Research Priorities for Phasor Measurement Units

Chris Greer

Director
NIST Smart Grid & Cyber Physical Systems Program

NASPI Work Group Meeting
March 22, 2017

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National Institute of Standards and Technology
U.S. Department of Commerce

NIST's Mission

To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life

Energy Independence and Security Act

NIST has *"primary responsibility to **coordinate** development of a **framework** that includes protocols and model standards for information management to achieve **interoperability** of smart grid devices and systems…"*

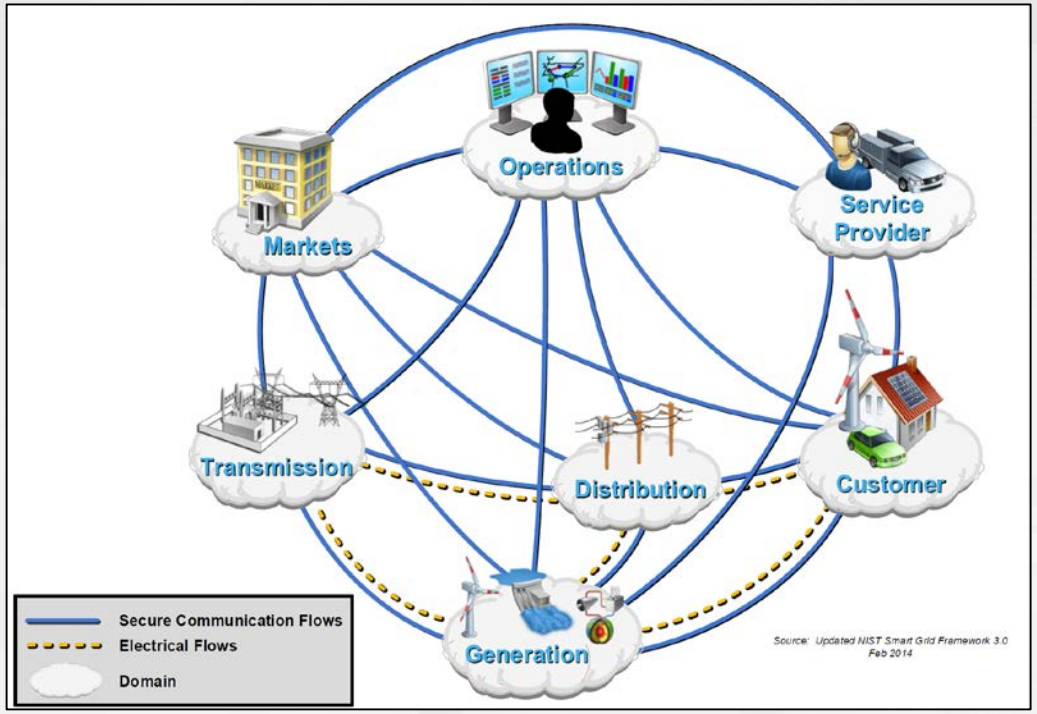
NIST Smart Grid Program team

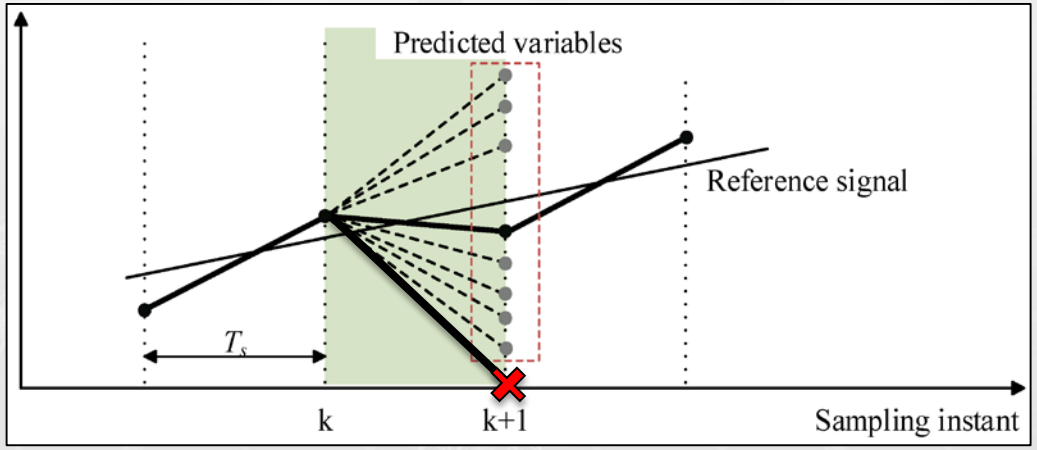
- Dhananjay Anand
- Gerald FitzPatrick
- Hamid Gharavi
- Allen Goldstein
- Avi Gopstein
- Ya-Shian Li-Baboud
- Cuong Nguyen
- Wei Yu

- Paul Boynton
- Martin Burns
- Steven Bushby
- Nada Golmie
- Nelson Hastings
- David Holmberg
- Anand Kandaswamy
- Joshua Kneifel
- Tom Nelson
- Cheyney O’Fallon
- Farhad Omar
- Eric Simmon
- Eugene Song
- David Su
- Randy Wedin
- David Wollman

Uncertainty is a dominant challenge

- **Grid is highly distributed and complex**
  - Increasing diversity of device, resource, and control
- **Uncertainty is growing**
  - Growing numbers and increasing dynamics of variables lessen the likelihood of well-behaved, predictable system
  - Legacy models and tools incapable of addressing the growing uncertainty
- **Progress needed across multiple dimensions**
  - New grid physics
  - Networked measurements
  - Diversified applications
  - Expanding customer-base

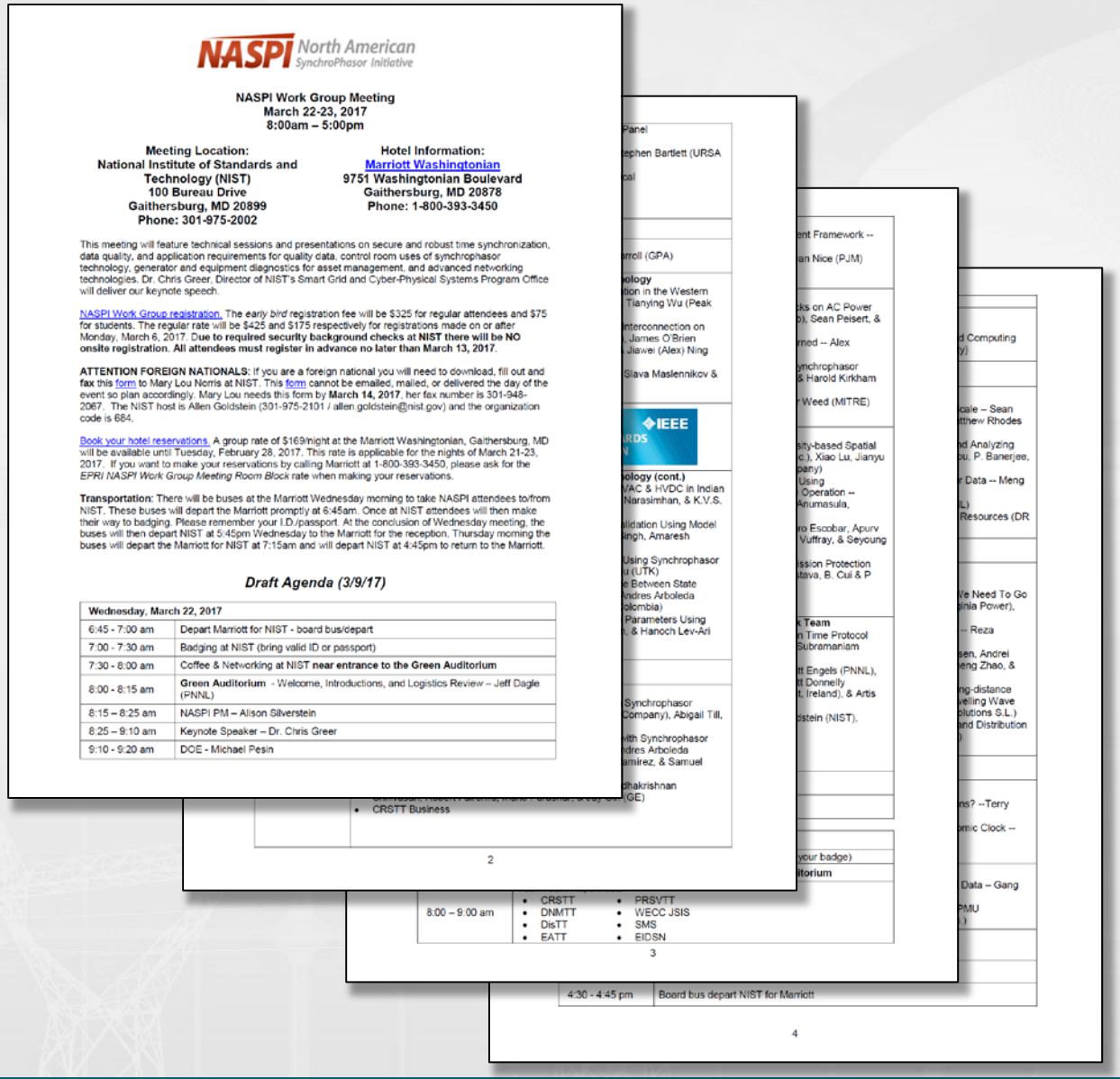




Diverse research, common objectives

Measurement science key to grid observability

- Timing
- Measurement uncertainty
- System modeling
- Cybersecurity through physics
- Communications
- Synchrometrology
- Applications



NASPI North American SynchroPhasor Initiative

NASPI Work Group Meeting
March 22-23, 2017
8:00am – 5:00pm

Meeting Location:
National Institute of Standards and Technology (NIST)
100 Bureau Drive
Gaithersburg, MD 20899
Phone: 301-975-2002

Hotel Information:
Marriott Washingtonian
9751 Washingtonian Boulevard
Gaithersburg, MD 20878
Phone: 1-800-393-3450

This meeting will feature technical sessions and presentations on secure and robust time synchronization, data quality, and application requirements for quality data, control room uses of synchrophasor technology, generator and equipment diagnostics for asset management, and advanced networking technologies. Dr. Chris Greer, Director of NIST's Smart Grid and Cyber-Physical Systems Program Office will deliver our keynote speech.

NASPI Work Group registration. The *early bird* registration fee will be $325 for regular attendees and $75 for students. The regular rate will be $425 and $175 respectively for registrations made on or after Monday, March 6, 2017. **Due to required security background checks at NIST there will be NO onsite registration. All attendees must register in advance no later than March 13, 2017.**

ATTENTION FOREIGN NATIONALS: If you are a foreign national you will need to download, fill out and fax this form to Mary Lou Norris at NIST. This form cannot be emailed, mailed, or delivered the day of the event so plan accordingly. Mary Lou needs this form by **March 14, 2017**, her fax number is 301-948-2067. The NIST host is Allen Goldstein (301-975-2101 / allen.goldstein@nist.gov) and the organization code is 684.

