OAK RIDGE National Laboratory

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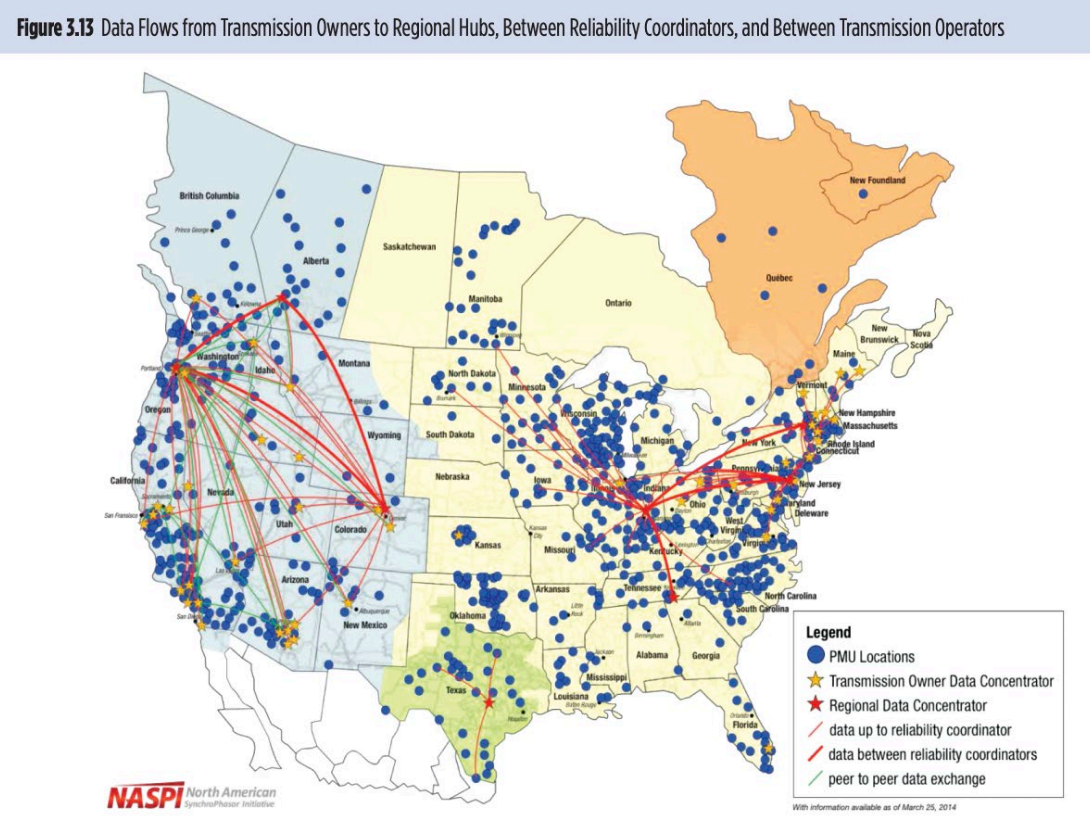
Hardware-in-the-Loop Testing of Timing Impairments in Synchrophasor Systems

Mohammed Olama and Ori Wu

Oak Ridge National Laboratory

Synchronization is Essential for Power Grid Operation

- Timing and synchronization are critical to grid operations in many traditional ways
  - OT device operations, IT services orchestration, data logging, etc.
- Timing is also critical to highly specialized grid use cases
  - Power system protection
  - Wide-area monitoring, protection, and control (WAMPAC)
  - Frequency stability and load balancing
  - Electrical event reconstruction
- 55,000+ substations with 1+ GPS antenna in the US

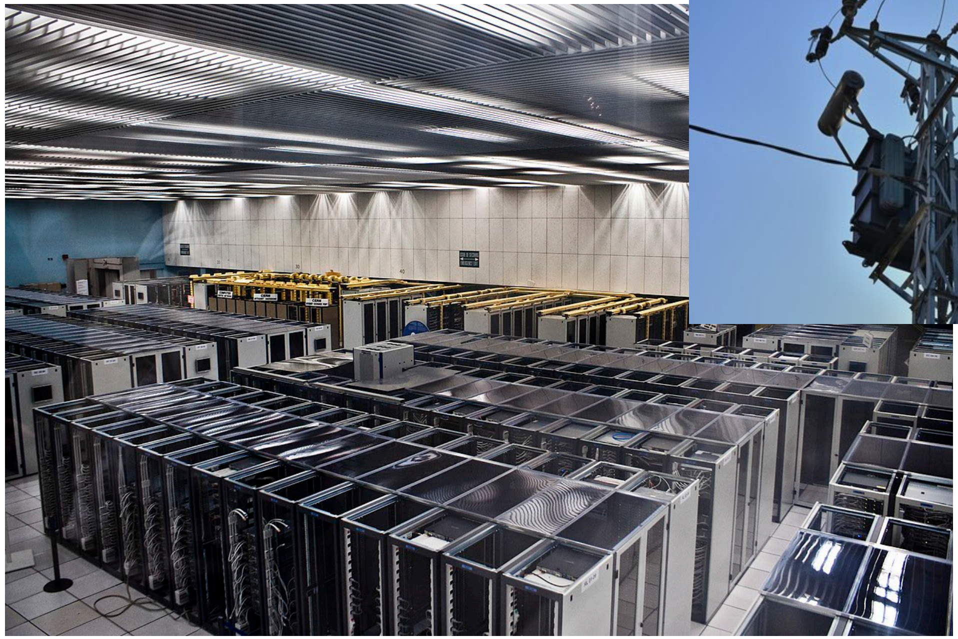


Thousands of networked PMUs deployed throughout the US (2015)

Image source: DOE Quadrennial Technology Review (2015) https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter3.pdf

Timing & Synchronization Now More Important than Ever

- Distributed generation is bringing thousands of new devices online
- Shift in grid structure and operations
  - Consumers = producers (bi-directional flows)
  - Data centers, Distributed control
- Wide-area monitoring through precision sensors and advanced analytics is critical to this transition



- Time synchronization across the sensors (and operational zones), to support analytics and inferencing, is necessary

Image source: https://commons.wikimedia.org/wiki/Category:Data_centers#/media/File:CERN_Server_03.jpg
Image source: https://commons.wikimedia.org/wiki/File:Car2Go_Charging_Station_Stuttgart_2013_01.jpg

