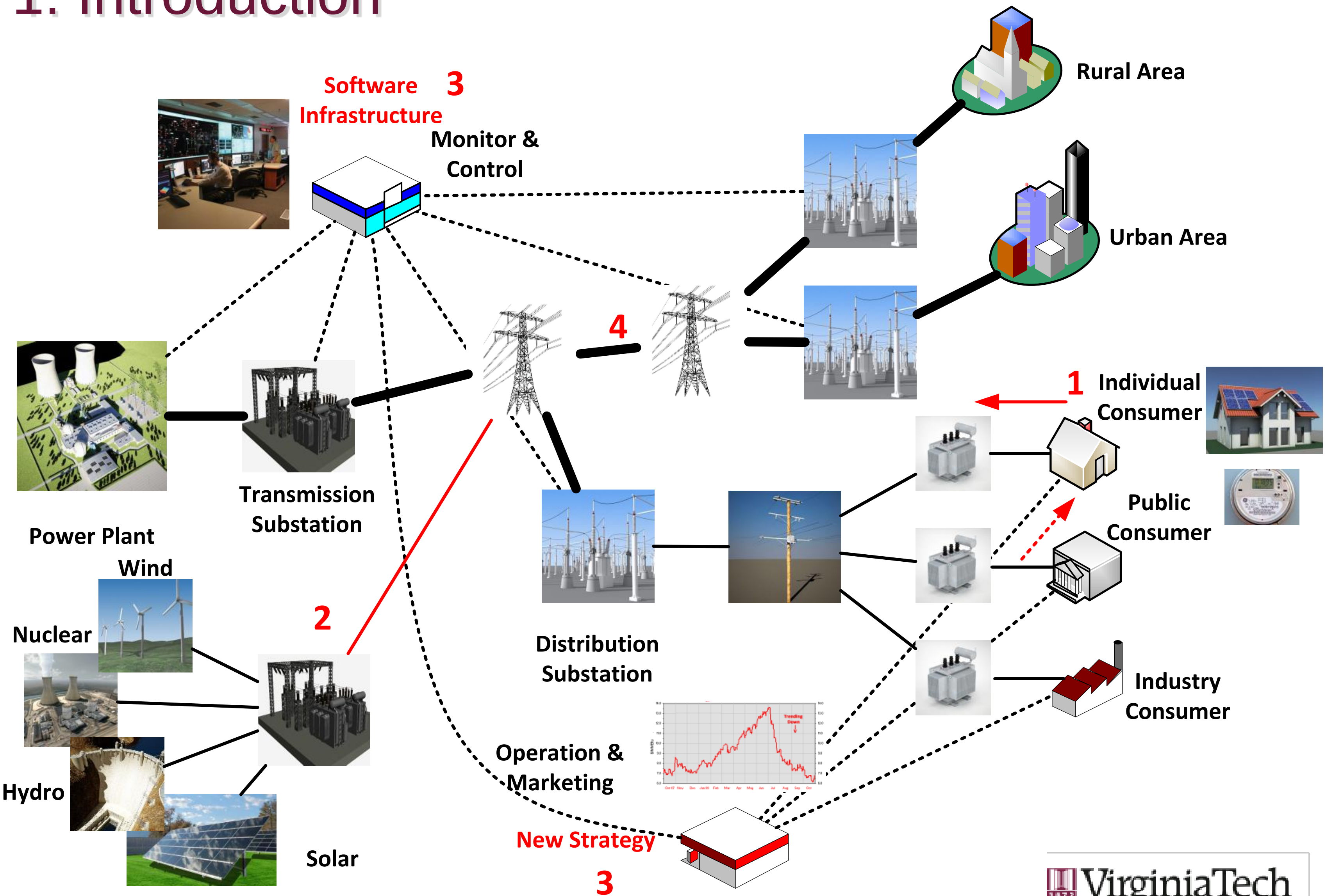
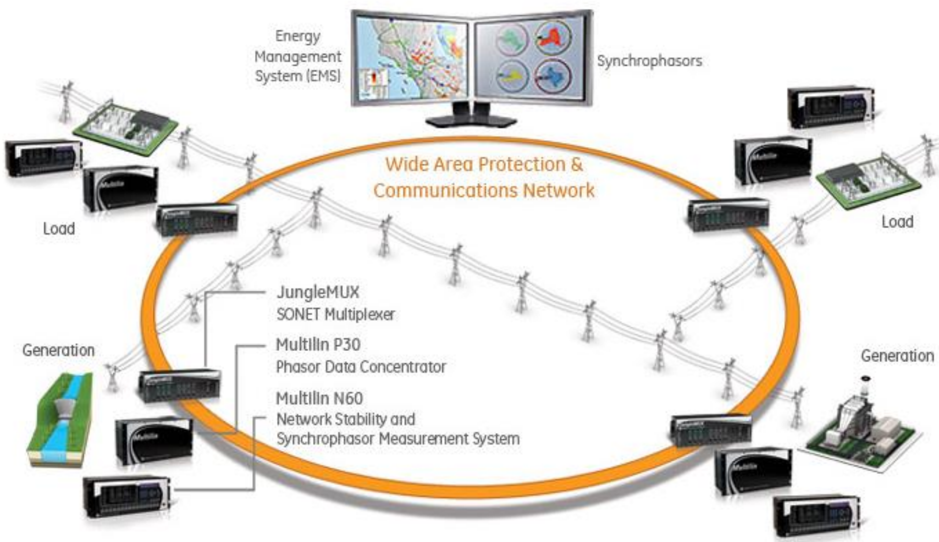
Outline

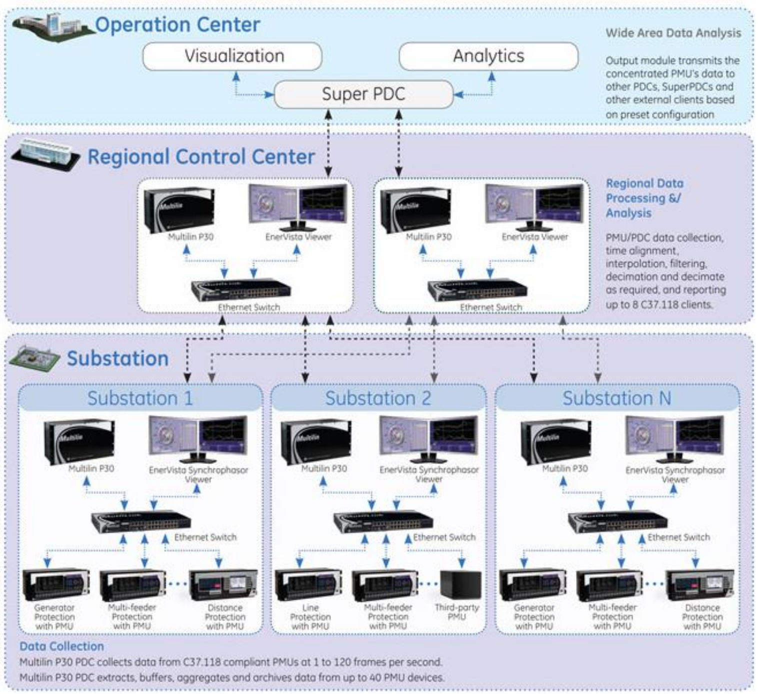
1. Introduction
2. Power Systems and Communication System Co-Simulation: GECO: a Modulized Global Event-driven CO-simulation Platform
3. Cyber Attack Simulation on PMU-based State Estimation
4. Co-simulation Case Study on PMU-based Out-of-step Protection
5. Conclusion & Future Research

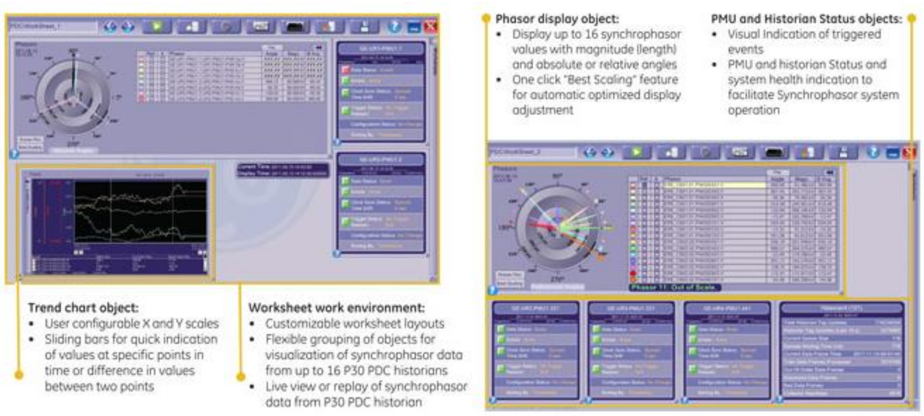
1: Introduction



GE's Solution on Wide Area Monitoring and Control – Synchrophasor Techniques







* From GE's Industrial Solution Website

TABLE I
COMPARISON OF INTEGRATED POWER/NETWORK SIMULATORS

	Target	Components	Synchronization	Scalability	Real-time
EPOCHS[13]	Dynamic simulation for WAMS applications	PSCAD, PSLF, NS2	Time-stepped	Good for large system	No
ADEVS[14]	Dynamic simulation for WAMS applications	Adevs, NS2	DEVS	Limited, have to rewrite codes for different systems	No
[15]	Dynamic simulation for WAMS applications	Simulink, OPNET	Not addressed	Medium size	No
VPNET[16]	Remotely controlled power devices	Virtual Test Bed, OPNET	Time-stepped	Limited to single or small number of power devices	No (but have plans to integrate RTDS)
PowerNet[17]	Remotely controlled power devices	Modelica, NS2	Time-stepped	Limited to single or small number of power devices	No
[18]	General network controlled system	OPNET only, power system part is virtualized	Delay estimation	Limited size due to virtualized power system	No
SCADA CST[19]	SCADA cyber security, system virtualization	PowerWorld, RINSE	N/A (static)	Good for large system	Yes (communication network only)
TASSCS[20]	SCADA cyber security, system virtualization	PowerWorld, OPNET	N/A (static)	Good for large system	Yes (communication network only)
GECO	Dynamic simulation for WAMS applications	PSLF, NS2	Global event-driven	Good for large system	No