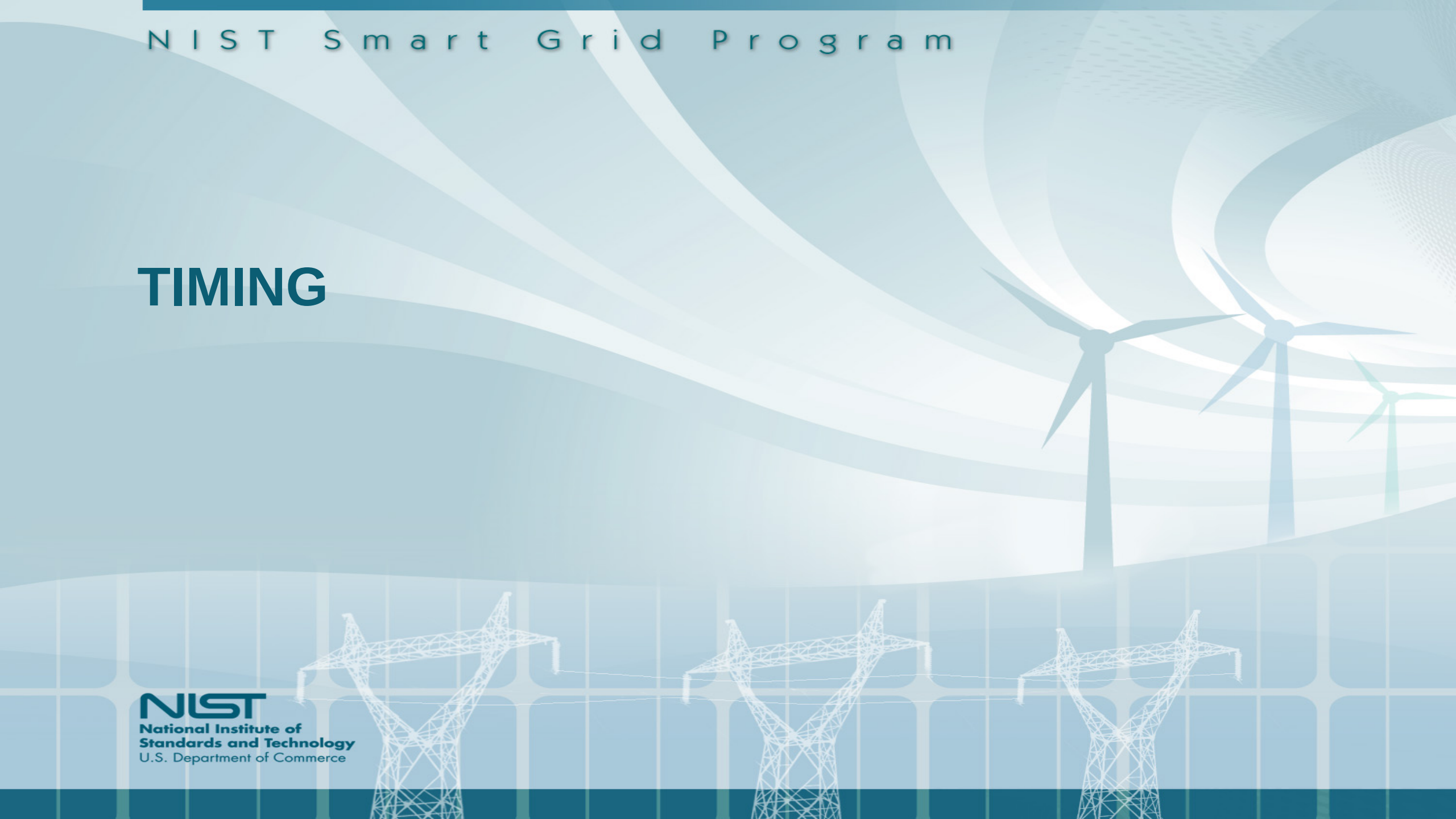
Book your hotel reservations. A group rate of $169/night at the Marriott Washingtonian, Gaithersburg, MD will be available until Tuesday, February 28, 2017. This rate is applicable for the nights of March 21-23, 2017. If you want to make your reservations by calling Marriott at 1-800-393-3450, please ask for the *EPRI NASPI Work Group Meeting Room Block* rate when making your reservations.

Transportation: There will be buses at the Marriott Wednesday morning to take NASPI attendees to/from NIST. These buses will depart the Marriott promptly at 6:45am. Once at NIST attendees will then make their way to badging. Please remember your I.D./passport. At the conclusion of Wednesday meeting, the buses will then depart NIST at 5:45pm Wednesday to the Marriott for the reception. Thursday morning the buses will depart the Marriott for NIST at 7:15am and will depart NIST at 4:45pm to return to the Marriott.

Draft Agenda (3/9/17)

Wednesday, March 22, 2017	
6:45 - 7:00 am	Depart Marriott for NIST - board bus/depart
7:00 - 7:30 am	Badging at NIST (bring valid ID or passport)
7:30 - 8:00 am	Coffee & Networking at NIST **near entrance to the Green Auditorium**
8:00 - 8:15 am	**Green Auditorium** - Welcome, Introductions, and Logistics Review – Jeff Dagle (PNNL)
8:15 – 8:25 am	NASPI PM – Alison Silverstein
8:25 – 9:10 am	Keynote Speaker – Dr. Chris Greer
9:10 - 9:20 am	DOE - Michael Pesin

TIMING



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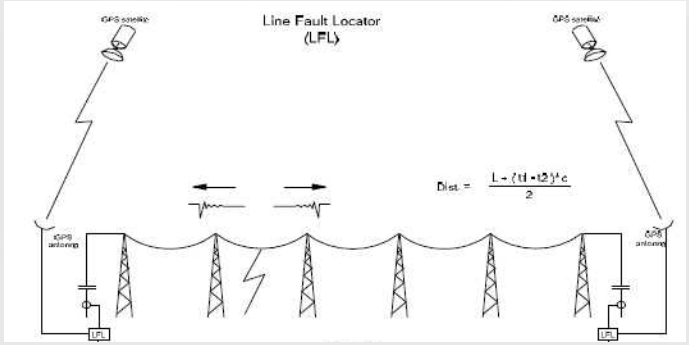
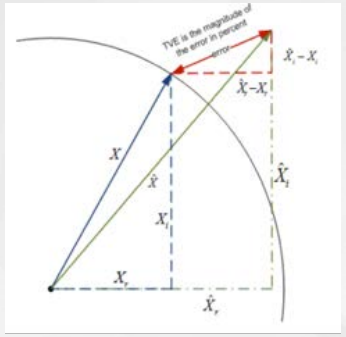
System physics drives timing requirements

Time of arrival accuracy determines location precision and accuracy



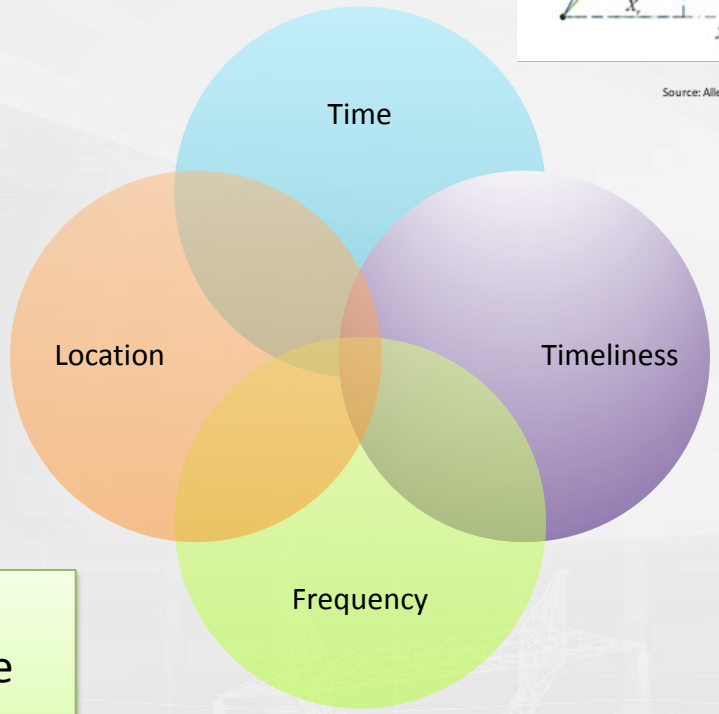
http://www.powerguru.org/keeping-the-electricity-flowing-in-southern-africa/

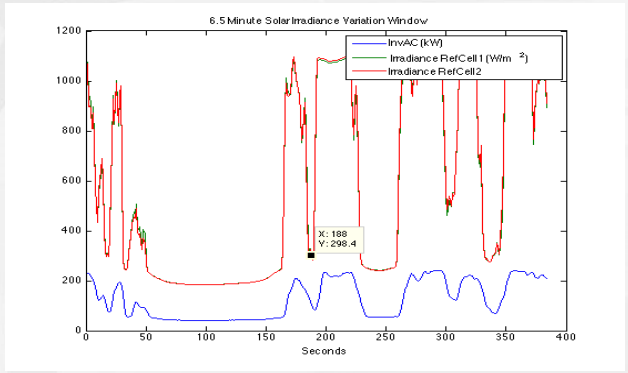
Requirement of < 1 µs synchronization



Source: Allen Goldstein

Time error manifests as measurement error



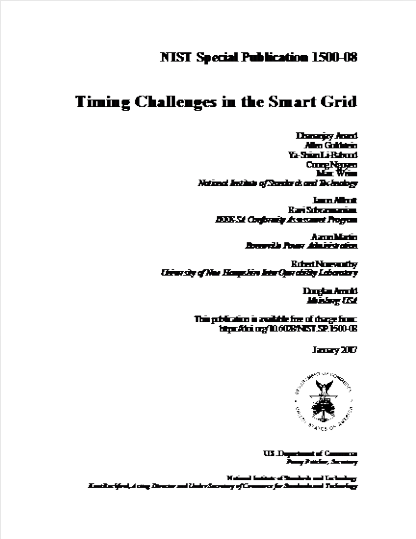


Data source: Matthew Boyd, NIST

High frequency transients require fast sampling

Changing dynamics require lower latencies

Timing Priorities (at NIST)

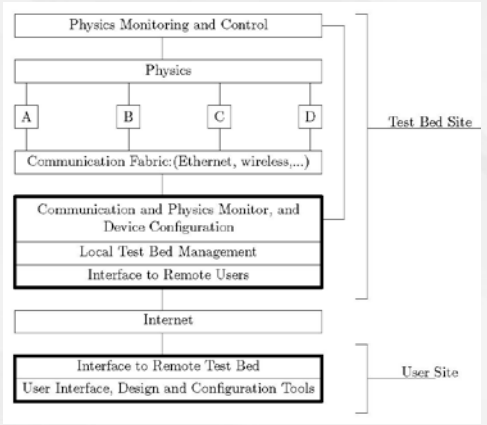


NIST Special Publication 1500-08

Timing Challenges in the Smart Grid

Improving integrity assurance in timing for power systems

Source: Julien Amelot, PTP Dashboard Software.



Andrade, H. A., Derler, P., Eidson, J. C., Shrivastava, A., Li-Baboud, Y. S., Stanton, K., & Weiss, M. (2015, December). Towards a reconfigurable distributed testbed to enable advanced research and development of timing and synchronization in cyber-physical systems.

Testing and certification

- Device conformity
- End-to-end system interoperability
- Quantifiable test methods
- Interoperability events

Monitoring and anomaly detection

- Real-time monitoring against traceable reference source
- Stochastic characterization of normal behavior