Timing and Dissemination Today

- Timing for deployed grid assets and systems today is largely delivered by GPS (GNSS)

- Timing for IT systems operating the grid is largely delivered by Network Time Protocol (NTP)


GPS antenna installation at WAPA site


Representation of GPS satellite

Name	IP Address	Location	Status
time-a-g.nist.gov	129.6.15.28	NIST, Gaithersburg, Maryland	All Services available
time-b-g.nist.gov	129.6.15.29	NIST, Gaithersburg, Maryland	All services available
time-c-g.nist.gov	129.6.15.30	NIST, Gaithersburg, Maryland	
time-d-g.nist.gov	129.6.15.27	NIST, Gaithersburg, Maryland	All services available
time-d-g.nist.gov	2610:20:6f15:15::27	NIST, Gaithersburg, Maryland	All services available
time-e-g.nist.gov	129.6.15.26	NIST, Gaithersburg, Maryland	All services available
time-e-g.nist.gov	2610:20:6f15:15::26	NIST, Gaithersburg, Maryland	All services available
time-a-wwv.nist.gov	132.163.97.1	WWV, Fort Collins, Colorado	All services available
time-b-wwv.nist.gov	132.163.97.2	WWV, Fort Collins, Colorado	All services available
time-c-wwv.nist.gov	132.163.97.3	WWV, Fort Collins, Colorado	All services available
time-d-wwv.nist.gov	132.163.97.4	WWV, Fort Collins, Colorado	All services available
time-d-wwv.nist.gov	2610:20:6f97:97::4	WWV, Fort Collins, Colorado	All services via IPv6
time-e-wwv.nist.gov	132.163.97.6	WWV, Fort Collins, Colorado	All services available
time-e-wwv.nist.gov	2610:20:6f97:97::6	WWV, Fort Collins, Colorado	new server, services via IPV6
time-a-b.nist.gov	132.163.96.1	NIST, Boulder, Colorado	All services available
time-b-b.nist.gov	132.163.96.2	NIST, Boulder, Colorado	All services available
time-c-b.nist.gov	132.163.96.3	NIST, Boulder, Colorado	All services available
time-d-b.nist.gov	132.163.96.4	NIST, Boulder, Colorado	All services available
time-d-b.nist.gov	2610:20:6f96:96::4	NIST, Boulder, Colorado	All services available
time-e-b.nist.gov	132.163.96.6	NIST, Boulder Colorado	All services available
time-e-b.nist.gov	2610:20:6f96:96::6	NIST, Boulder, Colorado	All services available

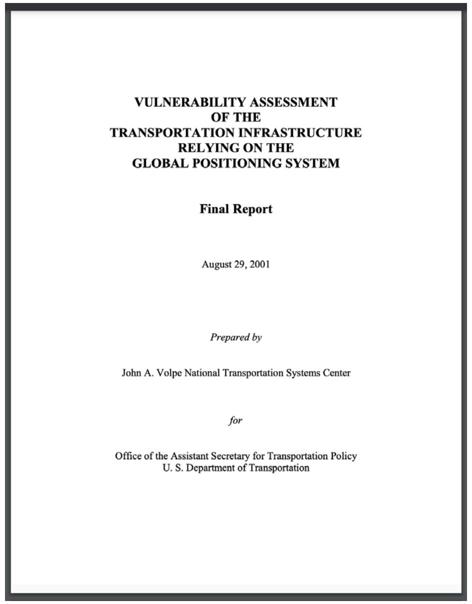
NIST NTP service dashboard

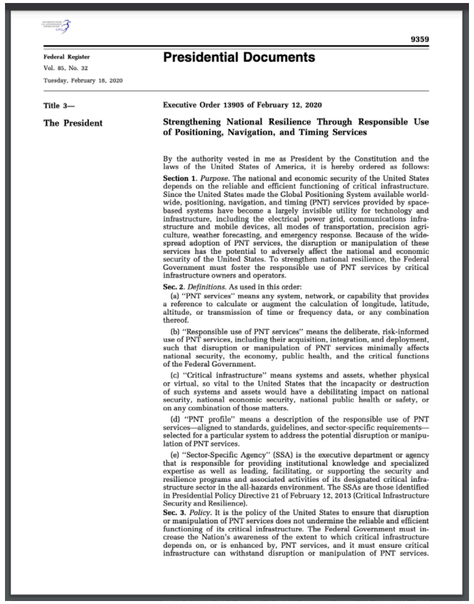
NIST image source: https://tf.nist.gov/tf-cgi/servers.cgi

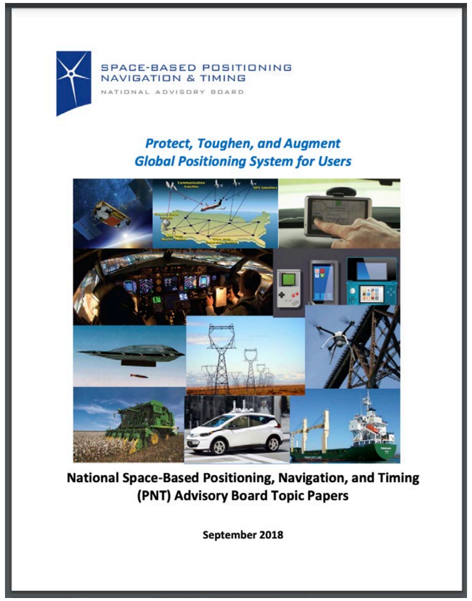
GPS image source: https://www.gps.gov/multimedia/images/GPS-III-A.jpg

GPS Risks and Vulnerabilities are Driving New Investments

- GPS vulnerabilities and the need for resilience have been well-documented
  - Signal is known and unencrypted
  - Jamming, spoofing accomplished with off-the-shelf gear
- NTP delivered via unencrypted service, vulnerable to being a cyber intrusion vector (e.g., man-in-the-middle attack)
- A **more secure** time delivery system is needed to ensure grid resiliency in the face of cyber threats.