Hua Lin; Veda, S.S.; Shukla, S.S.; Mili, L.; Thorp, J., "GECO: Global Event-Driven Co-Simulation Framework for Interconnected Power System and Communication Network," Smart Grid, IEEE Transactions on , vol.3, no.3, pp.1444,1456, Sept. 2012

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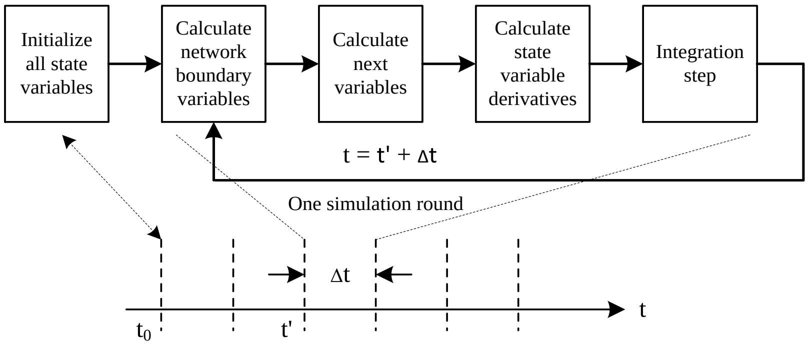
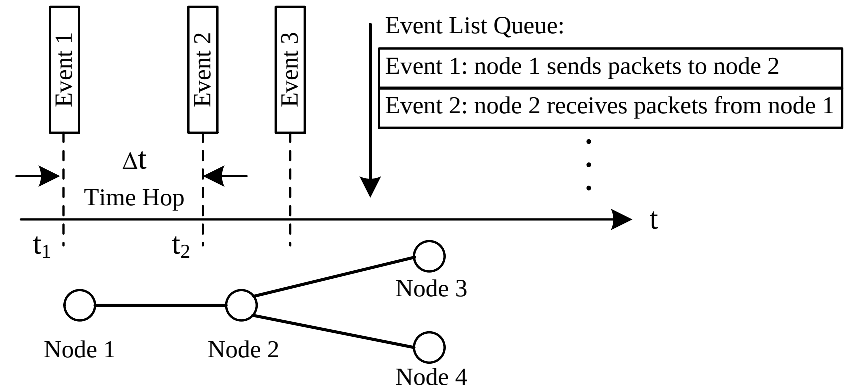
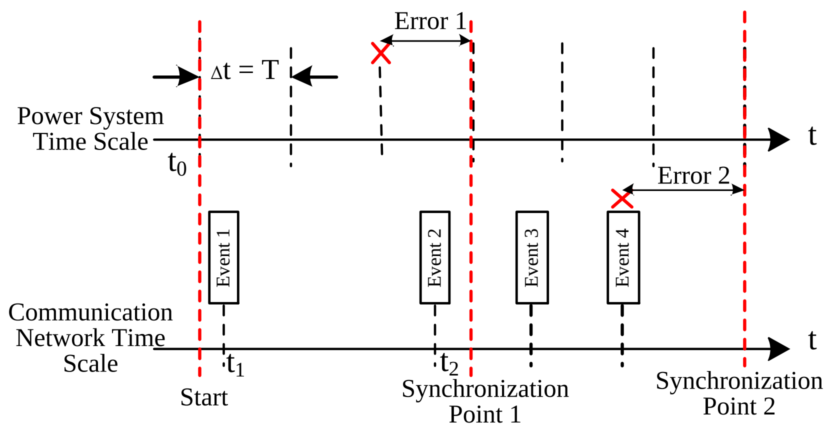
2: Global Event-Driven Synchronization



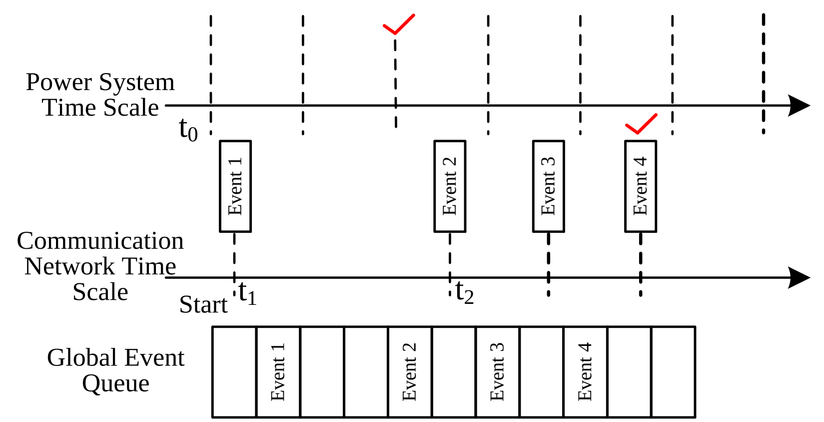
Dynamic Simulation Procedure of Power Systems