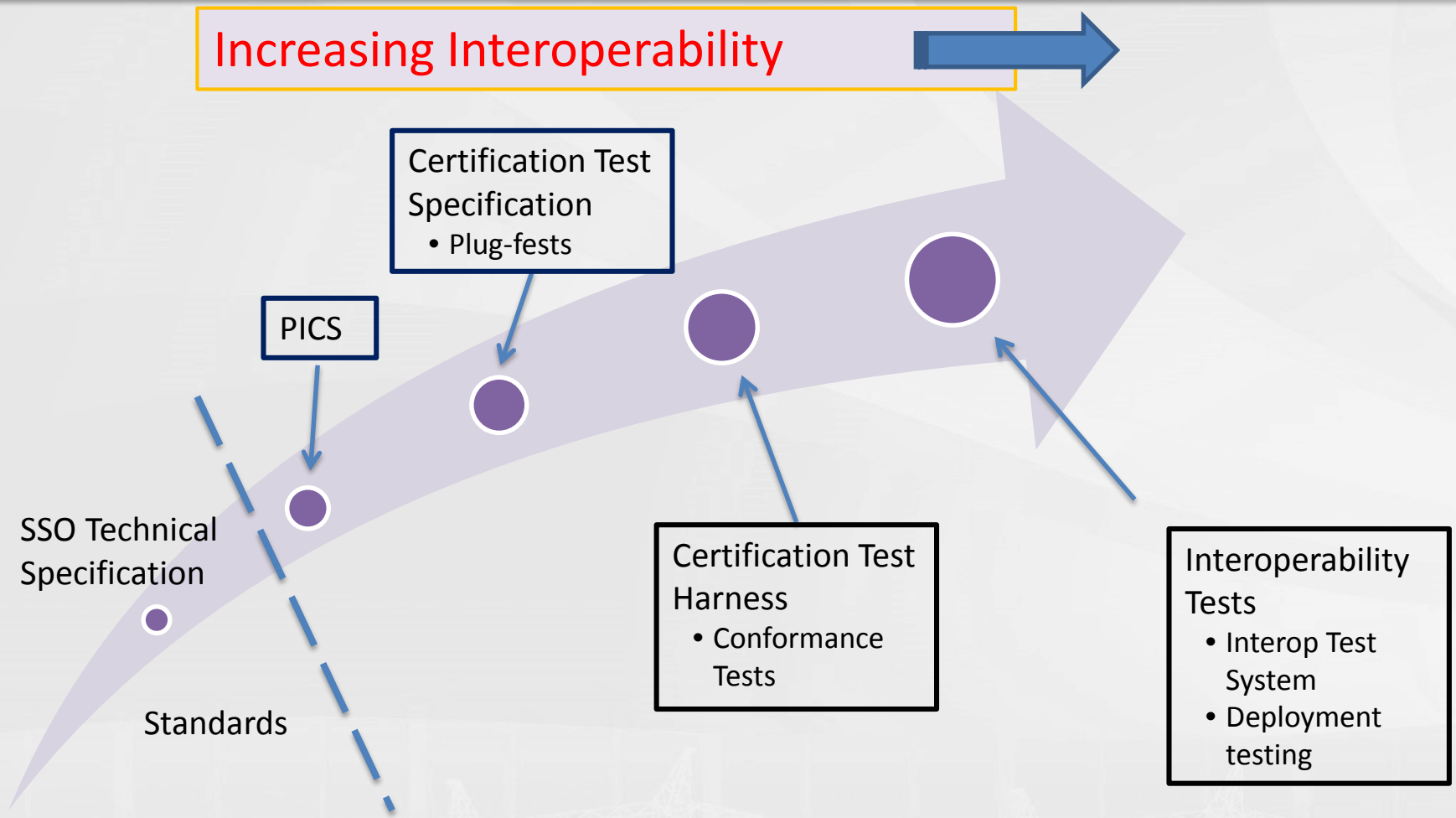
Applications driven requirements

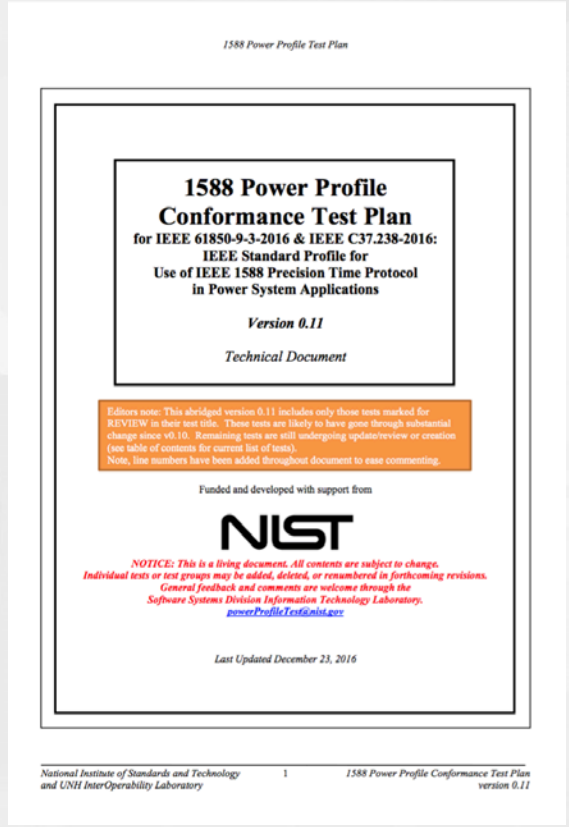
- Research system dynamics
- Parameterize performance metrics and requirements
- Explicit time specification

Alternative sources

- Terrestrial radio (eLORAN, WWVB)
- Network (PTP, NTP)
- Ensembling multiple sources

Conformance and Interoperability Testing




1588 Power Profile Test Plan

1588 Power Profile Conformance Test Plan
for IEEE 61850-9-3-2016 & IEEE C37.238-2016:
IEEE Standard Profile for
Use of IEEE 1588 Precision Time Protocol
in Power System Applications

Version 0.11

Technical Document

Editors note: This abridged version 0.11 includes only those tests marked for REVIEW in their test title. These tests are likely to have gone through substantial change since v0.10. Remaining tests are still undergoing update/review or creation (see table of contents for current list of tests).
Note, line numbers have been added throughout document to ease commenting.

Funded and developed with support from

NIST

NOTICE: This is a living document. All contents are subject to change. Individual tests or test groups may be added, deleted, or renumbered in forthcoming revisions. General feedback and comments are welcome through the Software Systems Division Information Technology Laboratory. powerProfileTest@nist.gov

Last Updated December 23, 2016

National Institute of Standards and Technology and UNH InterOperability Laboratory 1 *1588 Power Profile Conformance Test Plan version 0.11*

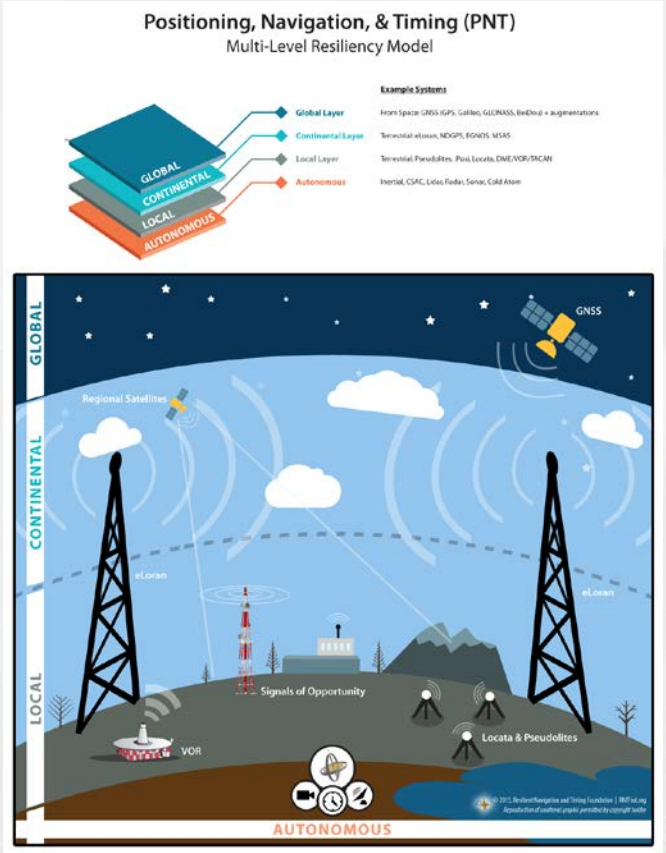
Source: Bob Noseworthy, et. al Draft 1588 Power Profile Conformance Test Suite Specification. University of New Hampshire Interoperability Lab.

- Collaborate with industry to accelerate the development of test programs for smart grid standards
- Support industry test programs through test methods development
- Participate in plug-fest and interoperability test events
- Build awareness and encourage adoption of test programs to enhance interoperability

Alternatives to GPS for wide area time distribution

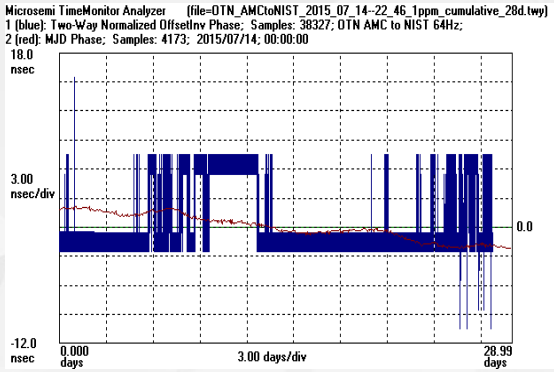
- GPS is known to be vulnerable to unintentional or intentional interference.
- If time sync becomes mission critical it must have redundant and differently routed sources.

Alternative sources

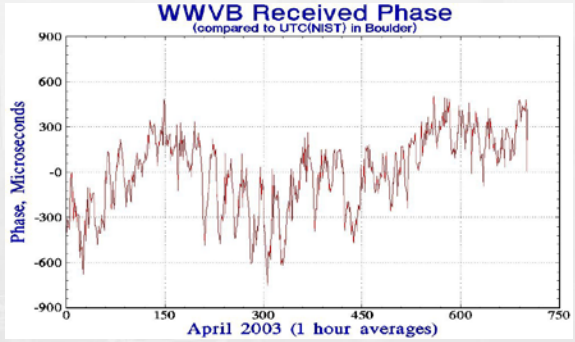


Credit: Resilient Navigation and Timing Foundation

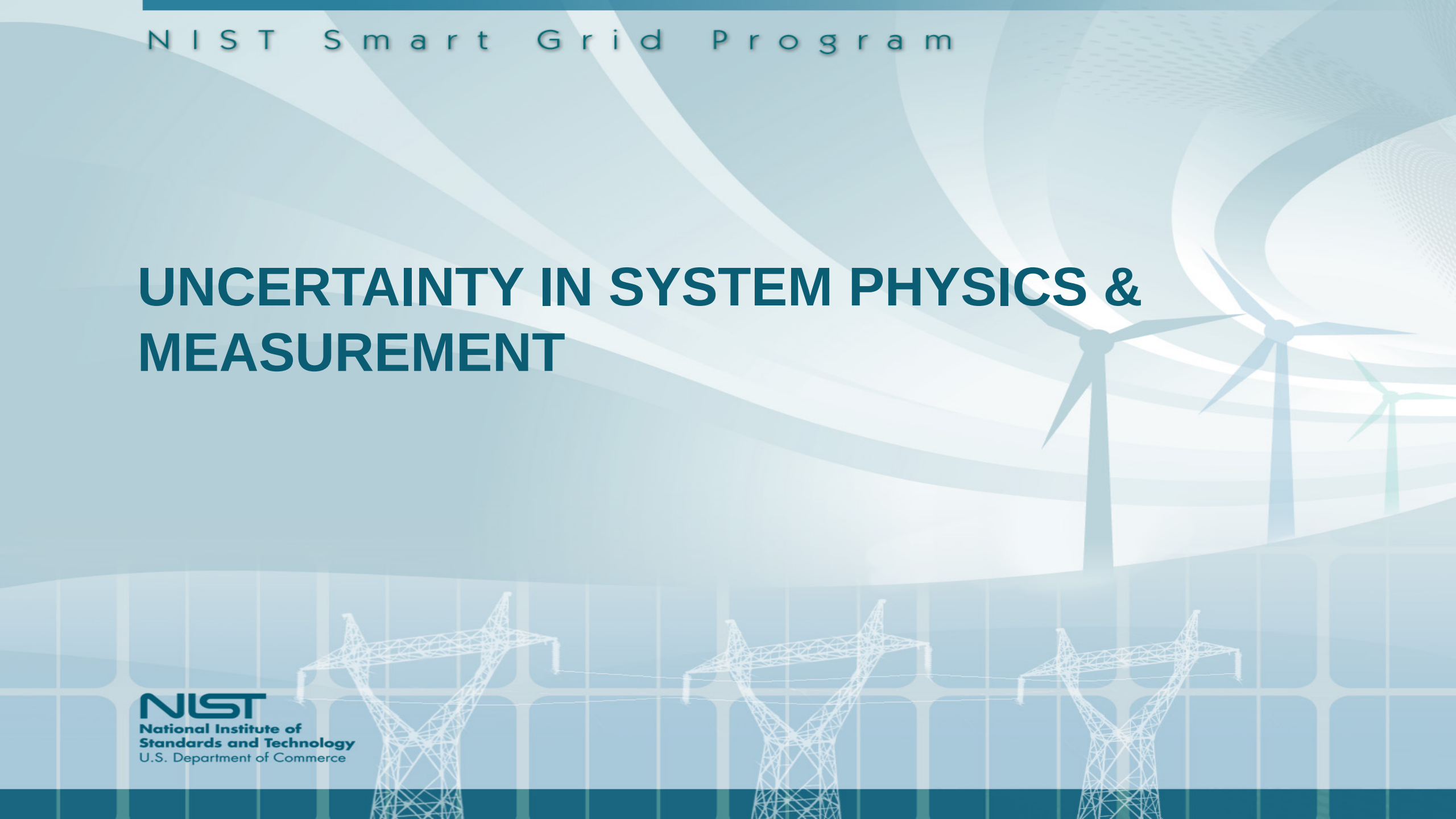
NIST-CenturyLink PTP over Fiber



WWVB



UNCERTAINTY IN SYSTEM PHYSICS & MEASUREMENT



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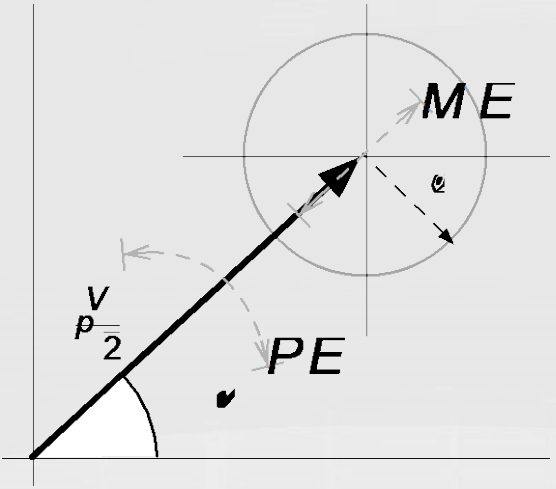
Uncertainty representation in sensor standards

PMU standards currently specify the error budget for the sensor but there is no explicit measure of uncertainty.