ORNL Timing & Synchronization Test Bed: Center for Alternative Synchronization and Timing (CAST)

One-of-a-Kind Technology Baseline

Multiple **atomic clocks**

- Three cesium clocks
- Eight rubidium clocks

Multiple **communications networks** integrated to the lab

- Dark Fiber
- DWDM
- Carrier Ethernet
- OTN
- Copper
- DOE ESNet
- Cellular+5G
- Ku-band SATCOM
- Satellite Internet
- Microwave

Variety of **routers, switches, and firewalls** for testing and benchmarking

Industry and Lab Partnerships for Testing and Development

Hardware Partners

- Adtran/Oscilloquartz
- Arista
- Juniper
- Microchip
- Nokia
- Palo Alto
- Safran/Orolia

Communications Partners

- ESNet
- AT&T
- InMarSat
- Iris Networks
- SES
- Verizon

R&D and Testing Partners

- Idaho National Lab
- Sandia National Lab
- Pacific Northwest National Laboratory
- Savannah River National Lab
- National Institute of Standards and Technology (NIST)
- Tennessee Valley Authority (TVA)
- Electric Power Board of Chattanooga (EPB)
- Dominion Energy
- Western Area Power Administration (WAPA)
- Bonneville Power Administration (BPA)

Accelerating Alternative Timing and Synchronization Modernization for the Grid

- Test, evaluate, and document the capabilities and limitations of today's technology for **augmenting GPS** timing in the grid
- Perform **R&D** and provide **technical assistance** to federal and commercial partners to implement alternative timing & synchronization solutions
- Design and test **complementary timing/synchronization architectures** that:
    - Drive **reliable** and economical scaling to large geographic areas
    - Easily integrate into existing technical environments to bolster **resilience**
    - Use **affordable** COTS capabilities
    - Ensure **security** and resistance to adversarial and natural disruptions

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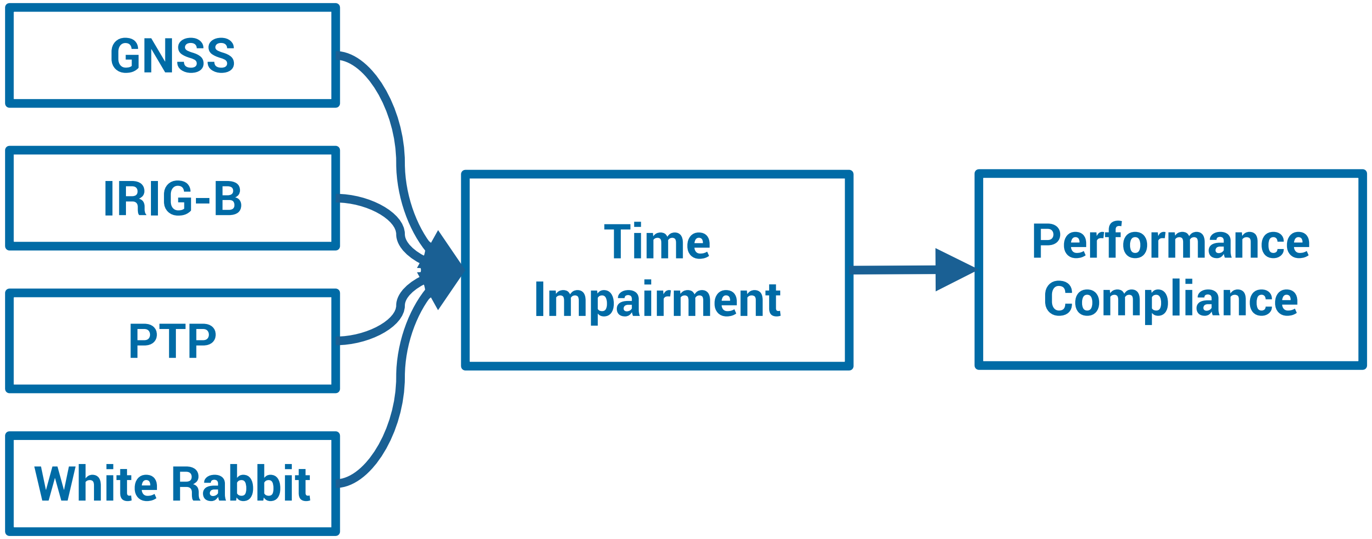
Motivation – The Need for HIL

Why HIL? To quantify the Error Chain.

- **Precision Under Stress**: While software simulations assume "ideal" timing, a physical HIL platform captures the real-world stochastic nature of network jitter and hardware latency that simple models overlook.
- **Controllable & Repeatable Impairment Injection**: Enables the injection of specific, quantified "timing impairments" in a safe, isolated environment.
- **Quantifying the Error Chain**: HIL uniquely allows for measuring end-to-end propagation error.

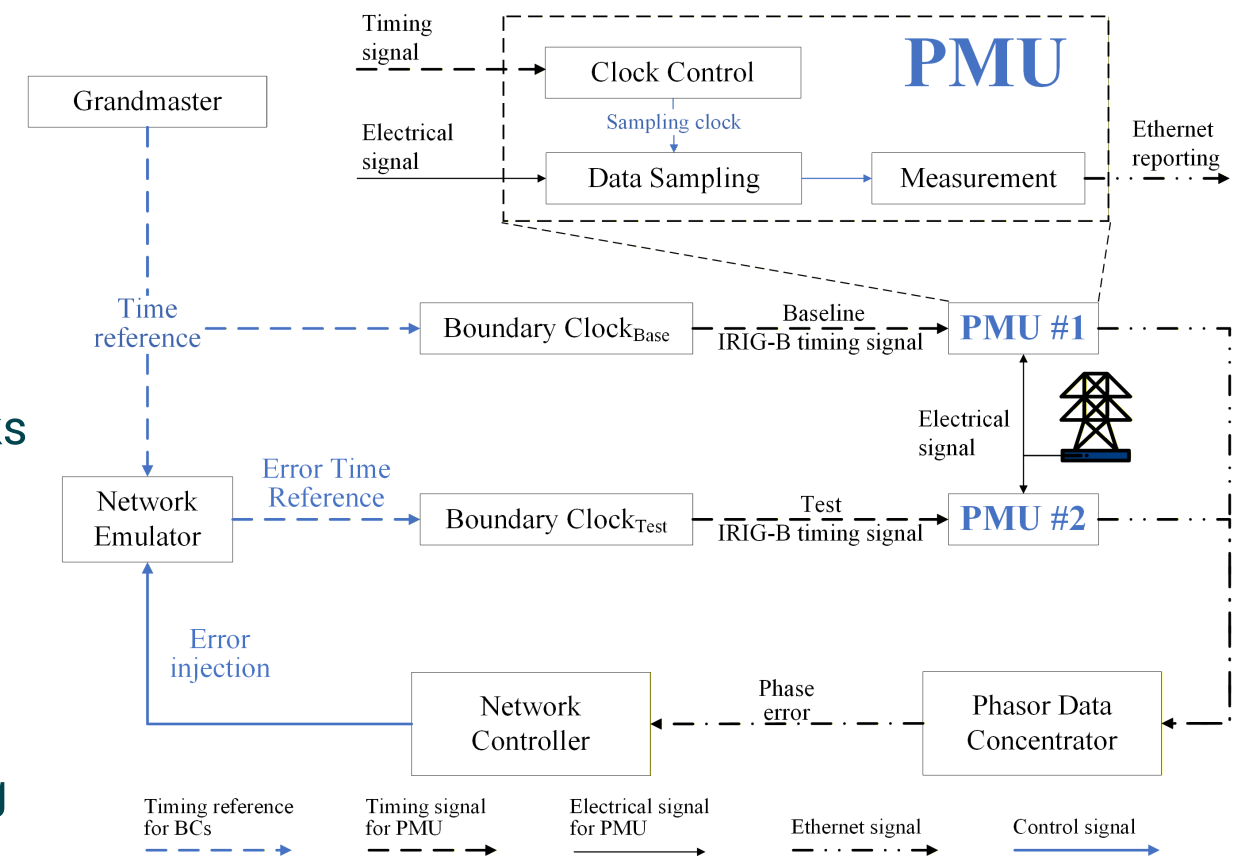
Evaluating Resilient Timing for Grid Services