Communication Network Simulation Procedure

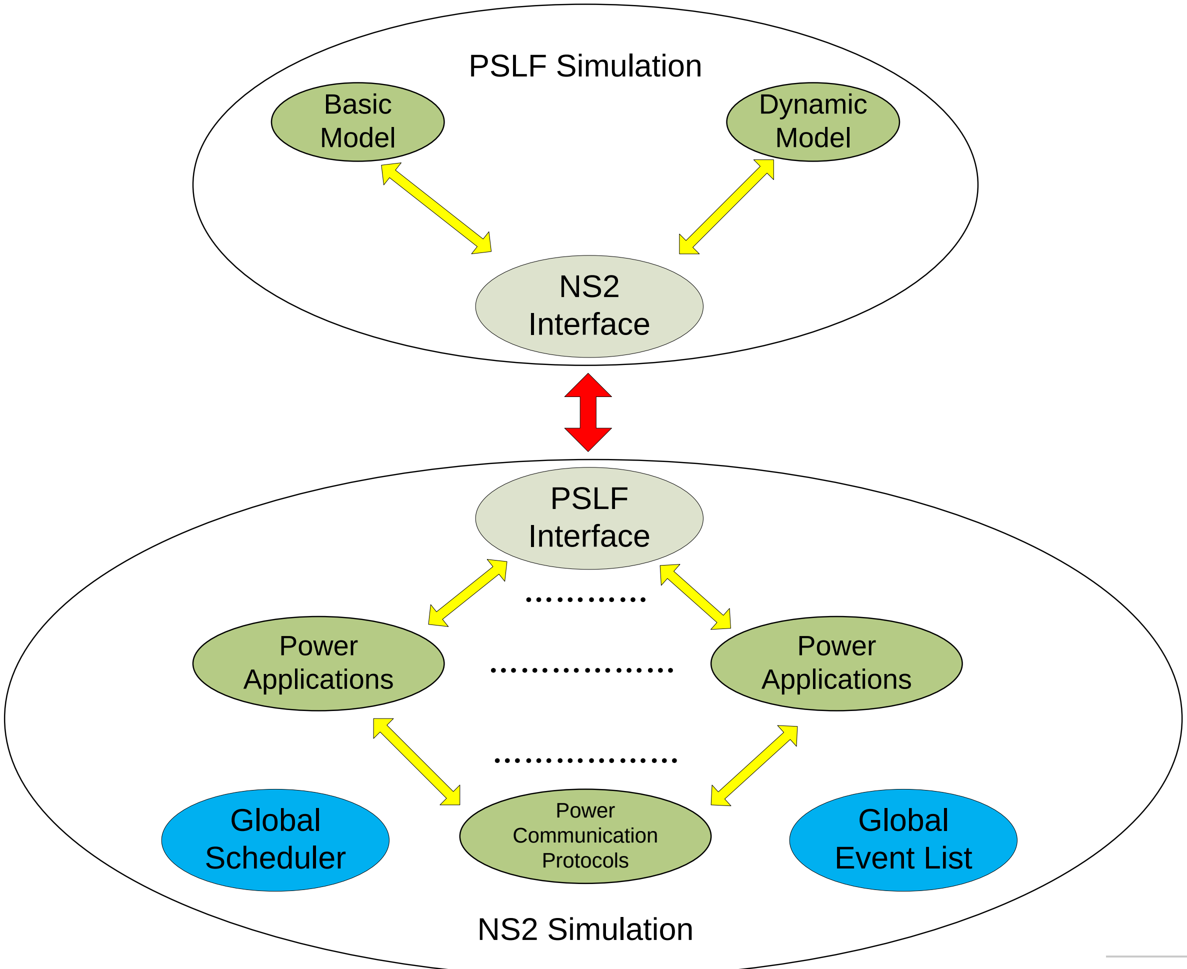


Two types of synchronization errors

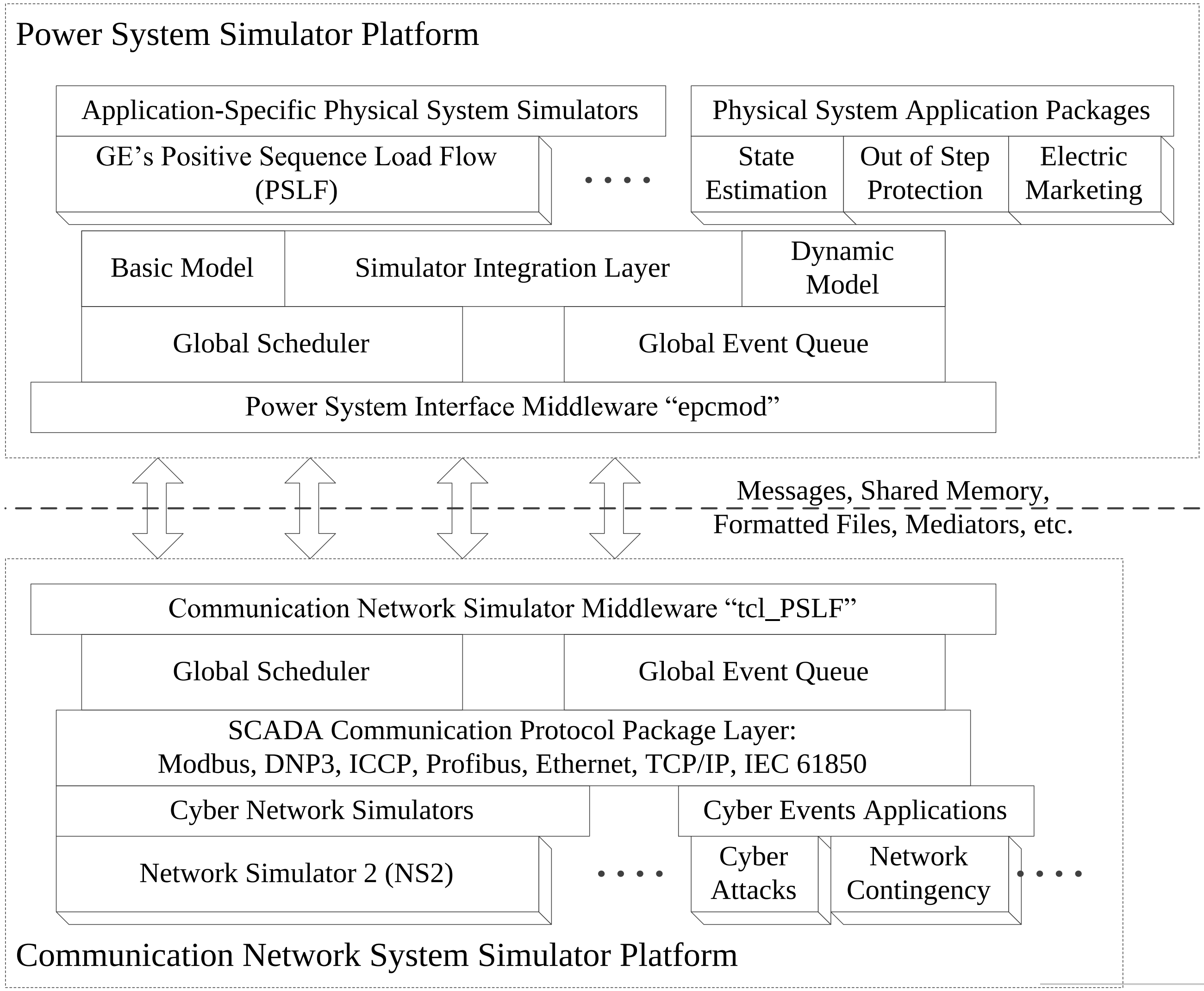


Event-driven synchronization without errors

GECO (Global Event-driven CO-simulation): Platform Structure



GECO: A Modulized *G*lobal *E*vent-driven *CO*-simulation platform



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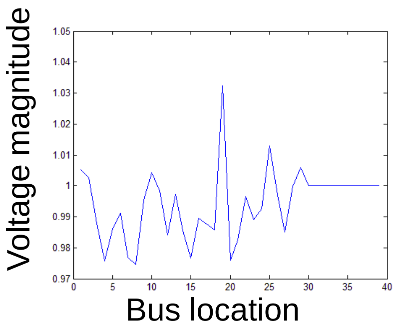
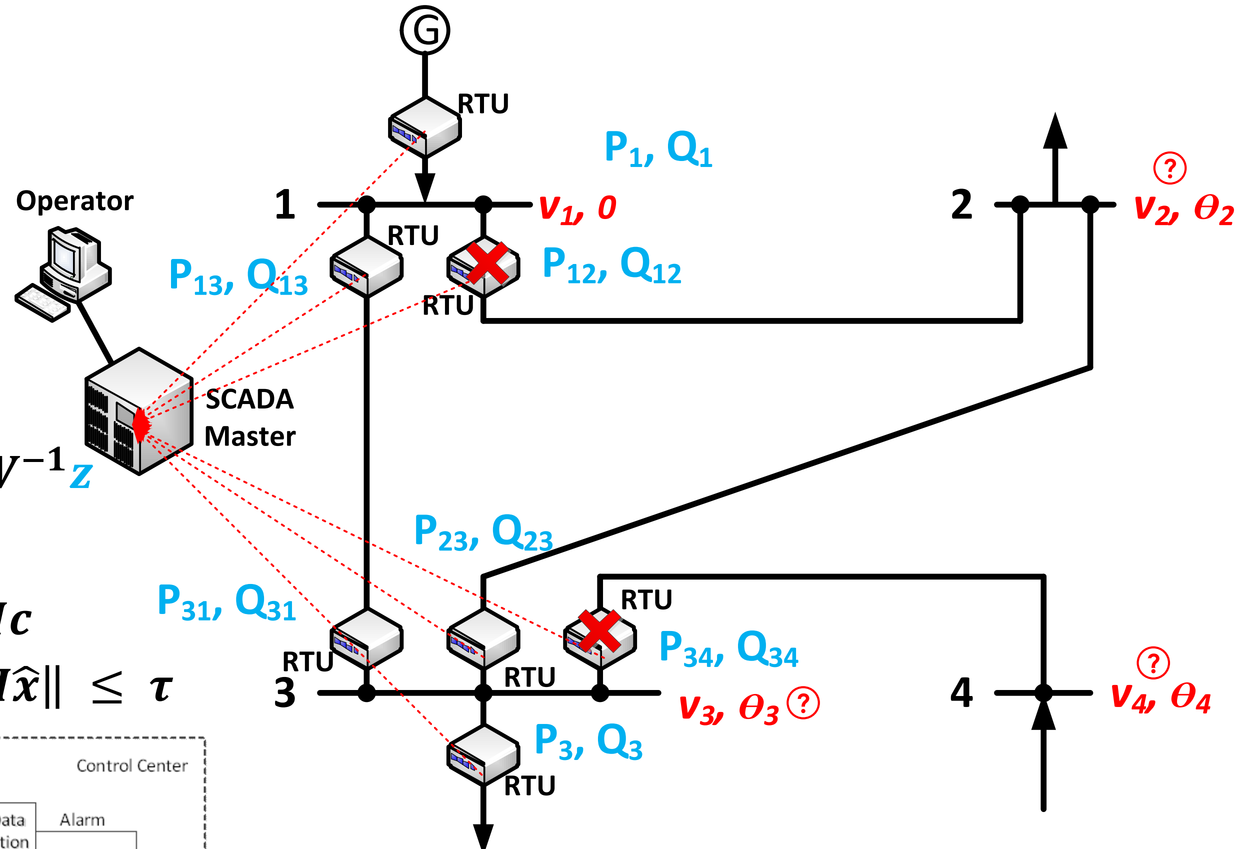
3: Problem Statement: Attack Model