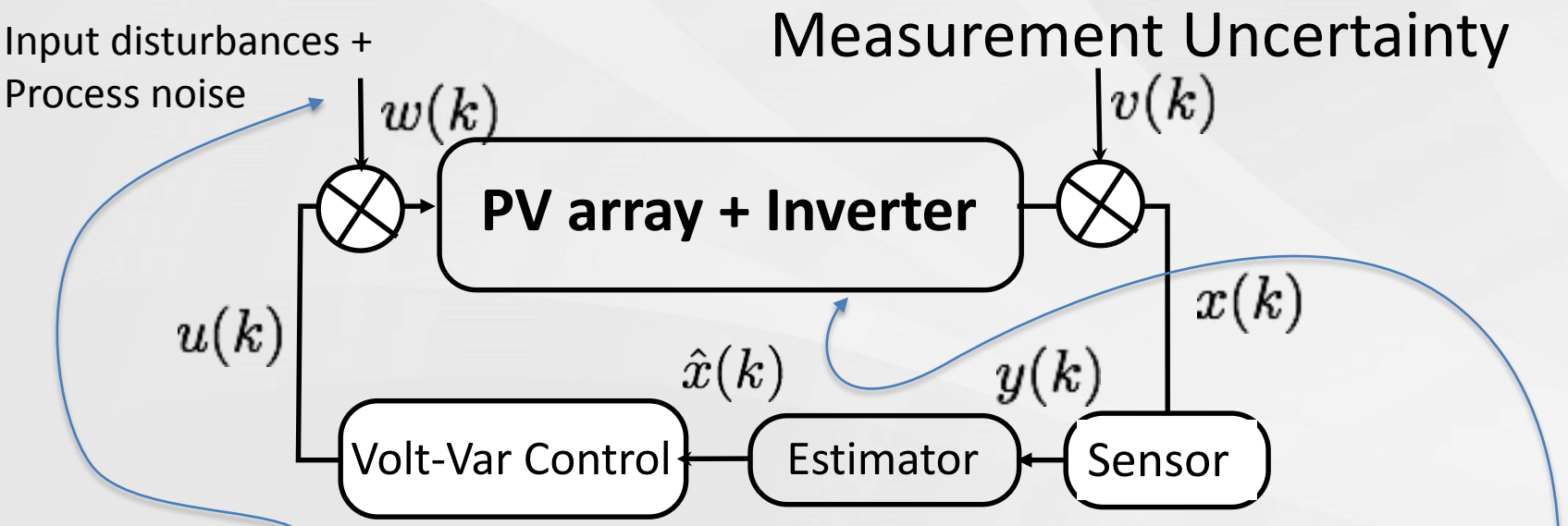


There are several applications being considered for PMUs in the distribution circuit.
Each of these applications use a different representation of uncertainty.

Dynamic State Estimation	Additive White Gaussian models
Monitoring and Protection	Confidence intervals
Fault Localization	Bayesian inference
Harmonic Estimation	Mixed Gaussian models
Load modeling	Markov models
Parameter estimation	Set theoretic models
Closed loop control of feeders	Stochastic optimization

Differentiating error vs. uncertainty and formally specifying uncertainty of sensor measurements and corresponding models will greatly aid in the ability of designers and operators to propagate uncertainty through multiple interacting components iand to develop confidence in system level performance.

Uncertainty in distribution circuits



In order to ensure traceability of the system level metrics, we need to combine measurement uncertainty with all the other widely disparate sources of uncertainty.