- **Protocol Agnostic Testing:** By focusing on "time impairments", the platform evaluates the unique **error signatures** of diverse synchronization sources—including **GNSS, IRIG-B, PTP, and White Rabbit**—quantifying their impact on grid stability regardless of the underlying transport layer.
- **Safety Margin Identification:** HIL platform can identify the "threshold", where timing degradation leads to **Control Maloperation**.
- **Operational Readiness:** Moving from theoretical resilience to hardware-validated resilience, ensuring new timing sources meet the IEC 60255.118.1 / IEEE C37.118.1 performance standards.



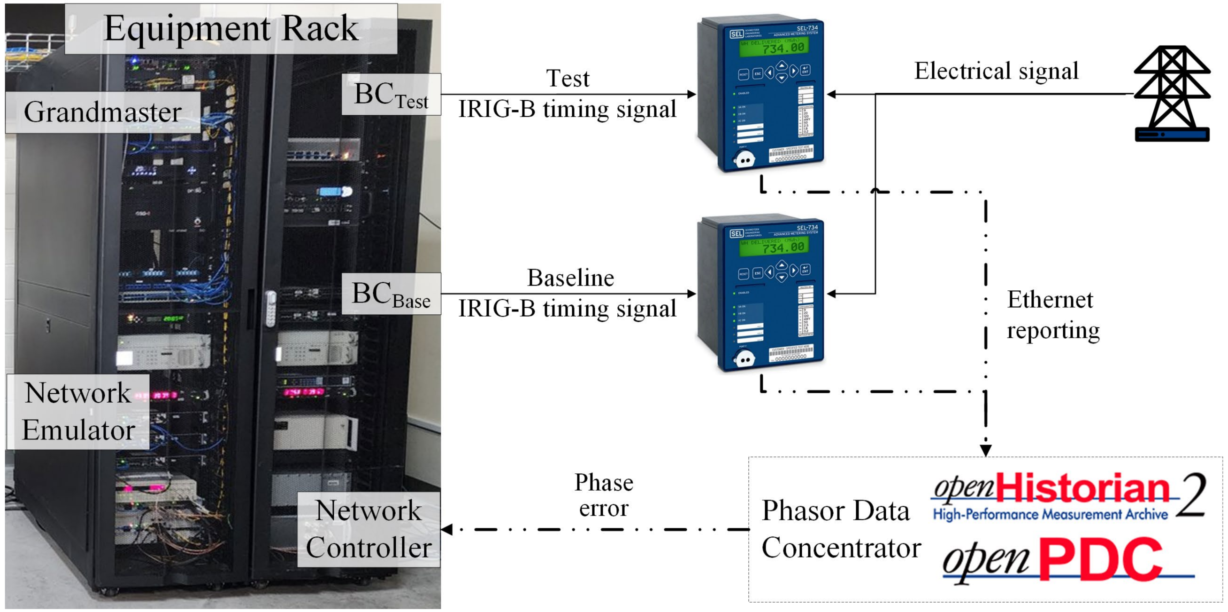
Architecture of Network Hardware-in-the-Loop Platform

- **Steady-state signal injection**:
  - Both PMUs receive the same 60 Hz steady-state signal to isolate timing-induced errors by eliminating power system transients.
- **Time reference & distribution**:
  - A UTC-aligned cesium atomic grandmaster distributes IEEE 1588 PTP to two boundary clocks (BCs).
  - A dual-chain compares a clean **Baseline Chain** (PMU #1) against an **Impaired Chain** (PMU #2).
- **Time impairment injection:**
  - A network emulator injects controlled PTP timing errors, quantifying how timing impairments propagate into synchrophasor measurements.



Architecture of Network Hardware-in-the-Loop Platform

- **Hardware Integration:**
  - A single equipment rack integrates the **Cesium Grandmaster**, **Boundary Clocks**, and the **Netropy Network Emulator**.
  - **Dual SEL-734 PMUs:** Connected to respective chains; both monitor the same electrical signal.
- **Data Management & Feedback:**
  - **OpenHistorian PDC:** Aggregates Ethernet-based PMU reports for real-time analysis.
  - **Closed-Loop Control:** Calculated **Phase Angle Error (PAE)** is fed back to the network controller.



Time Error Analysis: From PTP Packets to Phasor Measurements

- **PTP Clock Offset Estimation**:

$$\text{Path}_{\text{delay}} = \frac{(t_2 - t_1) + (t_4 - t_3)}{2}$$
$$\text{T}_{\text{offset}} = (t_2 - t_1) - \text{Path}_{\text{delay}}$$

- **Network Impairment Injection**: The network emulator introduces an asymmetric delay ($\Delta\tau$) specifically to the t_3 or t_4.