Malicious Data Injection attack on State Estimation





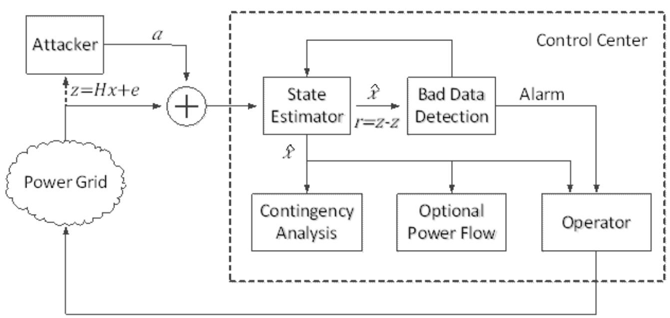
$$z = Hx + e$$

$$\hat{x} = \left(H^T W^{-1} H\right)^{-1} H^T W^{-1} z$$

$$z_a = z + a$$

$$a = Hc$$

$$\left\| z_a - H\hat{x}_f \right\| = \| z - H\hat{x} \| \leq \tau$$



We can't detect the attacks

The injected data will modify the state estimation results

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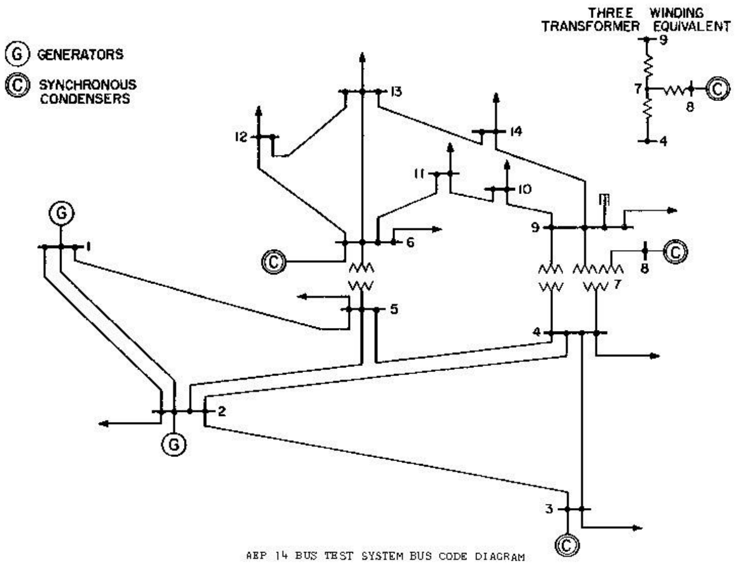
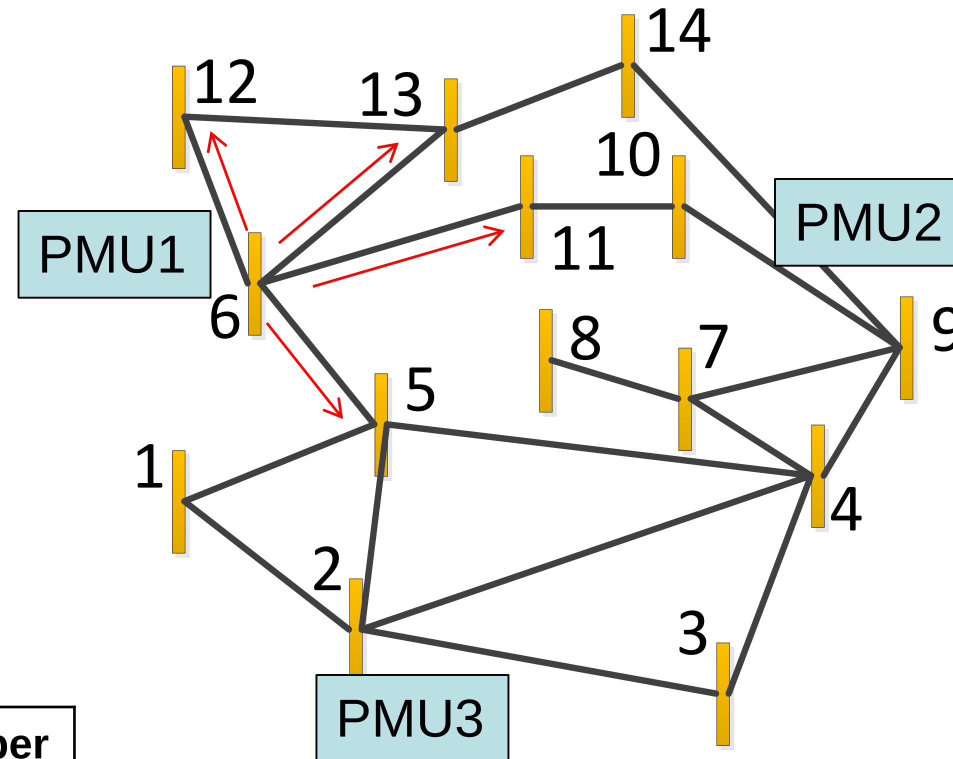
The Placement of PMUs

IEEE 14-Bus Example



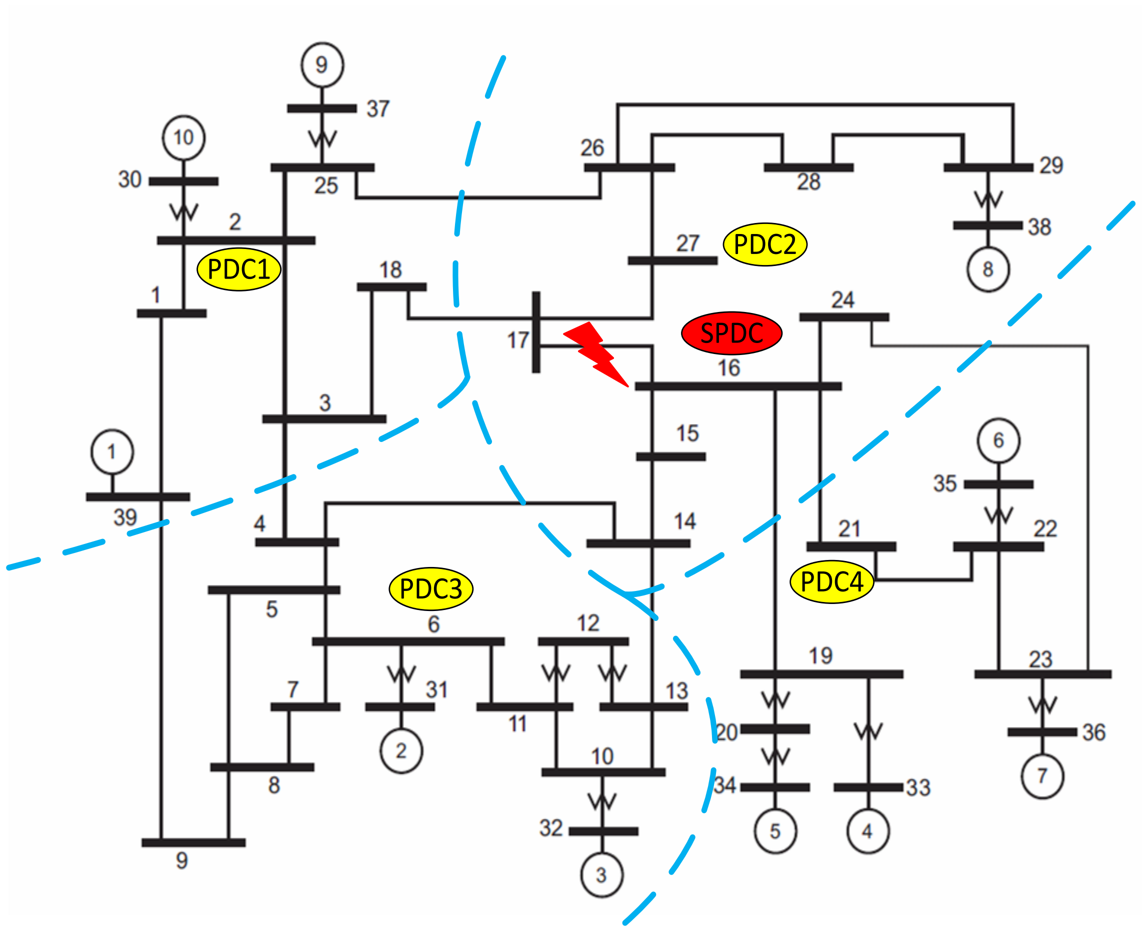
Test system	PMUs Number
IEEE 14-bus	3
IEEE 24-bus	6
IEEE 30-bus	7
New England 39-bus	8
IEEE 57-bus	11



Minimum number of critical places for installing PMUs

Secured PMUs installed in these places make the system observable

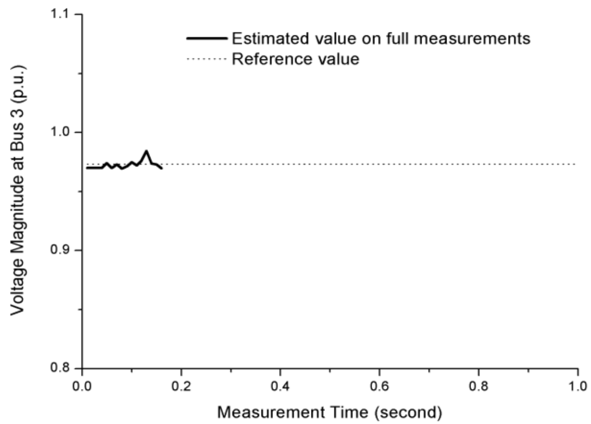
Case study:
New England 39-bus test system