Load models

Solar irradiance model

PV Array and Impedance model

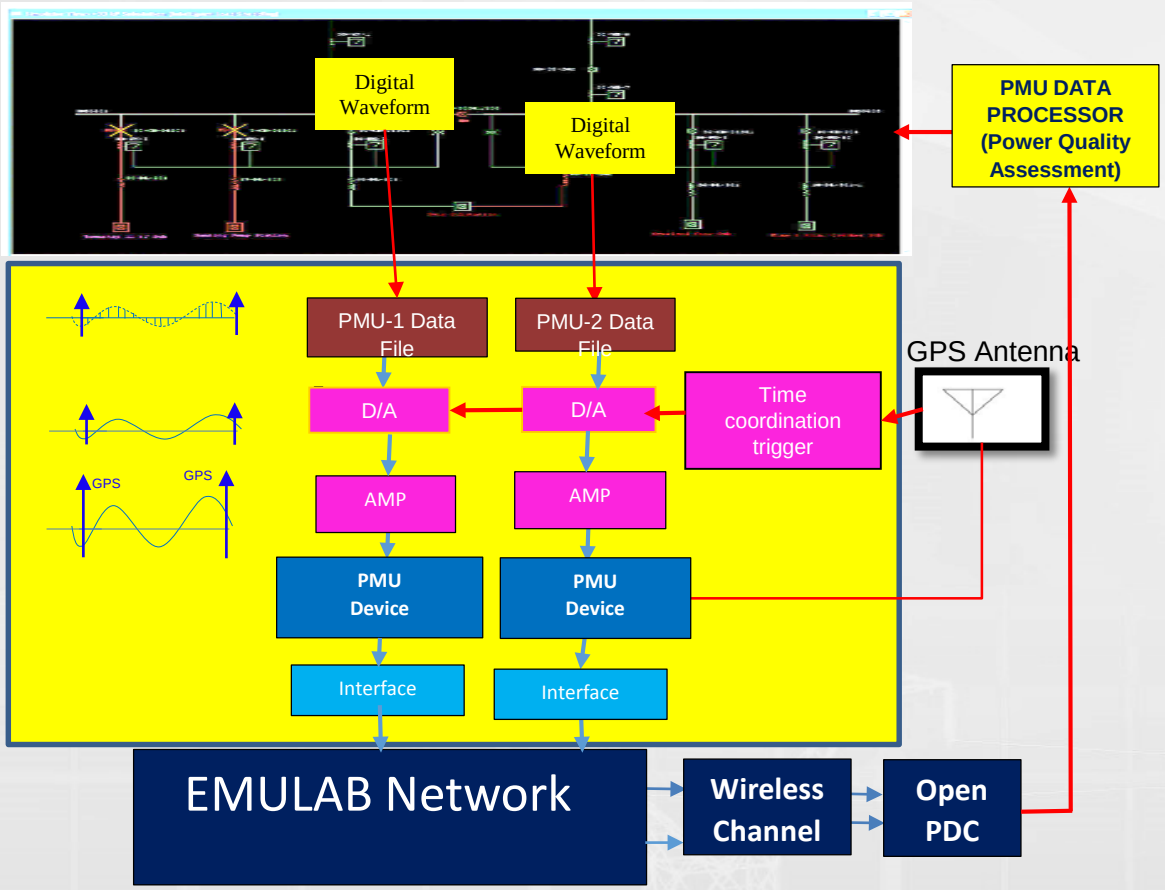
MPP Tracking and DC boost algorithm

3Phase inverter bridge model

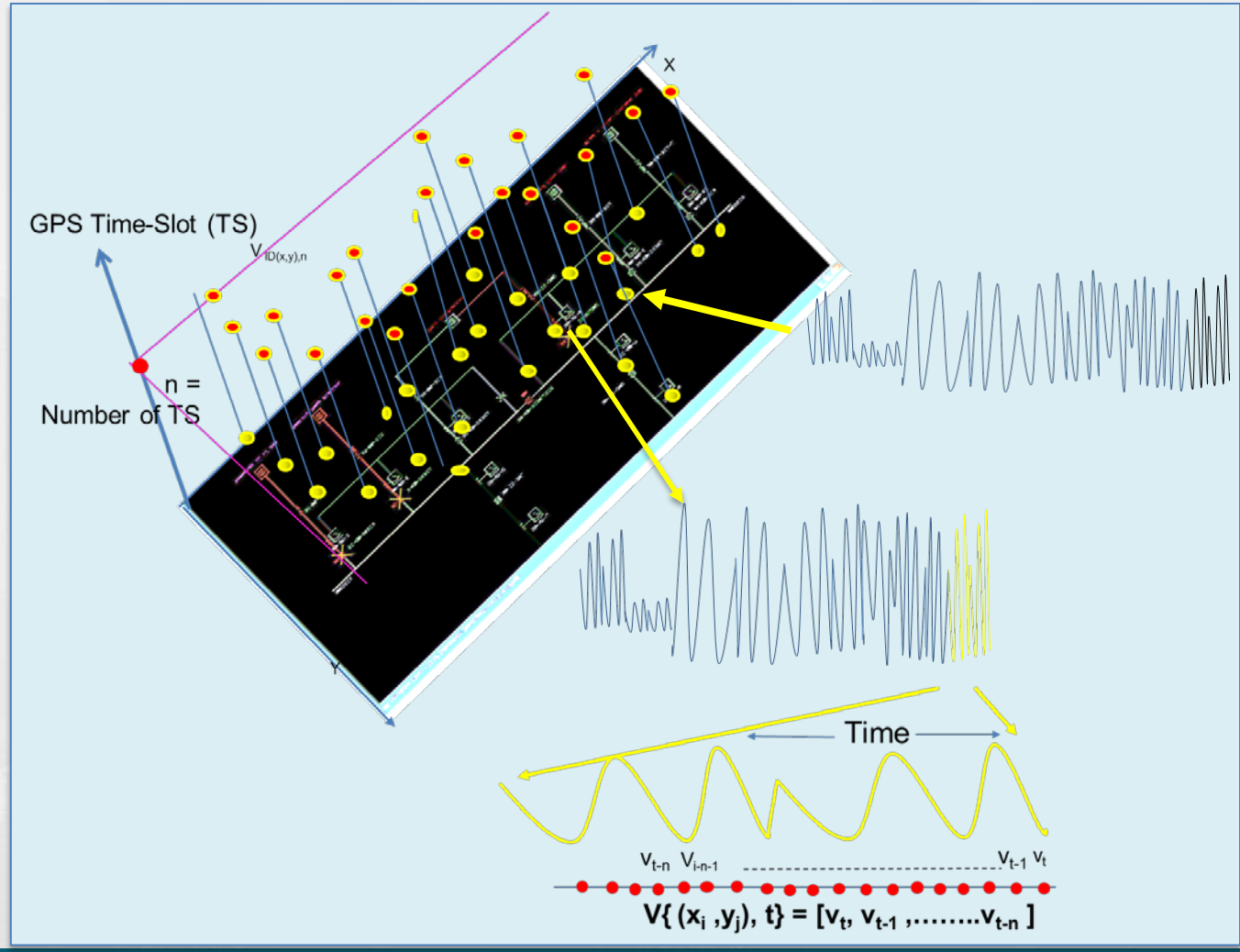
Nodal admittance and circuit model

Experimental approaches to uncertainty analyses

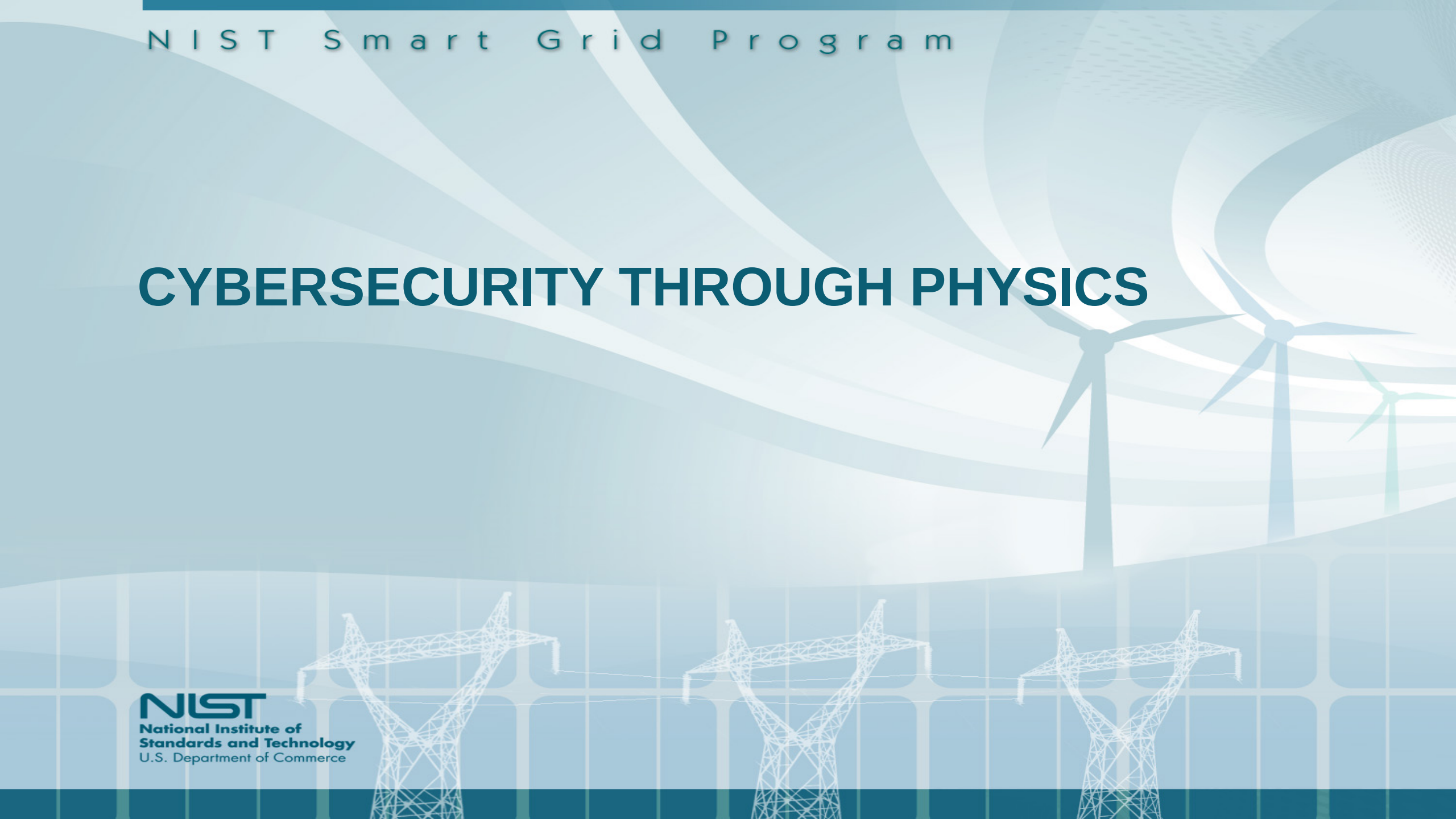
Hardware-in-the-loop experiments



New algorithms to enhance observability



CYBERSECURITY THROUGH PHYSICS



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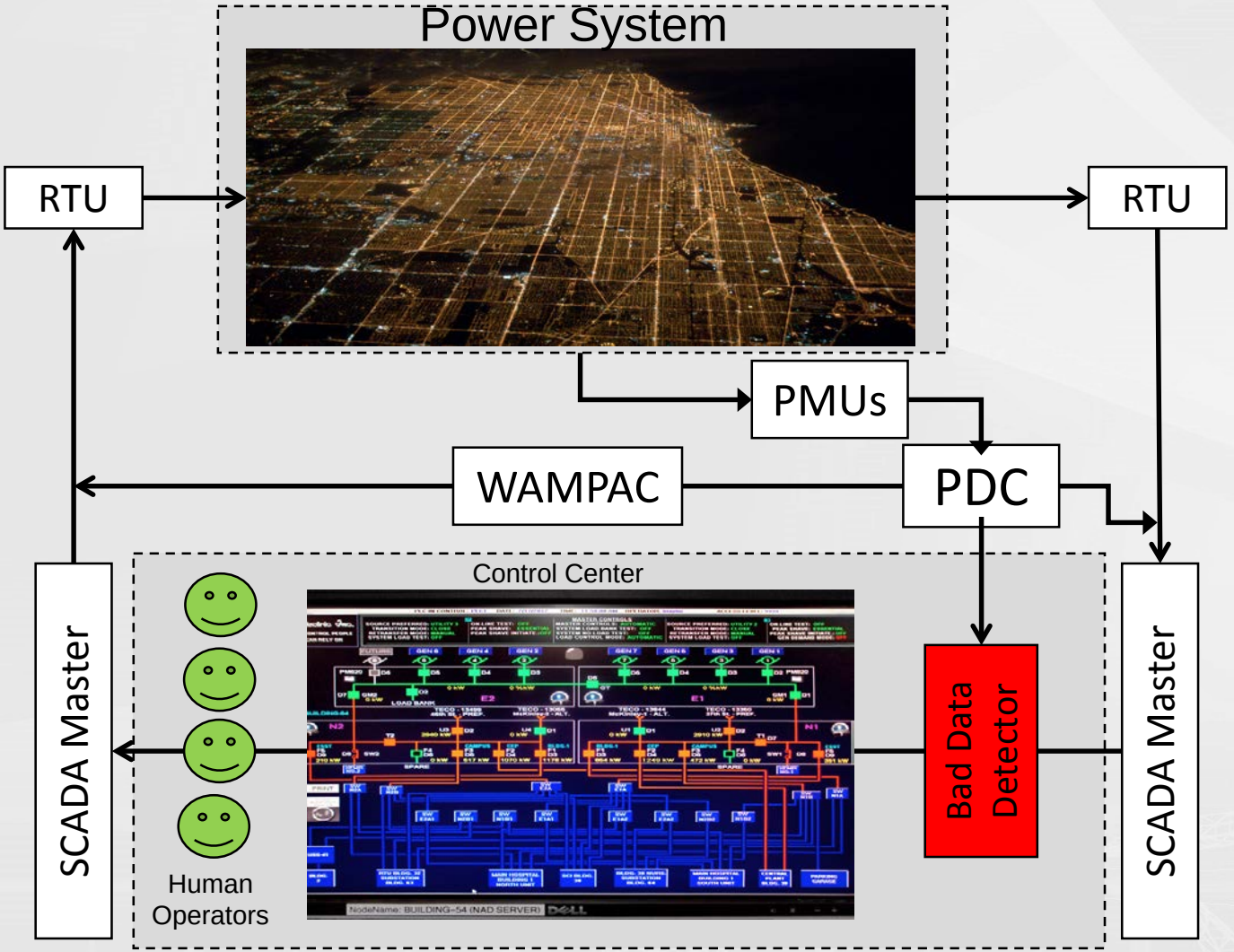
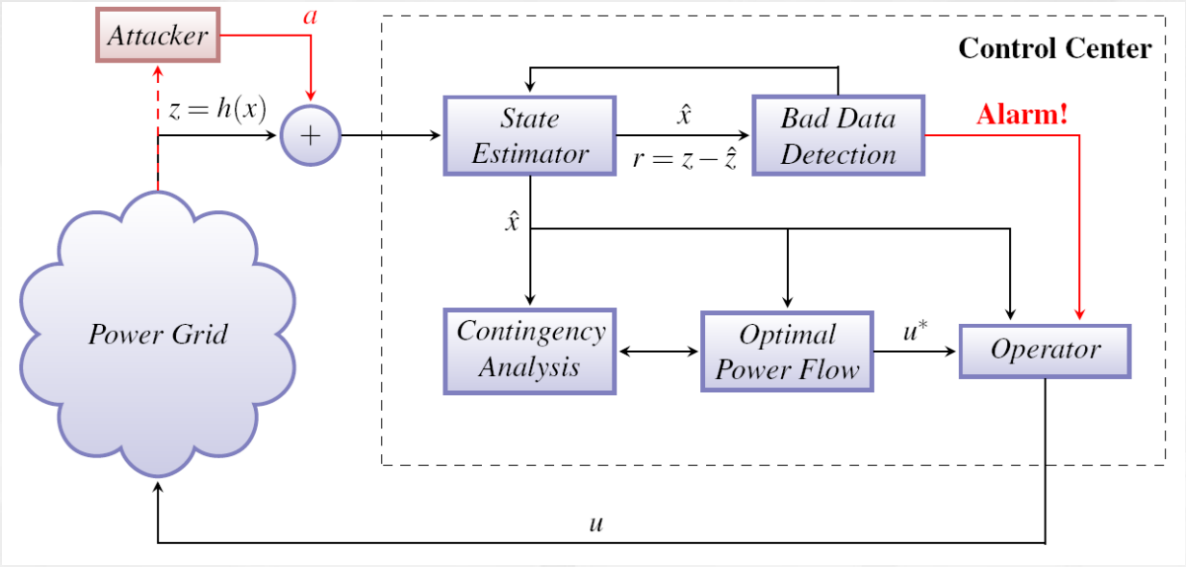
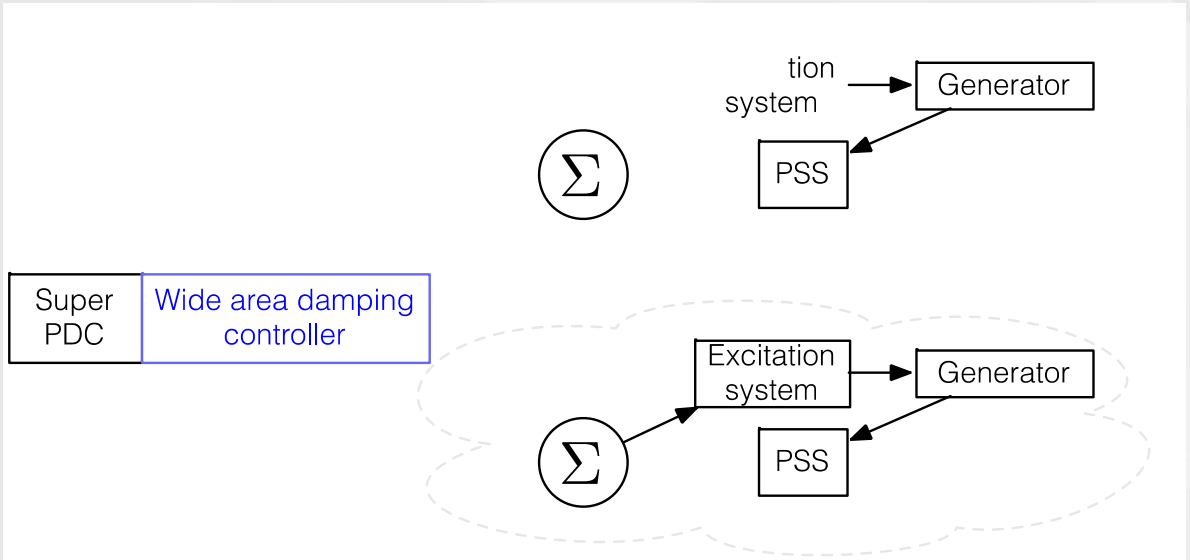
Characterizing cyber vulnerabilities by their physical impact