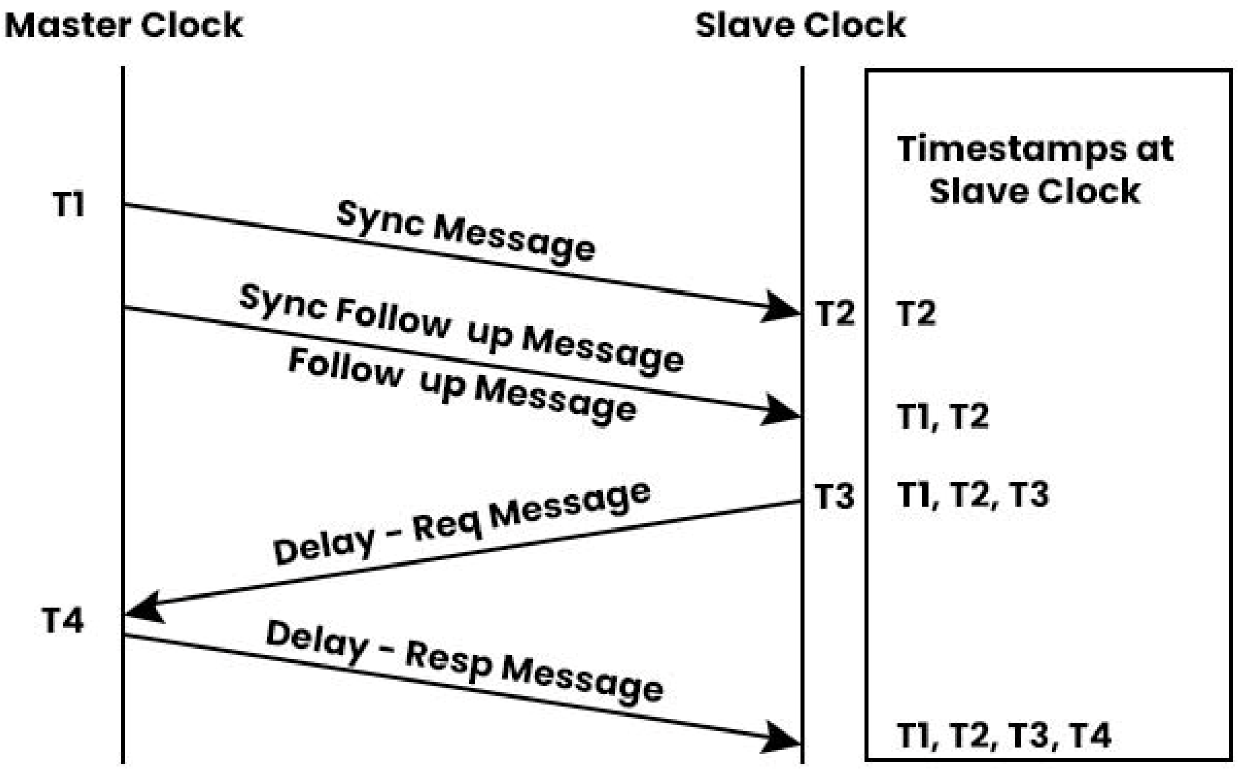
$$\text{Path}'_{\text{delay}} = \text{Path}_{\text{delay}} + \frac{\Delta\tau}{2}$$
$$\text{TE} = \frac{\Delta\tau}{2}$$

- Phasor calculation according to the timestamp:

$$v[n] = V_m \cos(2\pi f(t + \text{TE}) + \theta_0)$$

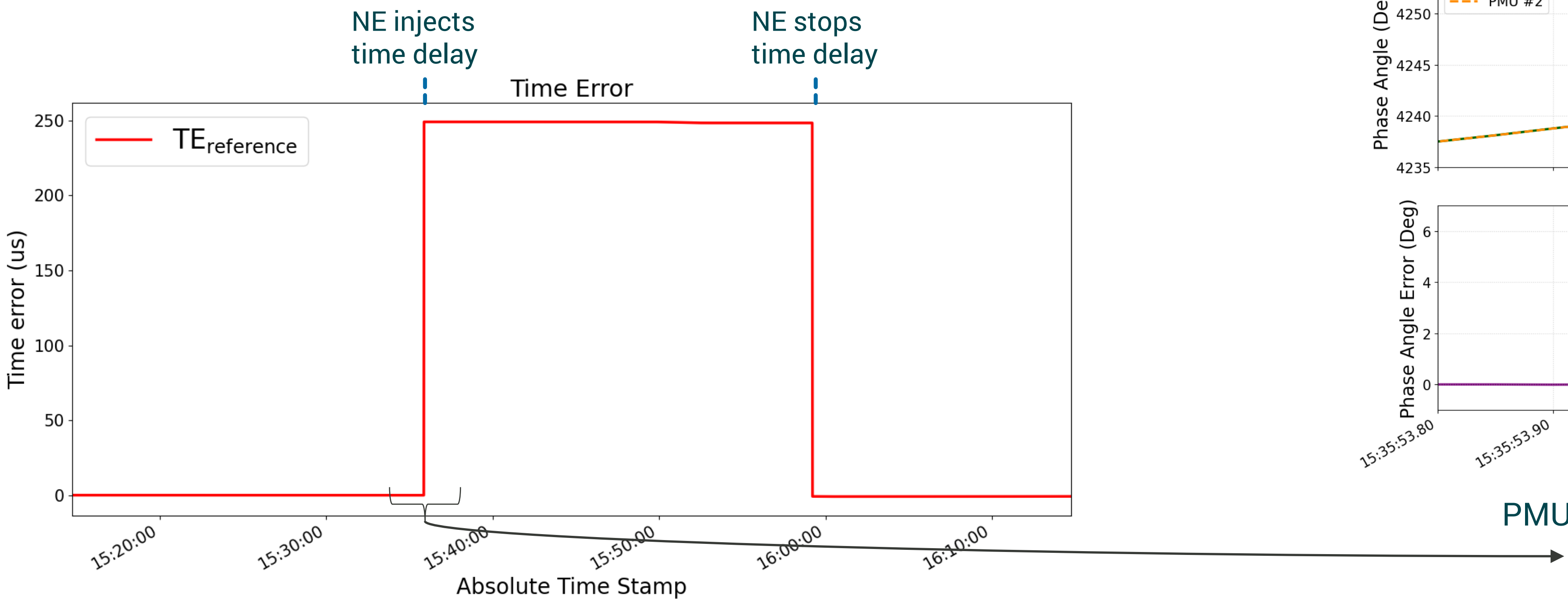
Leading to: $\text{Phase Angle Error} = 2\pi f \cdot \text{TE}$ (radian)