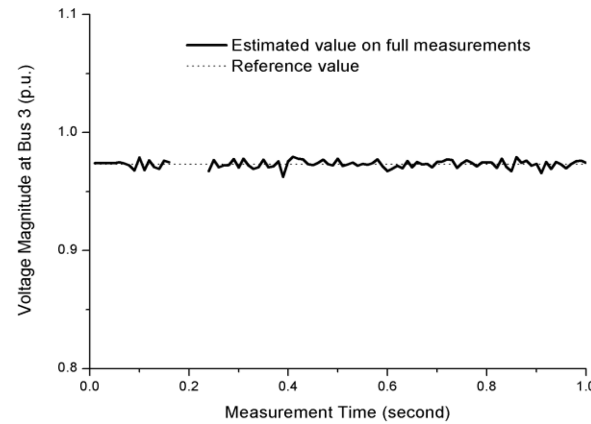
Cyber attack Simulation: on network channels

Single Network Link Failure

Bus16-Bus17 (Tp=50ms)

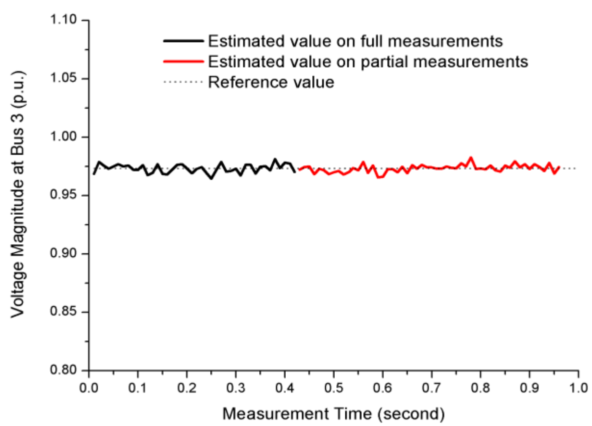


Bus16-Bus17 (Tp=60ms)

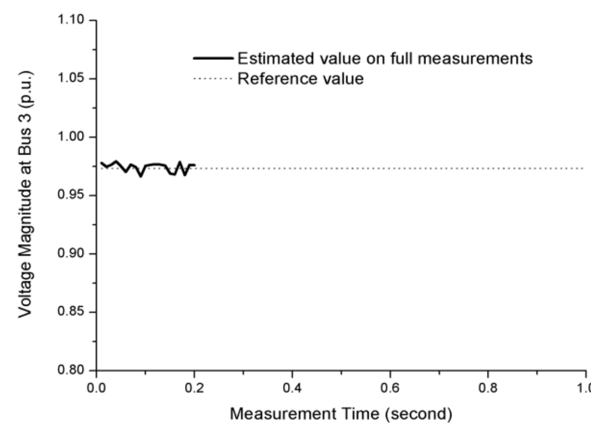


Saturation attacks

Network saturation 50%



Network saturation 85%



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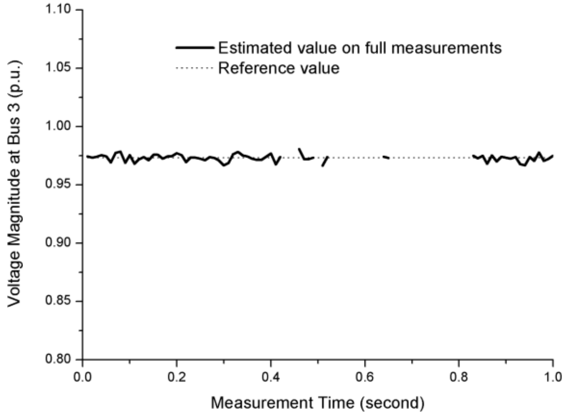
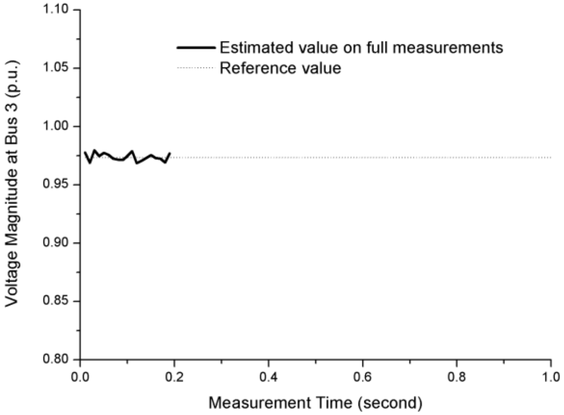
Cyber attack Simulation: on network nodes

Denial of Service Attack

DoS attack on the router at Bus 16

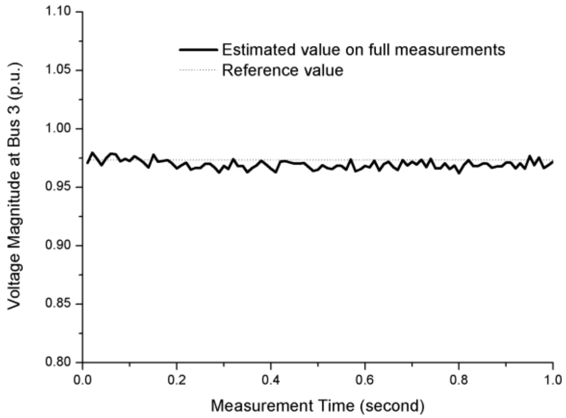


Enhanced DoS attack

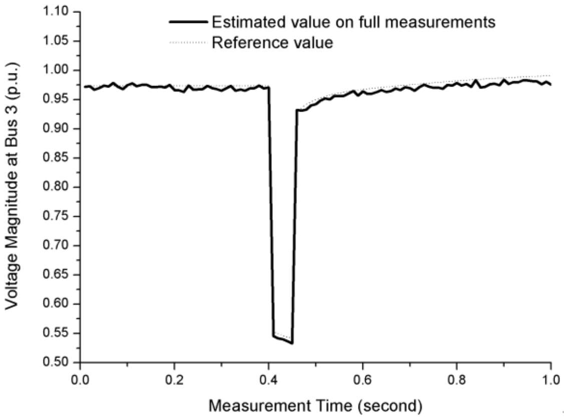


Data Spoofing

PMU spoofing on Bus 3



PMU spoofing in contingency



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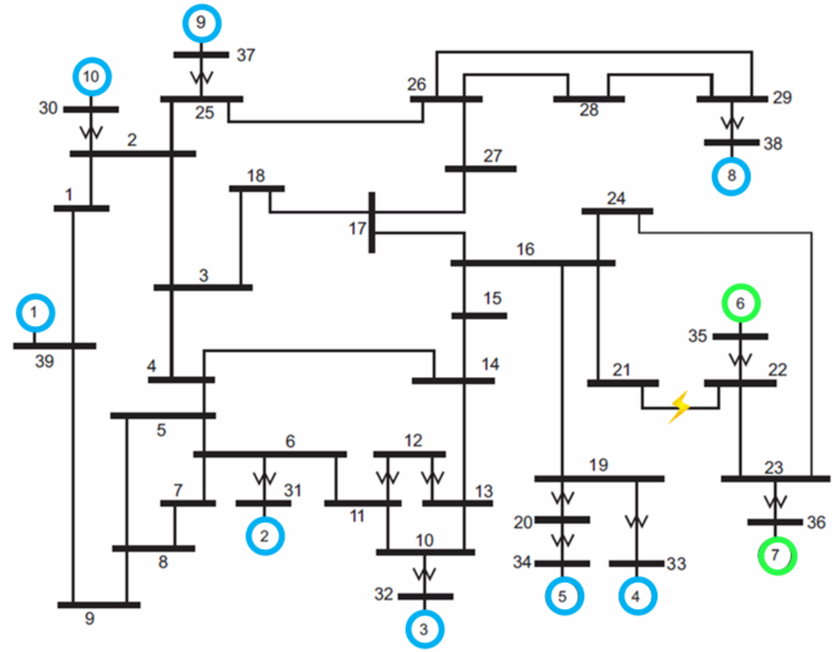
4: Out-of-Step Protection

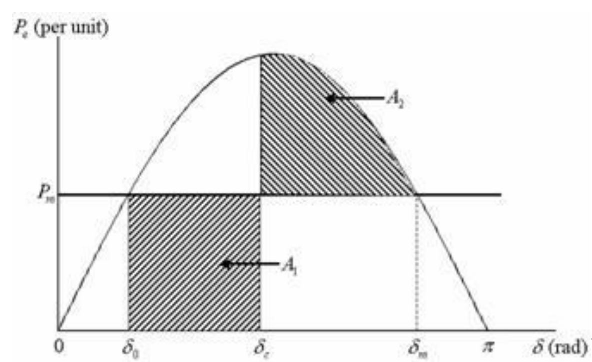
Cyber attack on power generator by Idaho lab



Coherent Group 1

Coherent Group 2

Out-of-Step (OOS) means a generator or a group of generators lose synchronism with the rest of the system.