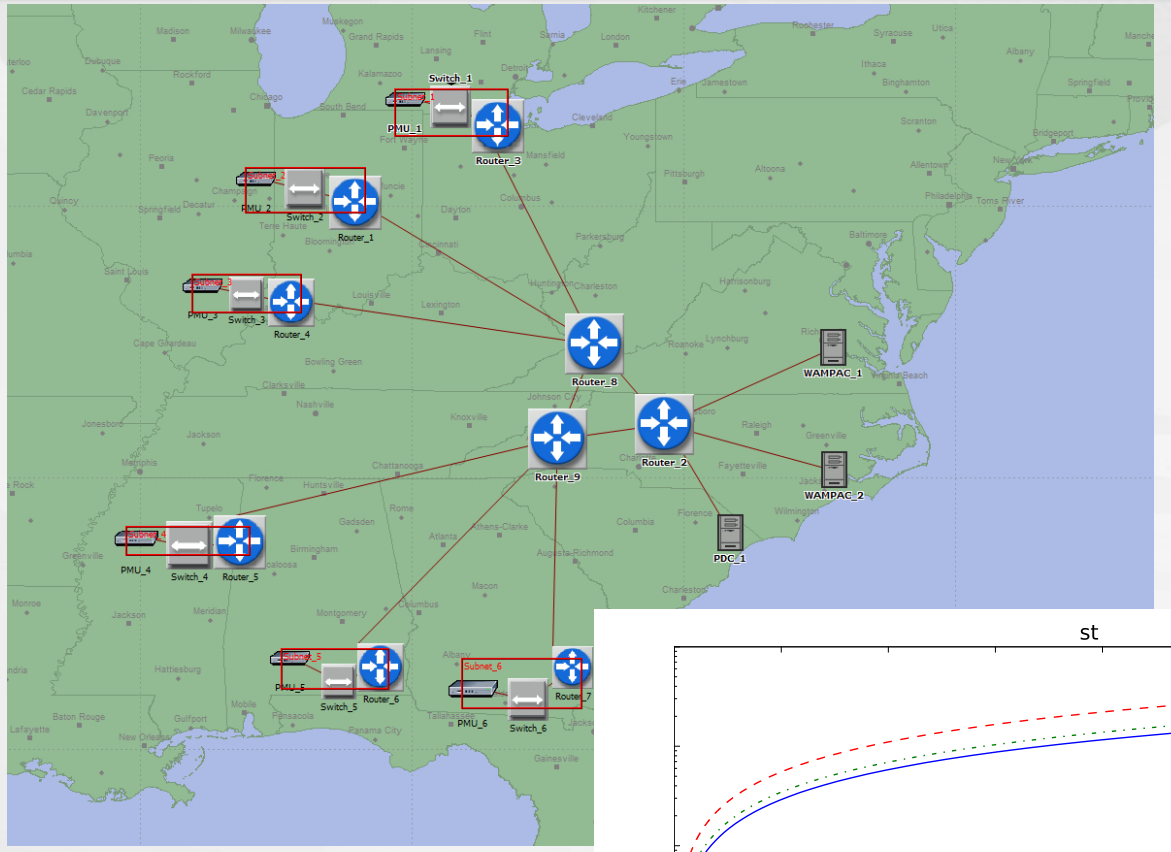


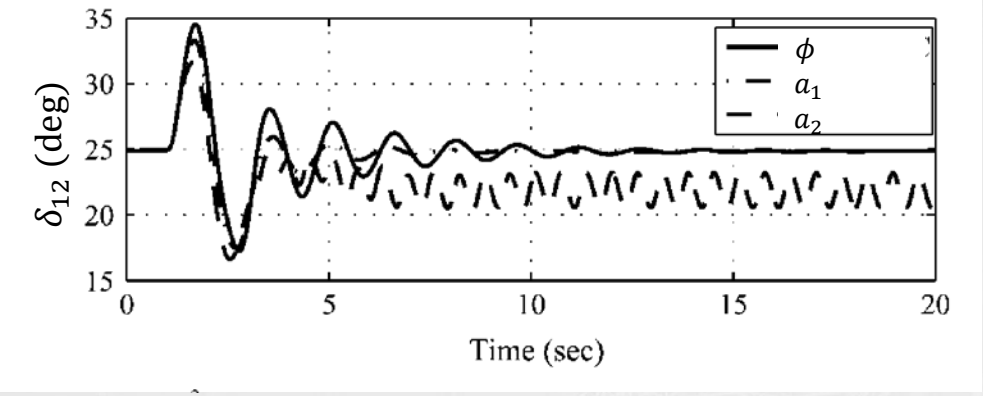


When sensors or sensor aggregators are attacked, the primary impact of the attack is on the state estimator. Inaccurate state estimates in turn may result in bad control decisions.

Using physical dynamics as a metric for security tools

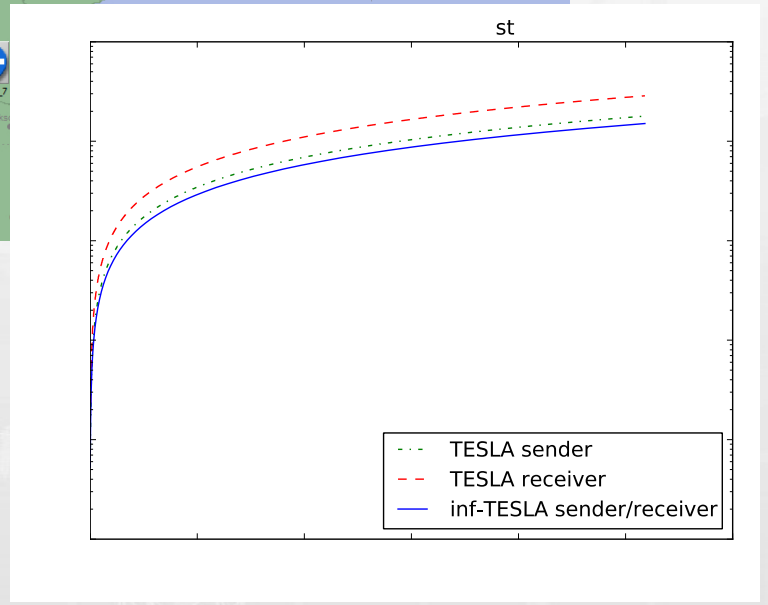






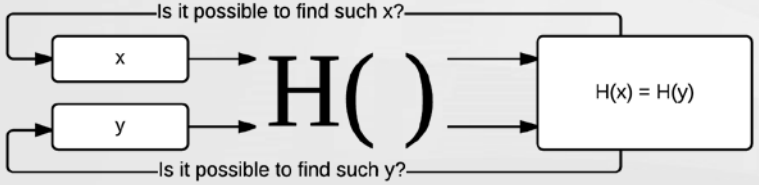
The delayed system is asymptotically stable if there exists real symmetric positive-definite matrices $P = P^T > 0$, $Q = Q^T > 0$ satisfying the LMI:

$$\begin{bmatrix} PA_s + A_s^T P + Q & PA_v \\ A_v^T P & -Q \end{bmatrix} < 0$$

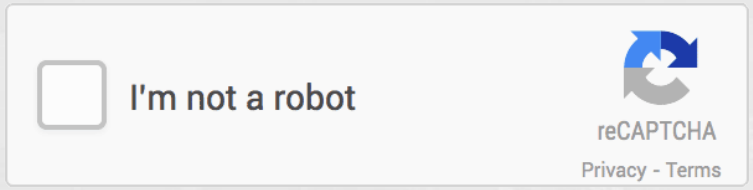


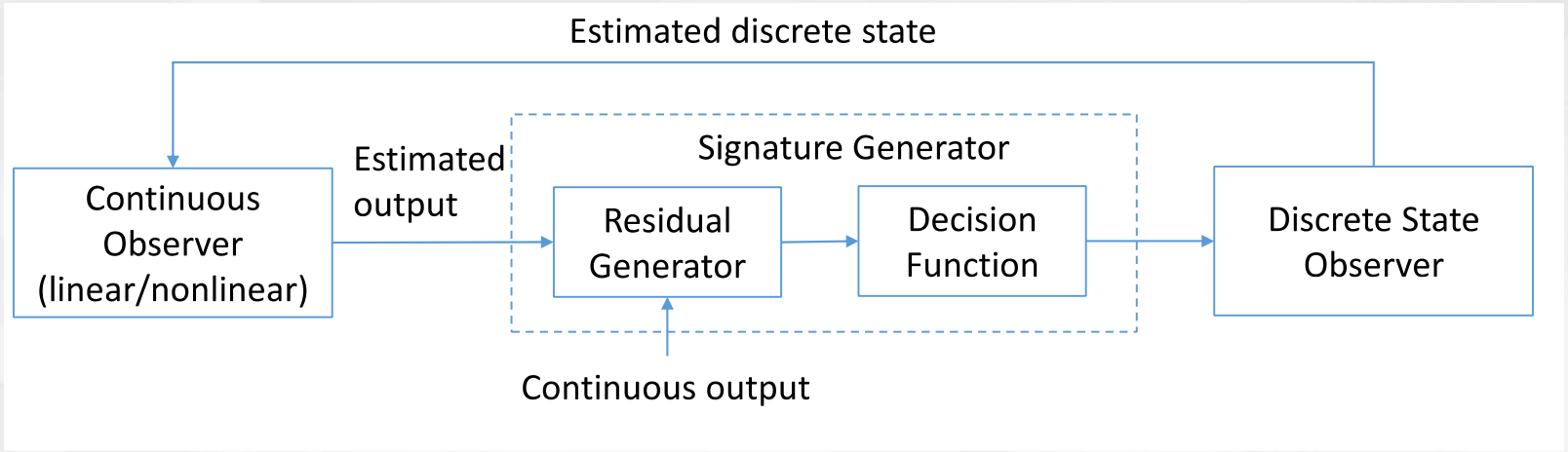
Using physical dynamics to detect intrusions

The null space of H is analogous to collision resistance criteria for hash functions used to secure passwords.



Consider the recent trend towards using noCaptcha reCaptchas to identify bot/ brute force attacks on the hashing algorithm.

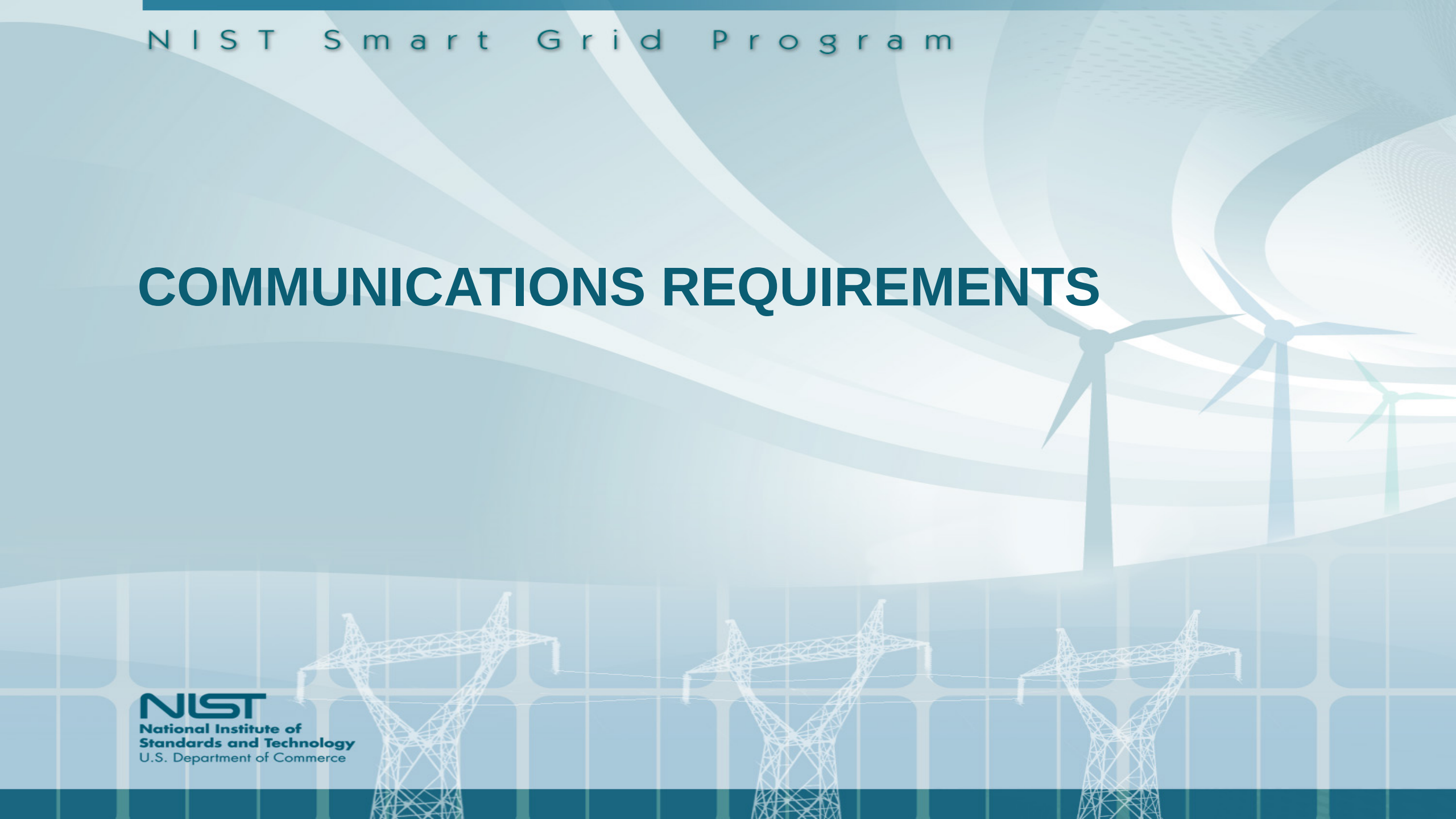




- Knowledge about dynamic state variables
- Higher fidelity models of transients
- Probabilistic dependencies between state variables
- Electrical correlation + Environmental correlation

We are at a unique position in being able to do this with advent of sensing and measurement investments made to the power system to capture dynamic or transient states.