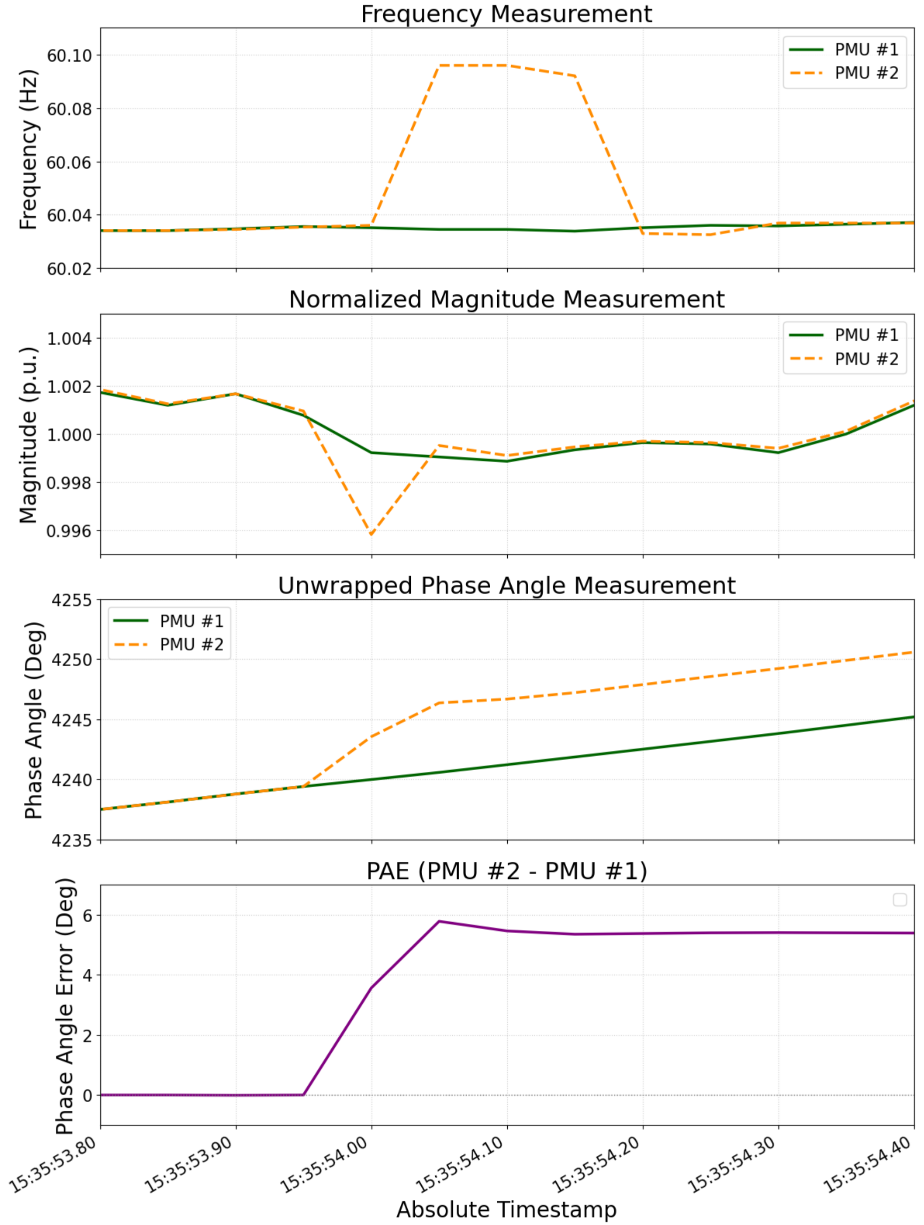
or: $\text{Phase Angle Error} = 360° f \cdot \text{TE}$ (degree)



Time Error Analysis: Experimental Results

- Experimental setup:
  - One-way time delay of 500us is injected by network controller.
  - $TE_{reference}$: extracted from the BC log files.
    - 250 us time error is observed.