Equal Area Criterion

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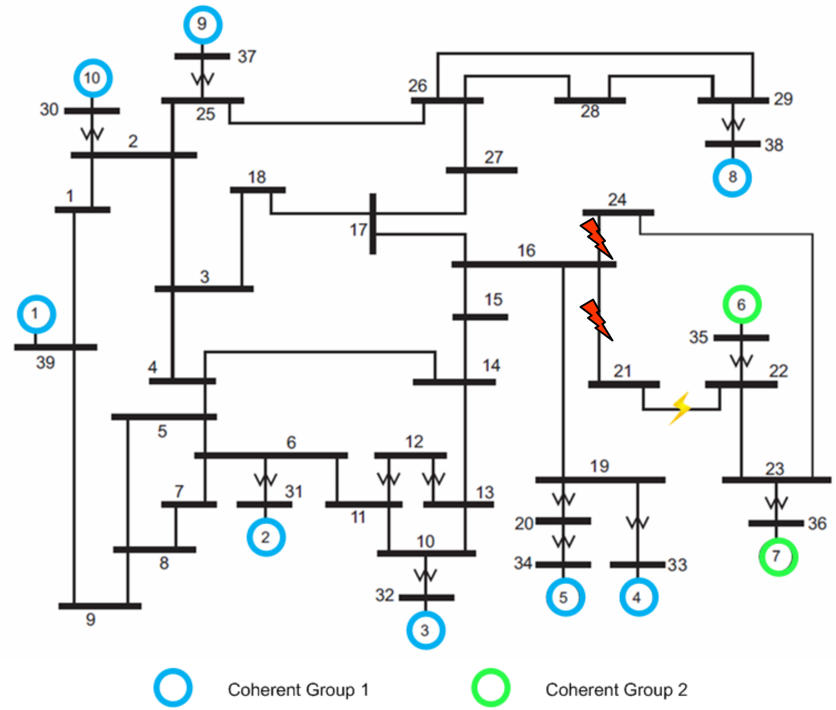
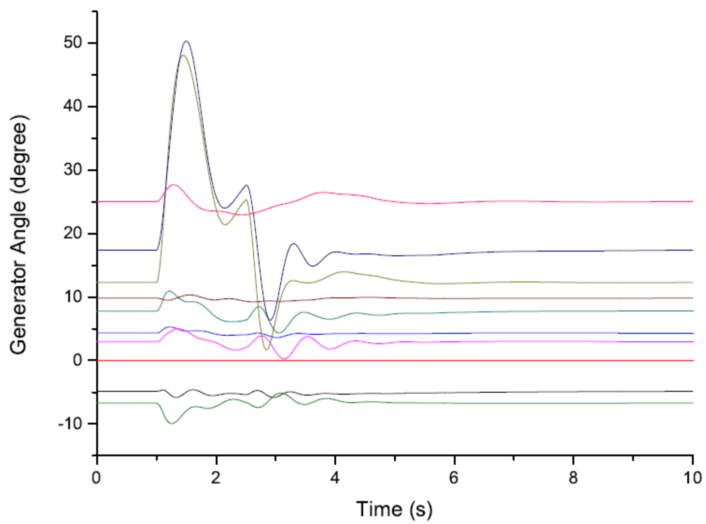
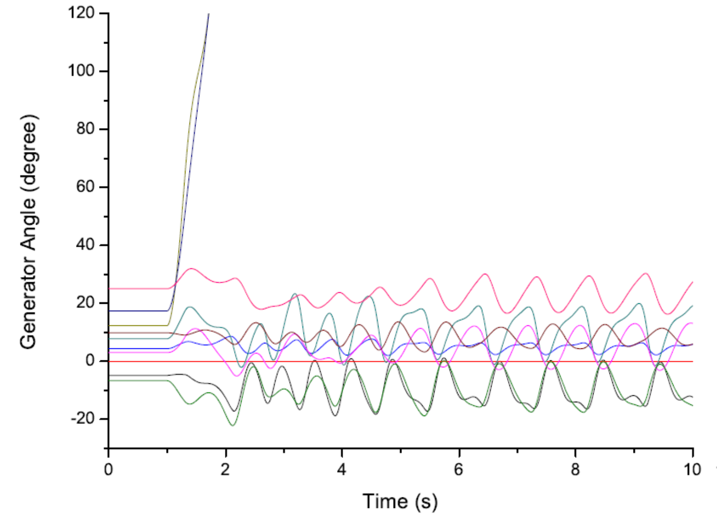
Out-of-Step Protection

- Out-of-Step (OOS) means a generator or a group of generators lose synchronism with the rest of the system.
- One effective method is to run time-domain dynamic simulations and monitor the generator angles.





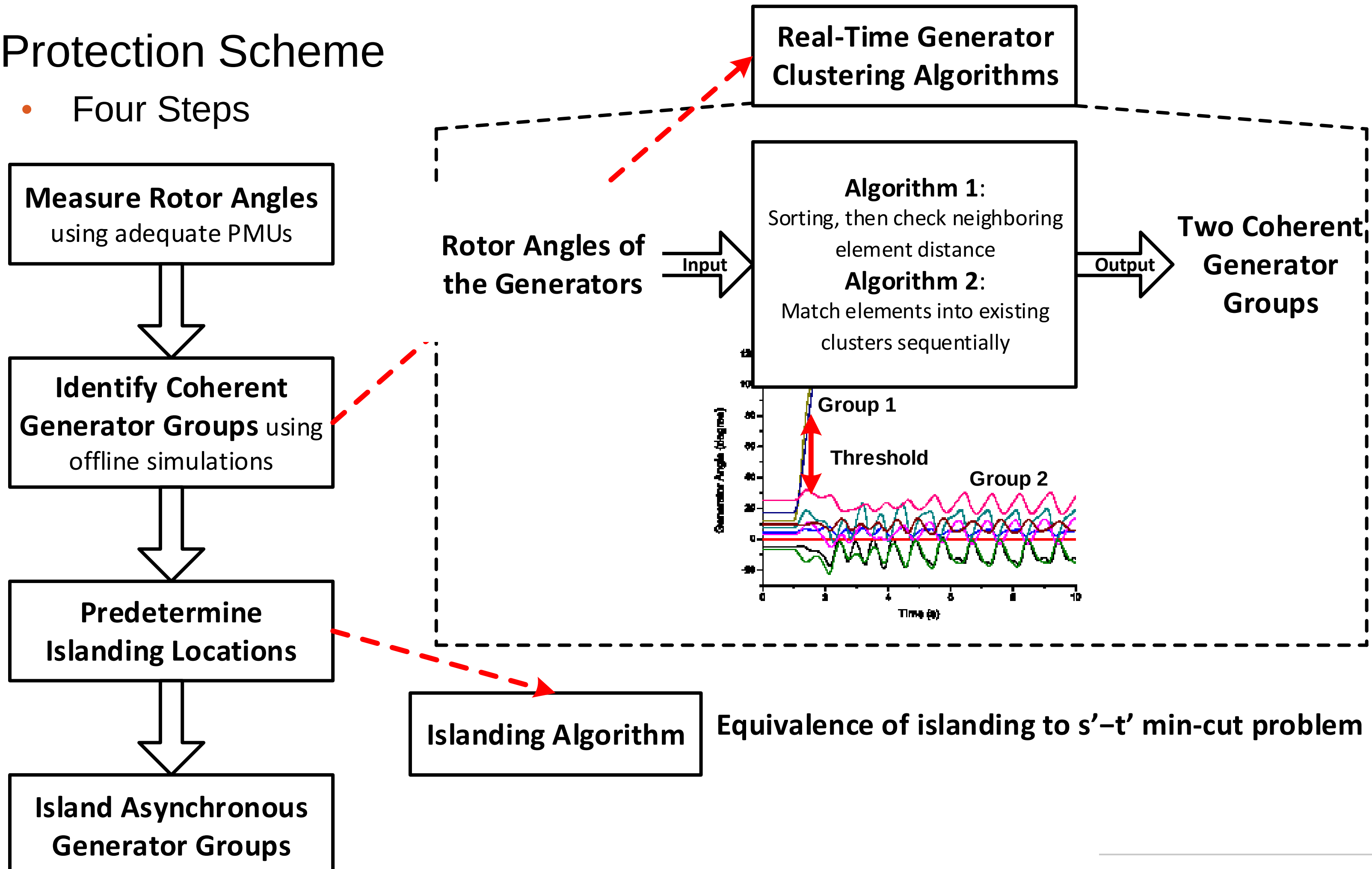
Fault cleared in 0.1 second, system back to normal condition



Fault cleared in 0.3 second, OOS condition is observed

PMU-based Out-of-Step Protection

- Protection Scheme
  - Four Steps



Clustering Algorithm for Coherent Groups

- Clustering algorithm refers to a group of algorithms whose goal is to divide data into subsets based on certain criteria.
- The first algorithm sorts the measured rotor angle and traverse the measured rotor angle sequentially. If the gap between two neighbors is greater than 120 degrees, then the OOS condition is identified.
- An alternative second algorithm processes the measured rotor angle one by one.