COMMUNICATIONS REQUIREMENTS



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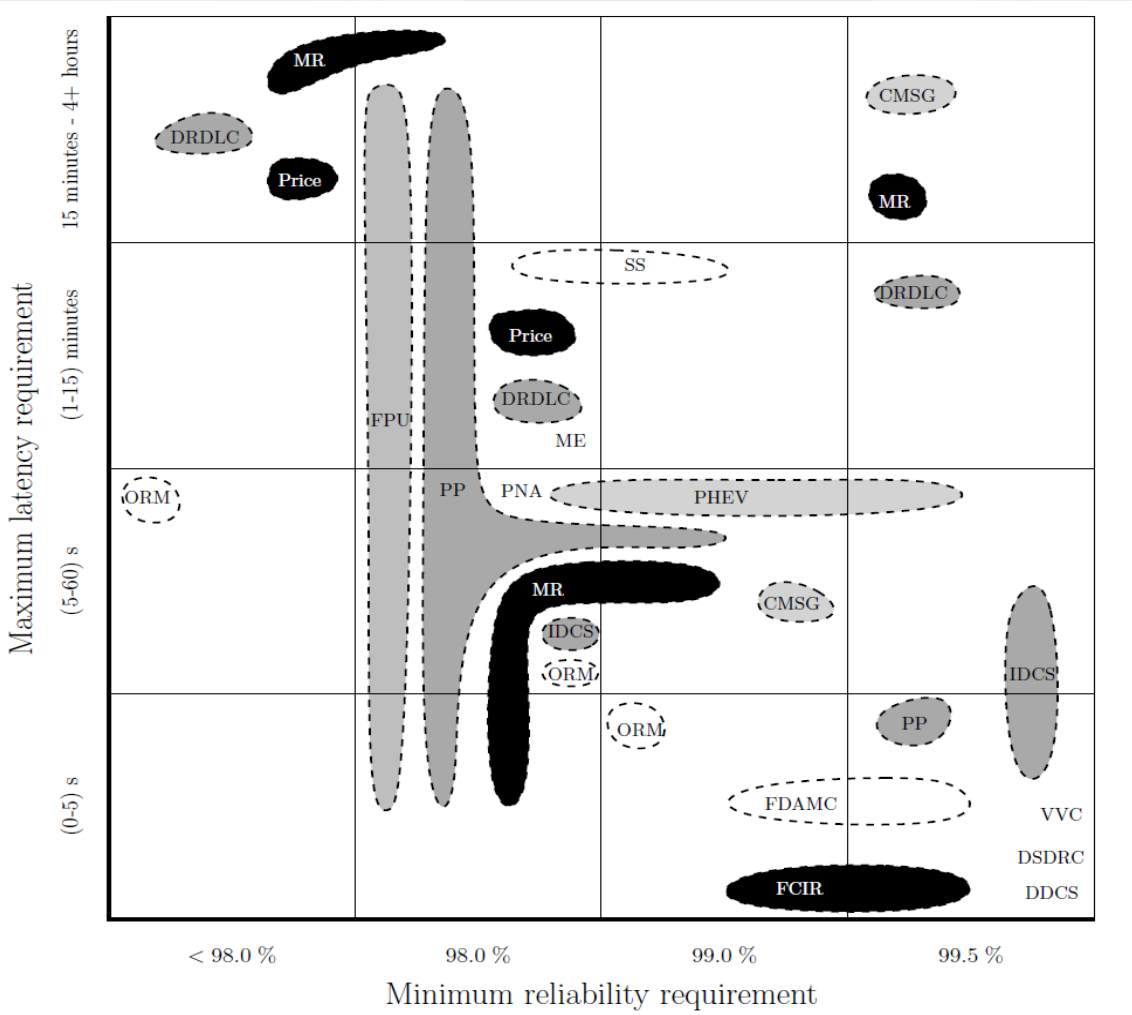
Varying QoS Requirements for Smart Grid Applications

- Right figure shows QoS requirements for a set of applications identified in the OpenSG Smart Grid Requirements matrix, as an outcome of Smart Grid Interoperability Panel (SGIP) Priority Action Plan 2 (PAP02)
- This calls for the study of future network technologies and architectures (5G, etc.) to support smart grid and other CPS

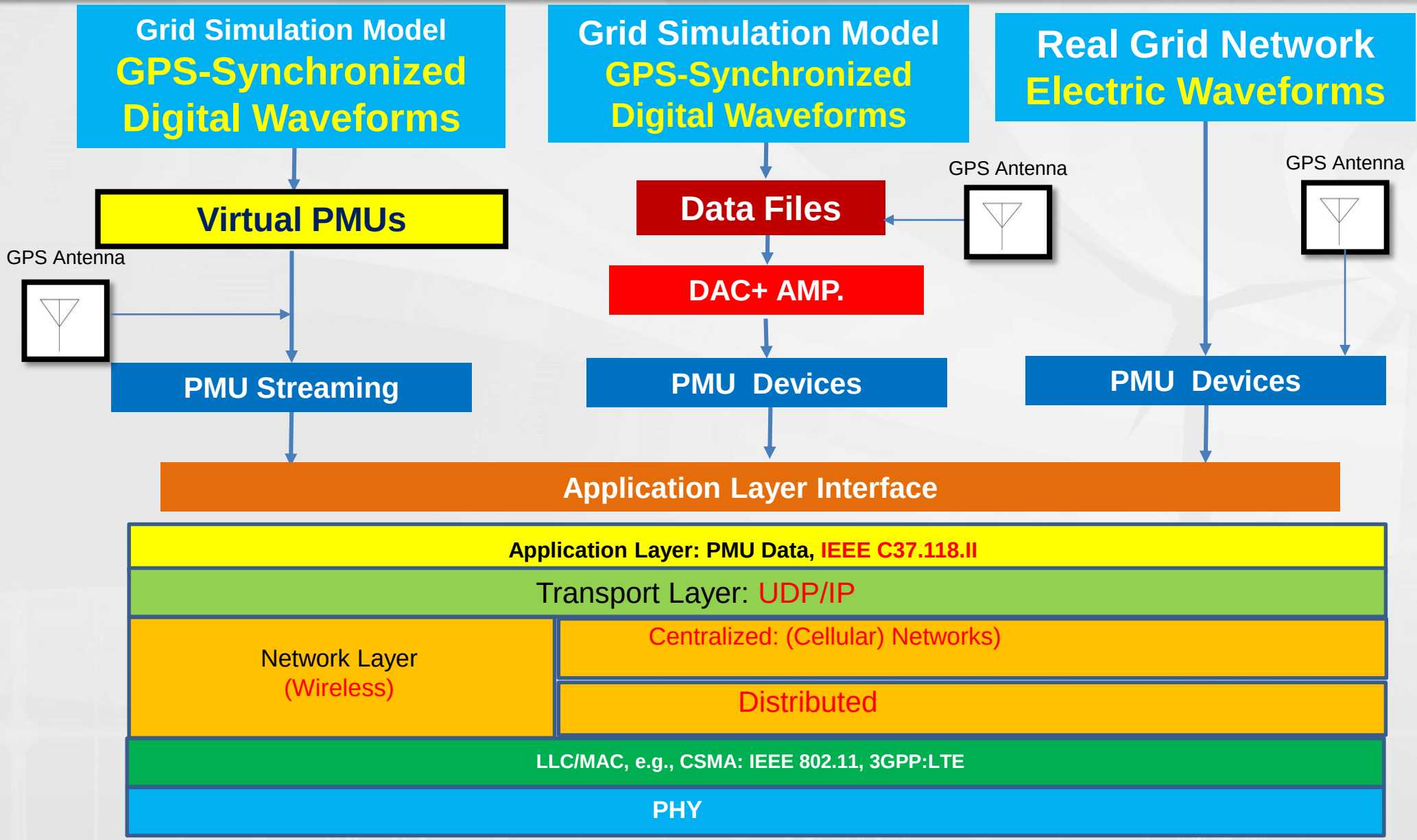


Use Cases

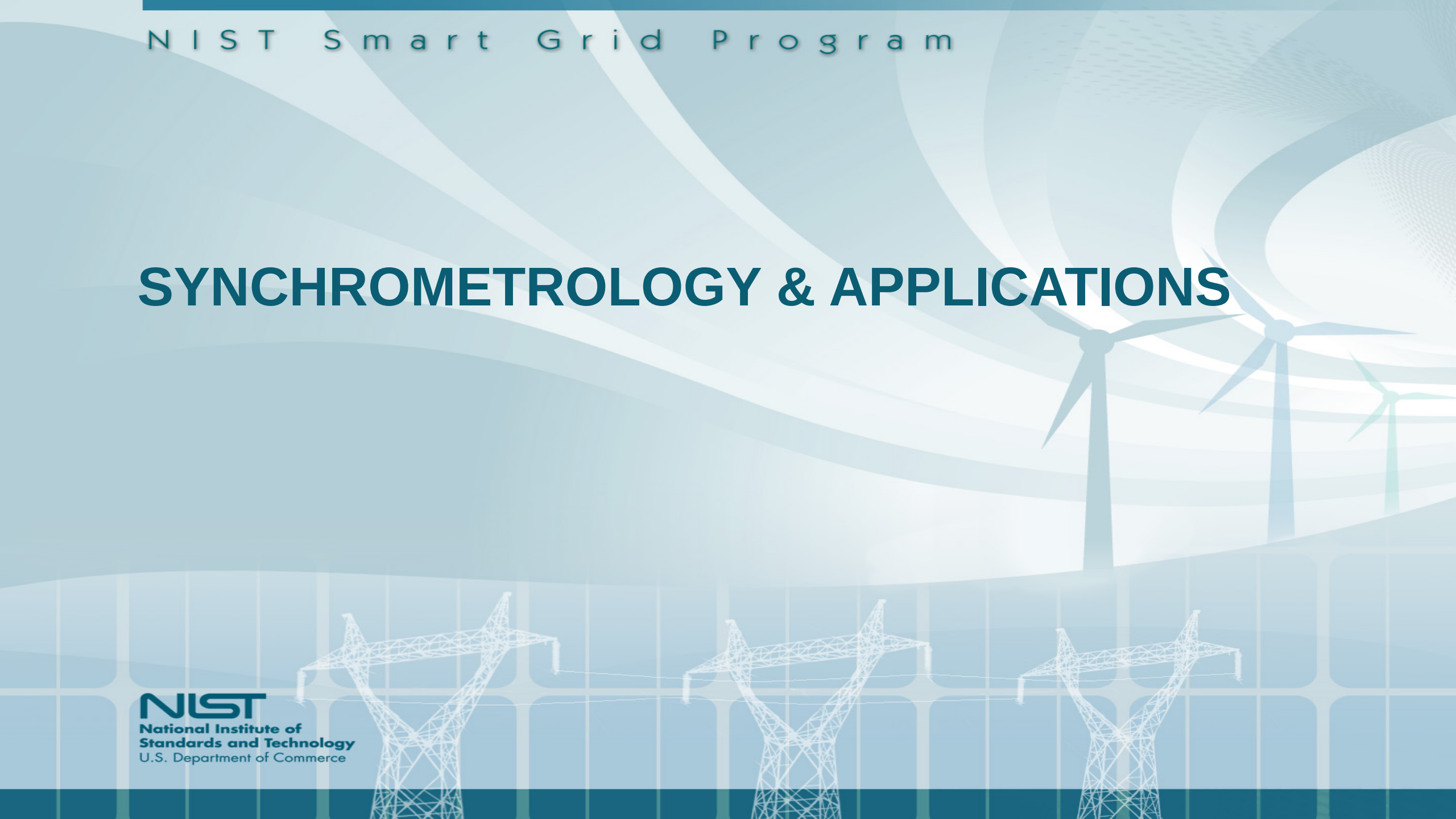
CMSG: Customer Information / Messaging
DDCS: Dispatch Distributed Customer Storage
DRDLC: Demand Response-Direct Load Control
DSDRC: Demand Response-Centralized Control
FCIR: Fault Clear, Isolation, and Reconfigure
FDAMC: Field Distribution Automation Maintenance-Centralized Control
FPU: Firmware/Program Update
IDCS: Islanded Distributed Customer Storage
ME: Meter Events
MR: Meter Reading
ORM: Outage Restoration Management
PHEV: Plug-in Hybrid Electric Vehicle
PNA: Premise Network Administration
PP: Prepay Price
SS: Service Switch
VVC: Volt/VAR-Centralized Control