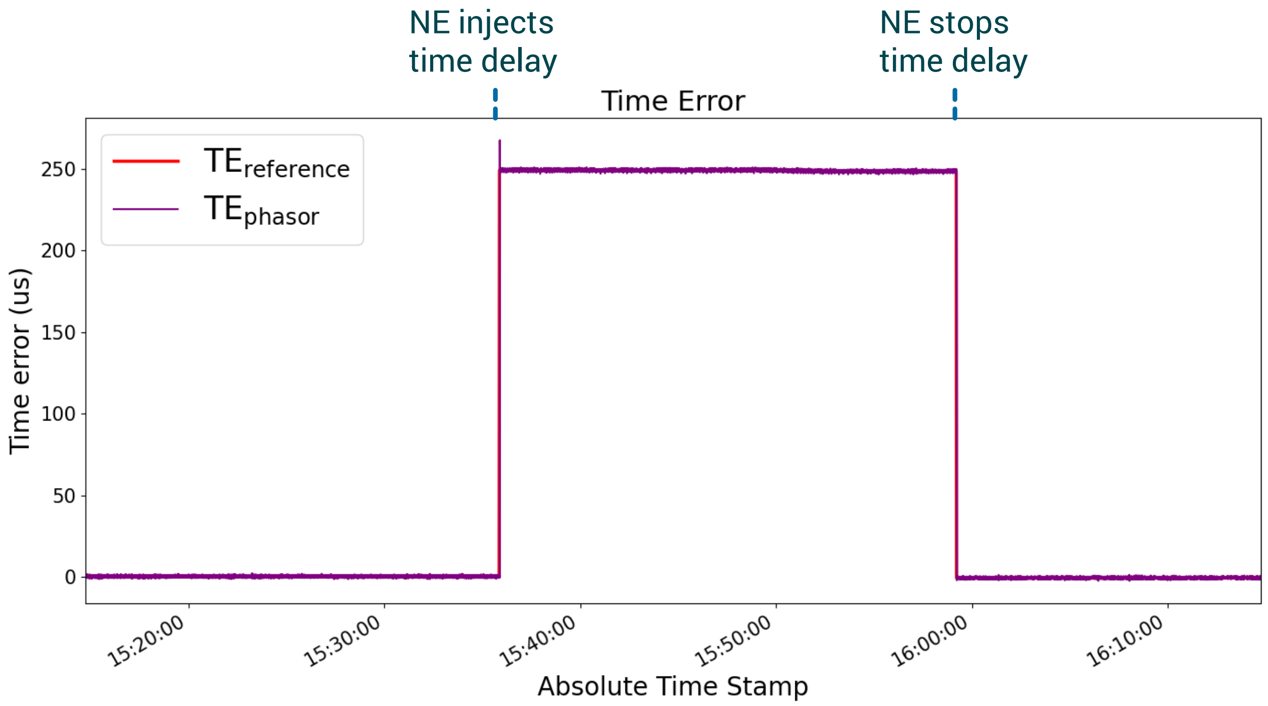


PMU measurements during transit
(20 frames per sec)

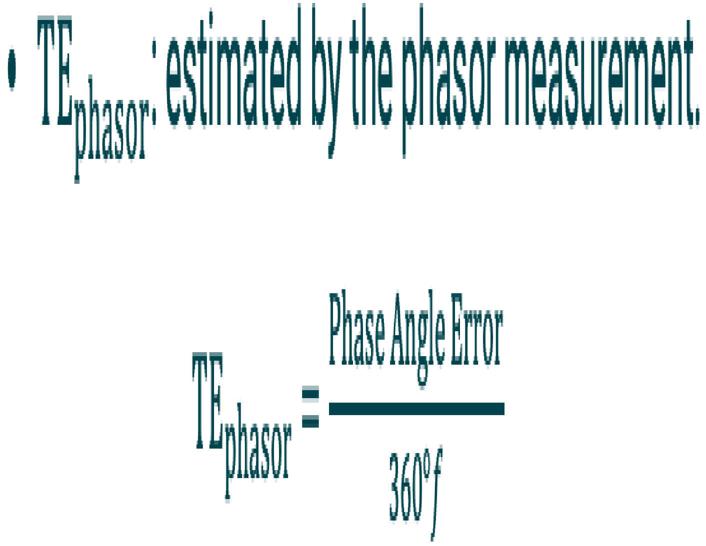
Time Error Analysis: Experiment Results

- Results comparison:
  - $\mathrm{TE}_{\mathrm{reference}}$: extracted from the BC log files.
  - $\mathrm{TE}_{\mathrm{phasor}}$: estimated by the phasor measurement.