CoherentGroup1(A) returns S, T

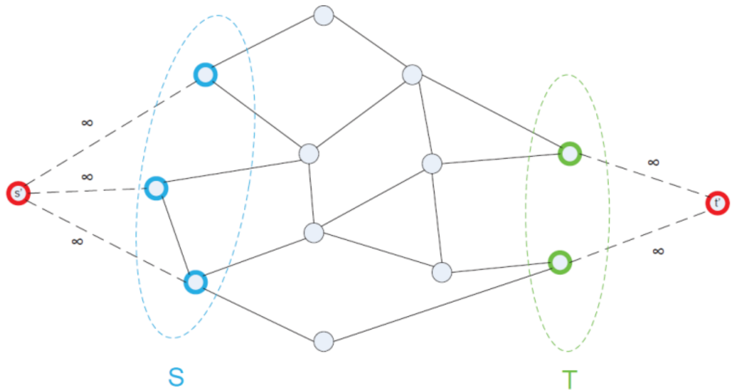
```
sort A
for i = 1 to A.size() − 1
    if A[i + 1] − A[i] > 120
        push generators associated with A[1] to A[i] into S
        push generators associated with A[i + 1] to A[A.size()] into T
        return
```

CoherentGroup2(A) returns S, T

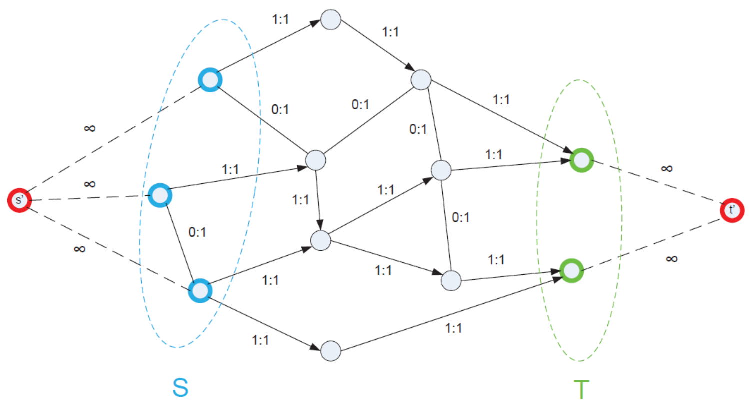
```
create a dynamic array G to hold clusters
for i = 1 to A.size()
    compare A[i] with the means of the clusters in G sequentially
    if one of the differences is smaller than 120 degree
        push pair of < i, A[i] > into that cluster, update the mean
    else
        create a new cluster holding pair of < i, A[i] > and push it into G
find the largest cluster in G
push the generators in this cluster into a set S
push the other generators into another set T
```

Islanding Algorithm

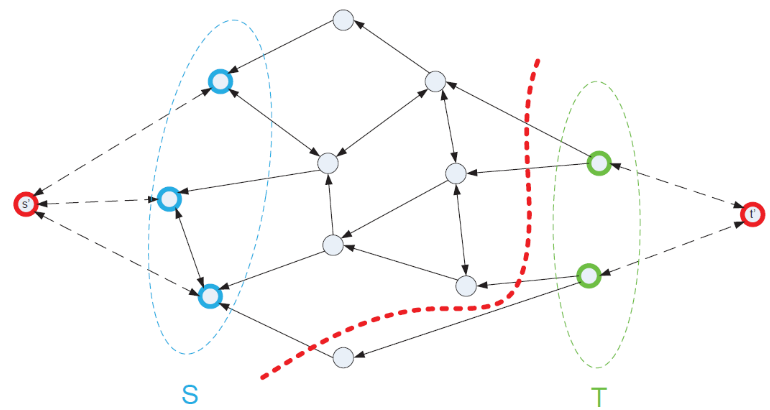
- As long as we have found two coherent generator groups *S* and *T*, the next step is to find a minimum cut of the entire power system that can separate *S* and *T*.
- Edmonds-Karp algorithm which is $O(|V||E|^2)$



Equivalence of islanding to $s - t$ min-cut problem

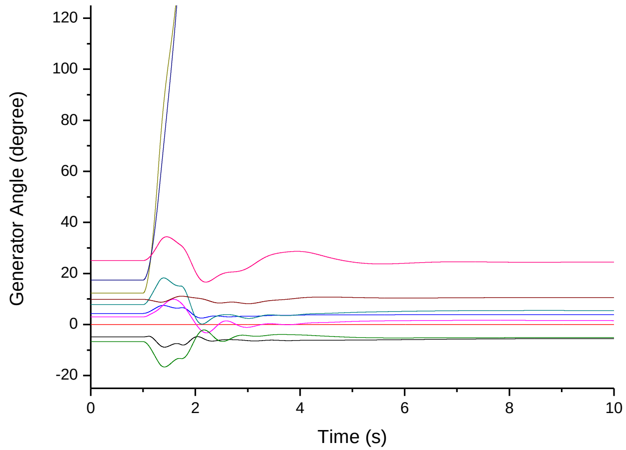


A max-flow example

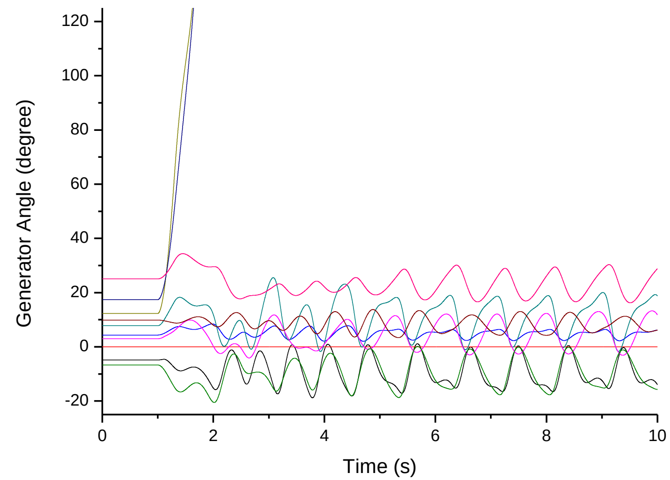


Find the min-cut on the residual network

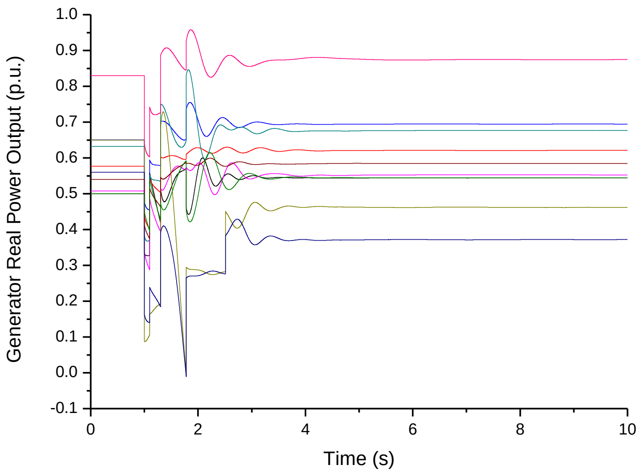
Simulation Results



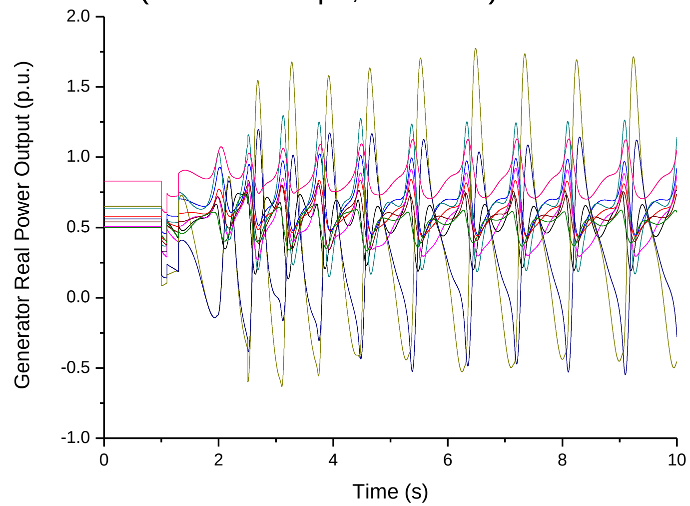
Generator angels showing OOS condition
(BW=1Gbps, D=5ms)



Generator angels with link failure
(BW=100Mbps, D=10ms)



Generator real power outputs
(BW=1Gbps, D=5ms)



Generator real power outputs with link failure
(BW=100Mbps, D=10ms)

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5: Conclusions & Future Research

- Implemented a co-simulation platform GECO, and integrated the dynamic state estimation and the out-of-step protection modules in the platform.
- Launched two case studies (all-PMU based state estimation and PMU based out-of-step protection) to reveal the cyber security vulnerabilities on co-simulation platform.

- Cloud-based virtual SCADA testbed for cyber security research
  - Centralize & Modulize computing and communication resources
  - Replaceable different communication protocols for security research
  - Seamlessly interact with power/control system simulators.