Figure: Major Smart Grid Use Cases, Categorized by Latency and Reliability Requirements
David Griffith, Michael Souryal, and Nada Golmie (NIST), "Wireless Networks for Smart Grid Applications," a Chapter in Book, Titled "Smart Grid Communications and Networking," Cambridge University Press, UK, 2012, ISBN: 9781107014138

Combined Grid/Communication With Multiple Test Configurations



SYNCHROMETROLOGY & APPLICATIONS



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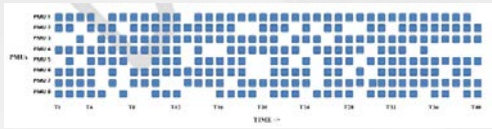
Synchrometrology for the electric power system

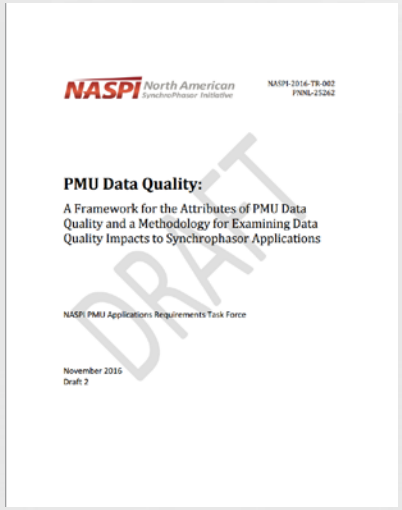
- Synchrometrology (a term coined by NIST's Jerry Stenbakken) is the scientific study of time-synchronized measurement.
- The NIST Synchrometrology Lab supports U.S. competitiveness and economic security through research and standards development in the field of time synchronized measurements in electric power generation, transmission, and distribution.
  - Co-funded by Departments of Commerce and Energy.
- Ongoing Projects:
  - Reducing measurement uncertainty in preparation for future requirements.
  - Collaborate in the assessment of the impact of errors in synchronized measurement on power system applications.
  - Collaborate in development of voluntary consensus standards and guides:
    - IEEE Standards Association
    - International Electrotechnical Commission.
  - Collaborate in the development of conformity assessment methods.

PMU Application Requirements

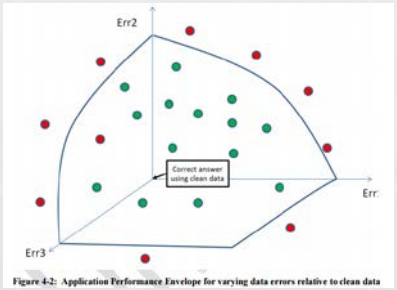
- Two years ago, NASPI formed the PMU Applications Requirements Task Force
  - NASPI-wide, about 40 members



Data drop outs

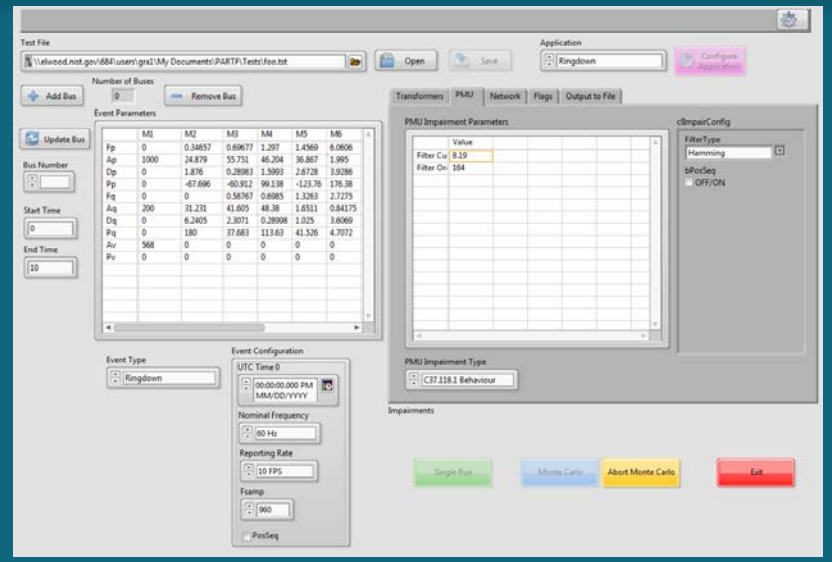


- NASPI, NIST, and PNNL collaborated on a white paper which is published by NASPI today. Provides guidelines and terminology for assessing application needs

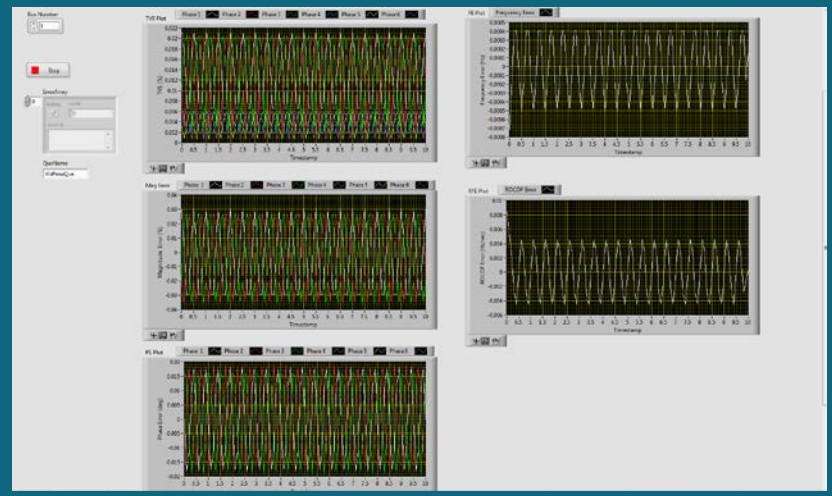


Application Performance Envelope

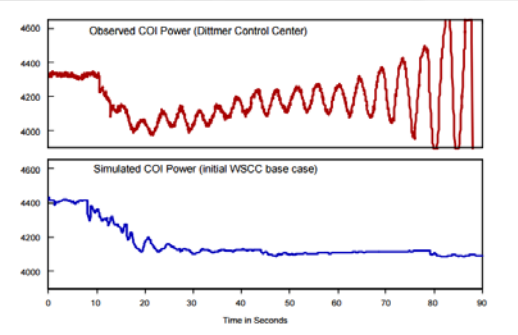
- Work is in progress at NIST, collaborating with PNNL, WSU, GE, BPA and other vendors, academics, and utilities to create an open source composable application testing framework.



Framework front panel and Visualization App

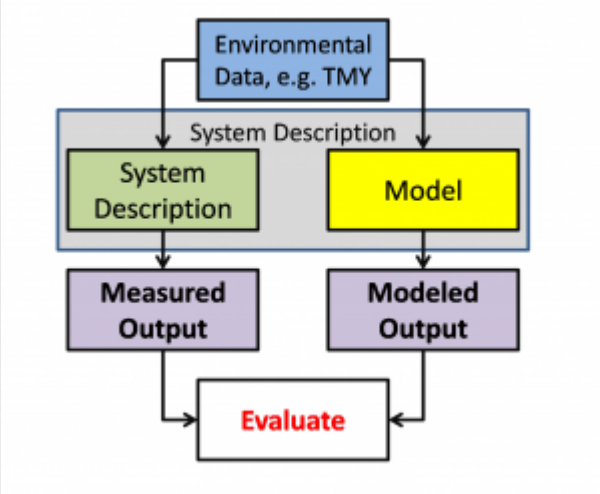


Model Validation



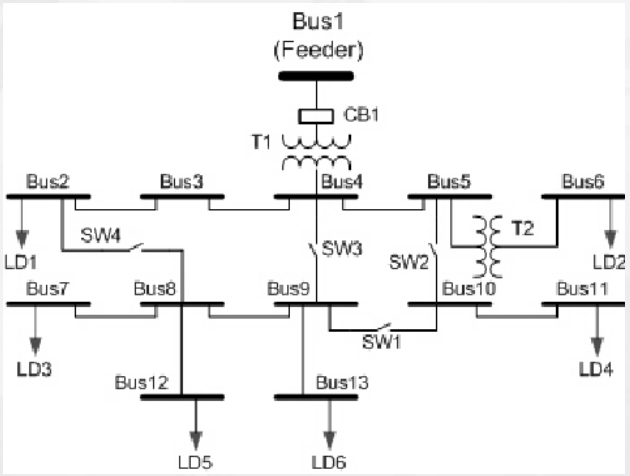
Credit: NERC Model Validation Task Force

- Models are relied upon throughout the power system.
- We compare measurements of “actual values” against model predictions to help validate the model
  - But how *actual* are the “actual values?”
    - *And how bad can they be before there is a problem?*



Credit: Sandia National Laboratory

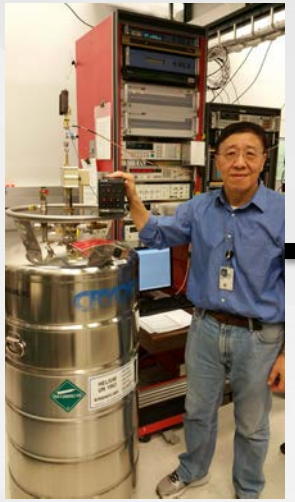
- NERC requires models to be validated
  - Many policies, reports and papers have been published on the topic.
- What is the impact of synchronized measurement error on model validation?



IEEE 13 Bus model

Conformity Assessment

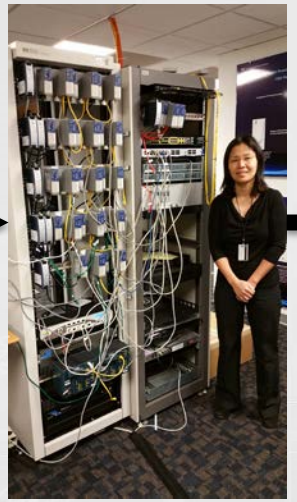
- NIST supports PMU conformity assessment by establishing traceability for the ICAP Synchrophasor Measurement Conformity Assessment Program (IEEE ICAP)



Yi-hua Tang, Josephson Array and Zener Diode

Richard Steiner, Multimeter Calibration System

Steve Jefferts and Tom Heavener, NIST-F2 Cesium fountain atomic clock



Ya-Shian Li-Baboud, Timing Source Calibration

Jerry Stenbakken calibrating The PMU Calibrator Calibration System

Allen Goldstein, taking a break from calibrating calibration systems to don a suit and tie…

Conclusion

Advancing measurement science is critical to meeting the challenge of increasing uncertainty

- Timing
- Measurement uncertainty
- System modeling
- Cybersecurity through physics
- Communications
- Synchrometrology
- Applications

Thank you