$$\mathrm{TE}_{\mathrm{phasor}} = \frac{\text{Phase Angle Error}}{360° f}$$



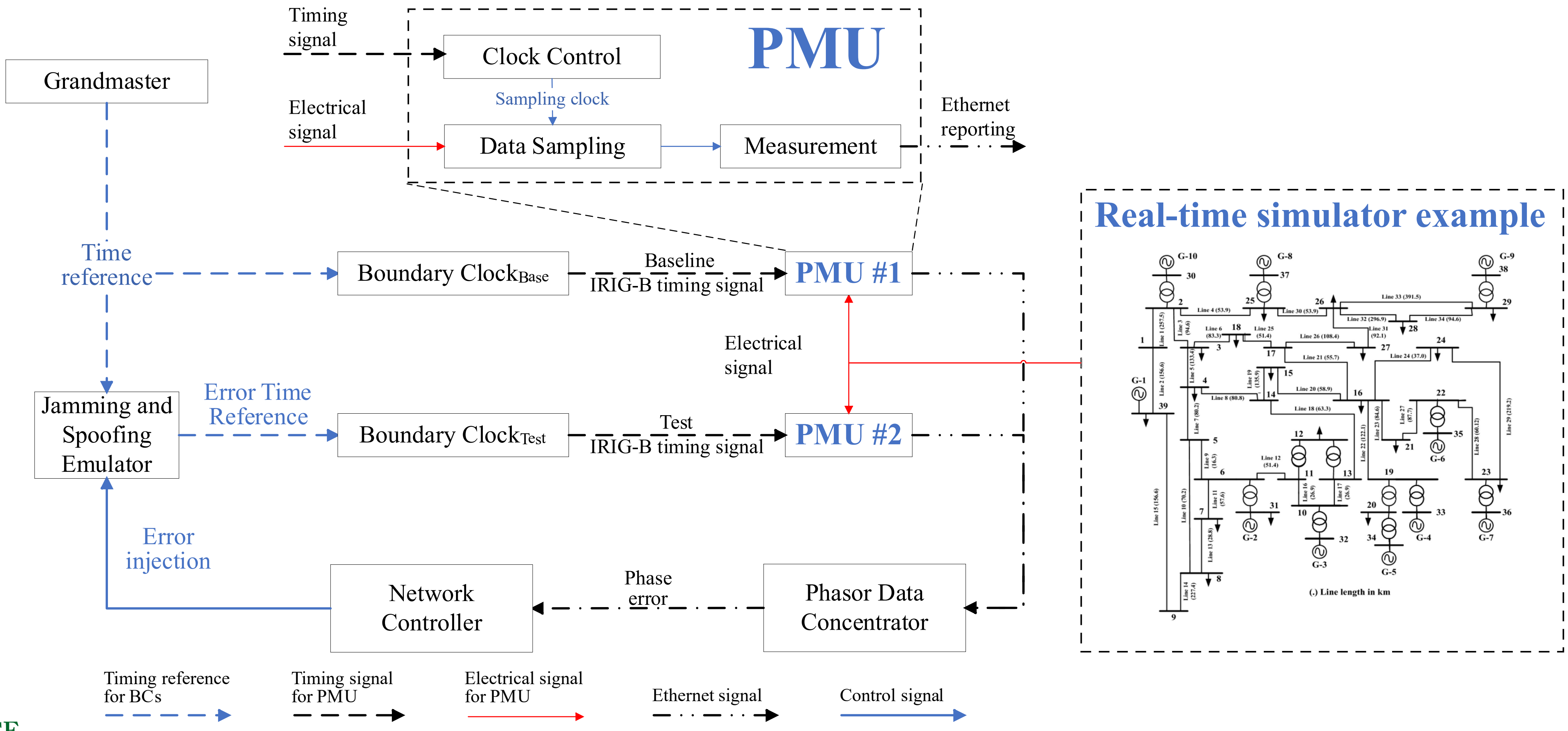
PAE conversion



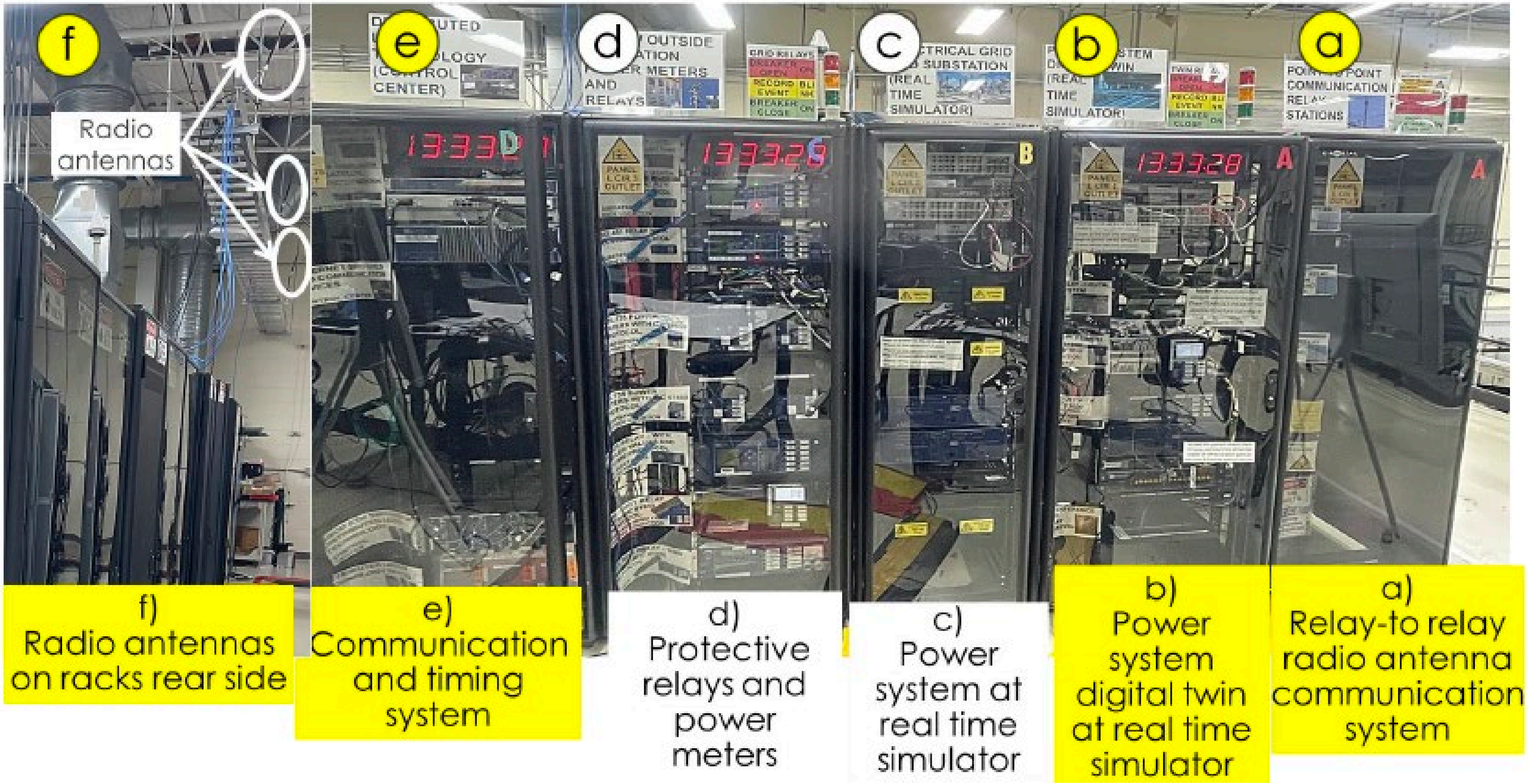
Injected one-way time delay (μs)	Average $\mathrm{TE}_{\mathrm{reference}}$ (μs)	Average $\mathrm{TE}_{\mathrm{phasor}}$ (μs)
10	4.58	4.47
100	49.69	49.81
500	248.87	249.11
1,000	499.52	499.83
5,000	2499.17	2499.55
10,000	5000.06	5000.47

HIL Integration with Real-Time Simulator

- We are currently integrating the network HIL with a real-time power system simulator to investigate the impact on various grid services.



Ongoing Experiment: Fully HIL Testing



Summary and Conclusion

- This study demonstrated the **high-fidelity** capabilities of an NHIL testbed for evaluating PMU performance under communication timing impairments.
- **Baseline** experiments verified that the PMUs operated well within the IEEE C37.118.1 accuracy requirements.
- Under **faulted conditions**, the NHIL environment enabled precise injection of network delays ranging from 10 micro-sec to 10 milli-sec, revealing a clear and repeatable correlation between cyber-side delay and synchrophasor measurement error.
- The time error estimated from the phasor data precisely **matched** both theoretical predictions and ground-truth IRIG-B measurements. This validation confirms the NHIL platform's ability to **accurately** translate cyber-side network anomalies into physically observable measurement degradation.
- Such measurement degradation can **severely compromise grid situational awareness**, leading to erroneous state estimation and false tripping of differential protection relays.
- Ensuring the immunity of synchronization protocols against network latency is not merely a compliance issue, but a **fundamental requirement** for preventing cascading failures in increasingly automated systems.
- Future work focuses on integrating this platform into a full HIL configuration with a **real-time power system simulator** to evaluate closed-loop control applications.

Information, Collaboration, and Technical Resources

- Contact CAST@ornl.gov
  - Technical assistance and collaboration opportunities
  - Equipment and network requirements
  - Timing/synchronization performance monitoring capabilities

- CAST Website: https://cast.ornl.gov
  - Access our technical resources and bulletins, live timing data, news items, and conference activities

Questions?