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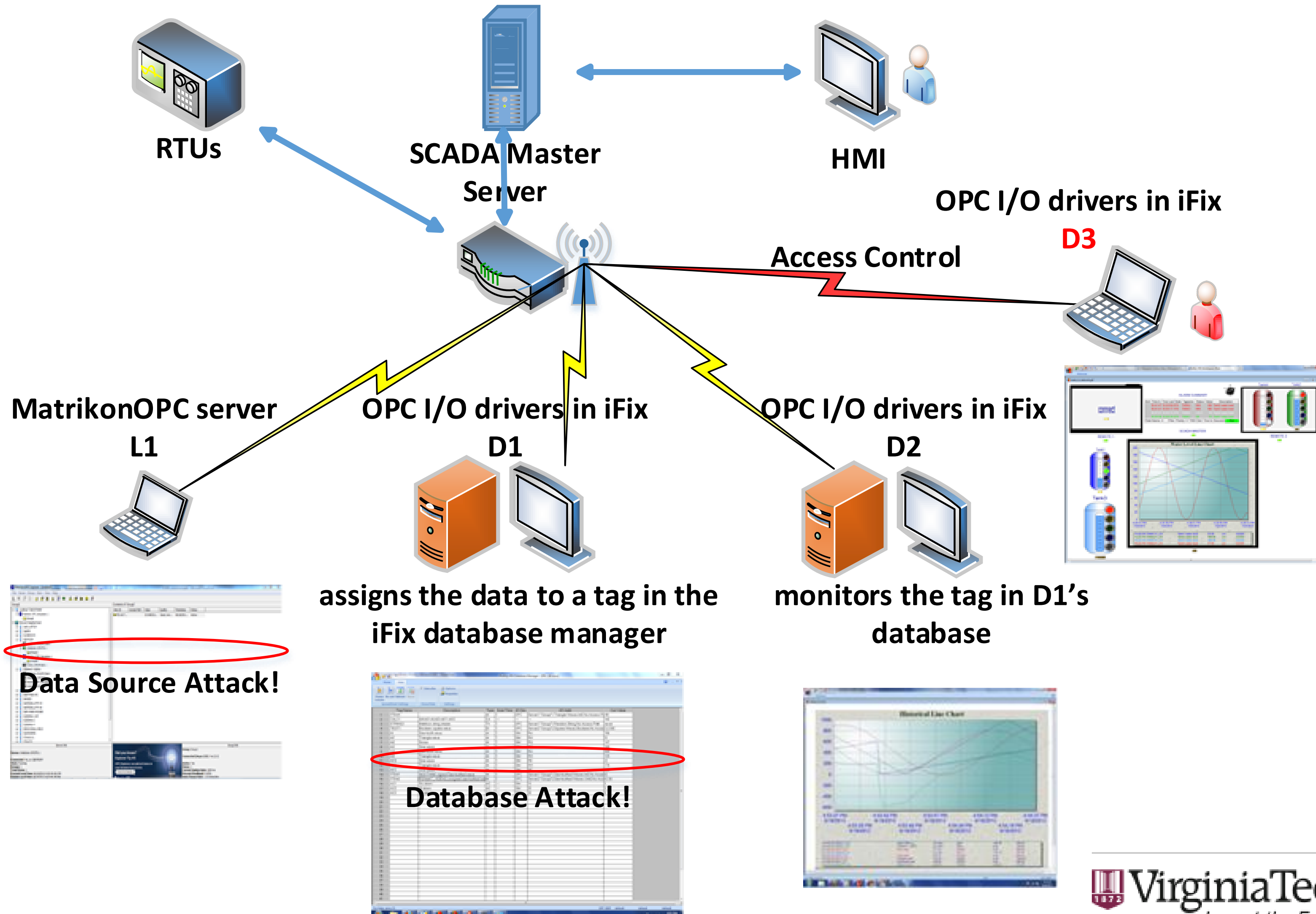
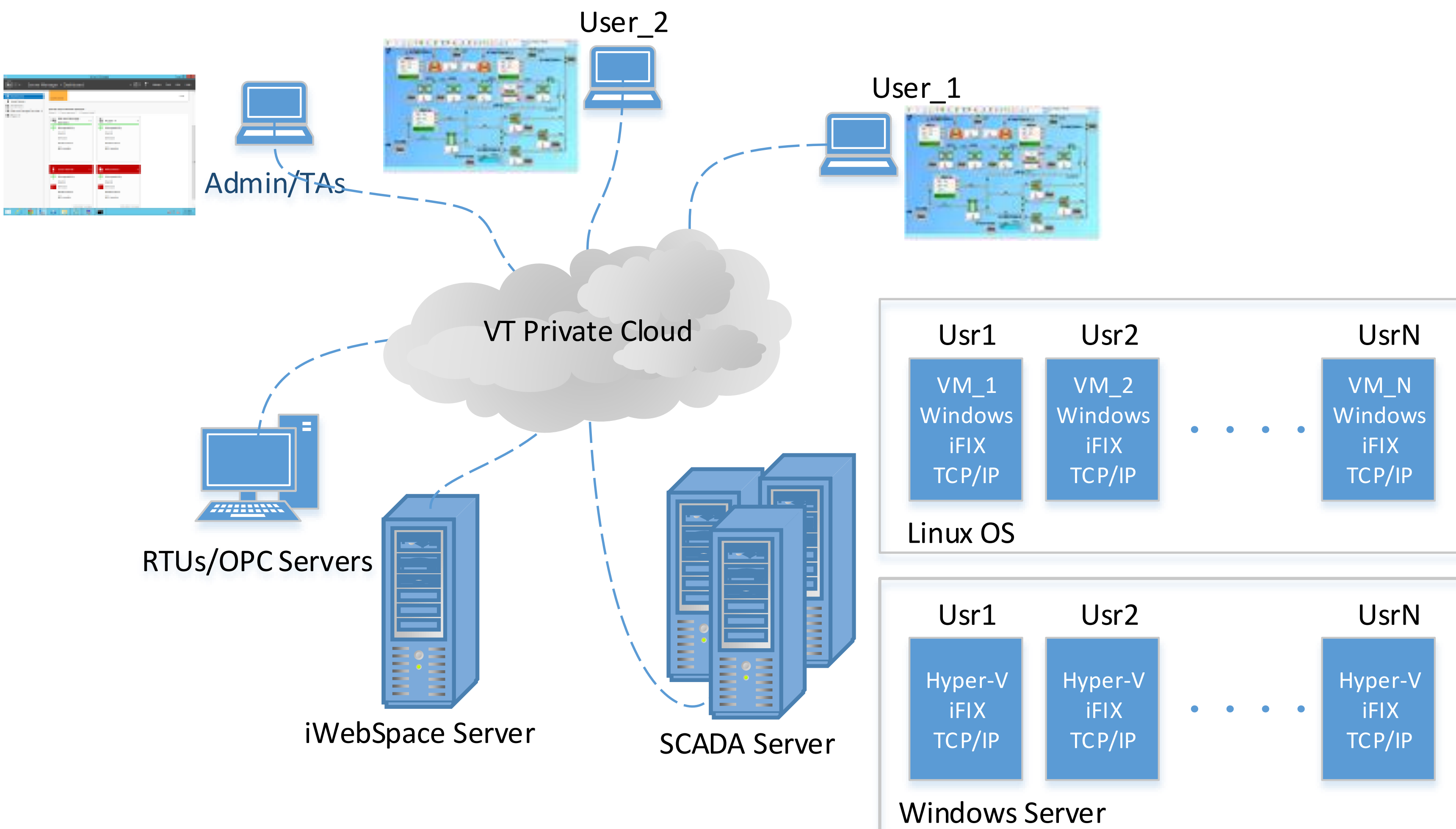
Virtual SCADA Testbed for Cyber Security Research



Cloud-based Virtual SCADA Infrastructure in VT



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2. Yi Deng, Sandeep Shukla, “Vulnerabilities and Countermeasures - A Survey on the Cyber Security issues in the Transmission Subsystem of a Smart Grid”, Journal of Cyber Security and Mobility, invited paper, 2012
3. Yi Deng, Hua Lin, Arun G. Phadke, Sandeep Shukla, and James S. Thorp, “Networking technologies for wide-area measurement applications” book chapter, “Smart Grid Communications and Networking” to be published, Cambridge University Press, UK, 2012
4. Yi Deng, Hua Lin, Arun G. Phadke, Sandeep Shukla, James S. Thorp, Lamine Mili, “Communication Network Modeling and Simulation for Wide Area Measurement Applications” IEEE PES Conference on Innovative Smart Grid Technologies, Jan. 2012
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6. H. Lin, S. Sambamoorthy, S. Shukla, L. Mili, J. Thorp, “GECO: Global Event-Driven Co-Simulation Framework for Interconnected Power System and Communication Network”. IEEE Transactions on Smart Grid, accepted, 2012
7. 1: Yi Deng; Hua Lin; Shukla, S.; Thorp, J.; Mili, L., "Co-simulating power systems and communication network for accurate modeling and simulation of PMU based wide area measurement systems using a global event scheduling technique," Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), 2013 Workshop on , vol., no., pp.1,6, 20 May 2013

Thanks for your attention!

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