Precision Timing in the Electric Grid

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U.S. DEPARTMENT of ENERGY

Agenda

- Overview of Timing Requirements in the Electricity Sector
  - Basic requirements
  - Testing Electric Power System Applications
- Bonneville Power Administration's (BPA) Precision Time Distribution Project *
  - Significance
  - Methodology and Test Setup
  - Results and Next Steps
- Standards supporting Time Resilience and Distribution
  - IEEE P1952
  - IEEE P2030.101

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*Special thanks to Ivan Barzallo, Tony Faris, Elvis Nguyen, and Toby Payne
Bonneville Power Administration

Timing Requirements in the Electricity Sector

- Timing is everything – pn**T**
- Synchronized and coordinated within a "time island"
- Power Grid currently heavily reliant on GNSS (GPS)
  - Requires time-of-day (ToD) for many functions
  - Most stringent requirements of Energy Sector
  - IRIG-B000 (with control bits specified in IEEE C37.237) derived from GPS
- Disruptions:
  - Natural/man-made (intentional or not)
  - Solar flares
  - Jamming
  - Spoofing
  - Signal delay or replay (meaconing)
  - Multi-path
  - Limited sky view (e.g., in dense urban areas)

Grid Function	Timing Requirement
Regulatory Disturbance Reporting	±2 ms (UTC) (ToD)
Sequence of Events (SoE)	±1 ms (ToD)
Line Current Differential Protection	±10 μs
IEC 61850 Sampled Values (~4kHz sampling synchronized at top of every second)	±1 μs
Synchrophasor Measurements	±1 μs (ToD)
Traveling Wave Line Fault Location	± 500 ns
Point on Wave switching	±100 ns (may not need time tagging)

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Timing Challenges in the Smart Grid, NIST SP 1500-08, January 2017 (augmented): https://nvlpubs.nist.gov/nistpubs/specialpublications/nist.sp.1500-08.pdf

PNNL's PNT Project Activities

Sponsor: U.S. Department of Energy (DOE)

PNNL's Role:

- Provide expertise to build and operate a **precision timing testbed**
- **Identify, test, and validate** alternative precision timing sources to GPS for use in substations
- Develop GPS vulnerability **risk mitigations** using simulated utility environments.
- Demonstrate **secure, scalable timing distribution** (e.g., PTP-based solutions) in real utility environments.
- **Maintain DOE's PNT profile** as directed by EO13905 for energy utilities to aid in adoption
- Produce actionable reports for **broader utility adoption** and support standards efforts (e.g., IEEE P1952 for resilient timing).
- **Lead IEEE P1952** Resilient PNT User Equipment Working Group, Electricity Use Cases
- Provide **technical assistance** and in some cases, **equipment** to project partners
- Foster **collaboration** among energy organizations (PMAs, utilities)

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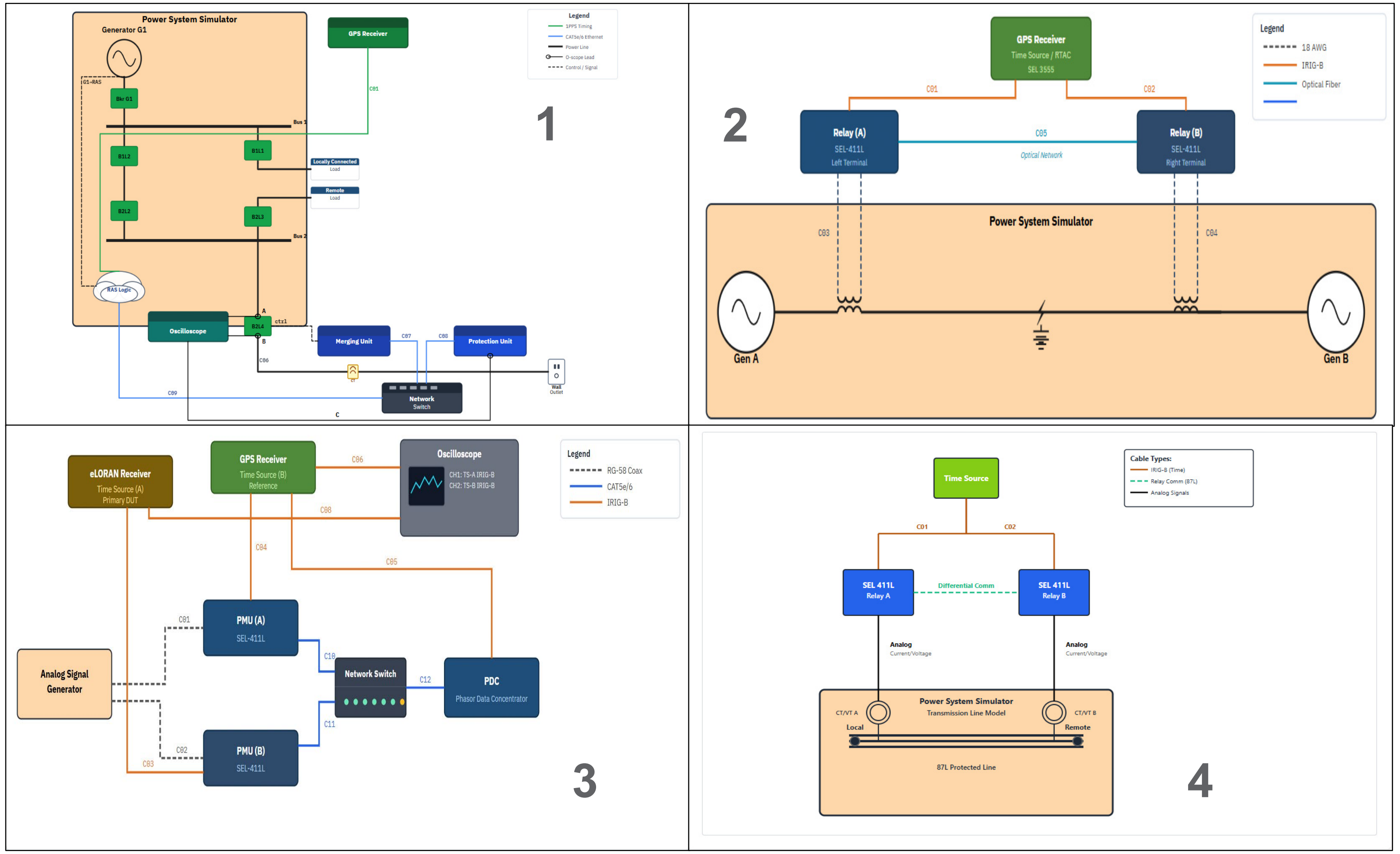
Testing Electric Power System Applications

- Focus on simulated real-world applications:
  1. Island/microgrid reconnection using IEC 61850 Sampled Values
  2. Traveling Wave Fault Location
  3. Synchrophasor Data Collection
  4. Current Differential Line Protection
- Simulated power system interactions and real substation equipment
- Combination of modern and legacy time receivers
- Combination of GNSS and non-GNSS time sources



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BPA's Precision Time Distribution Project

Goals

- Determine **best method for distributing precise time-of-day (ToD)** over BPA's utility communications system **with an accuracy of ±1 µs**
- Demonstrate **detection and alarming**

Multi-phase approach, increasing complexity

Phase 1 – Only Timing Devices and Relays – BPA Lab

Complete – Summer 2023

Phase 2 - Timing Devices plus Network – BPA Lab

Complete – Spring 2024

Phase 3 – Medium Scale Field Testing – BPA Comm System

Complete – Fall 2025

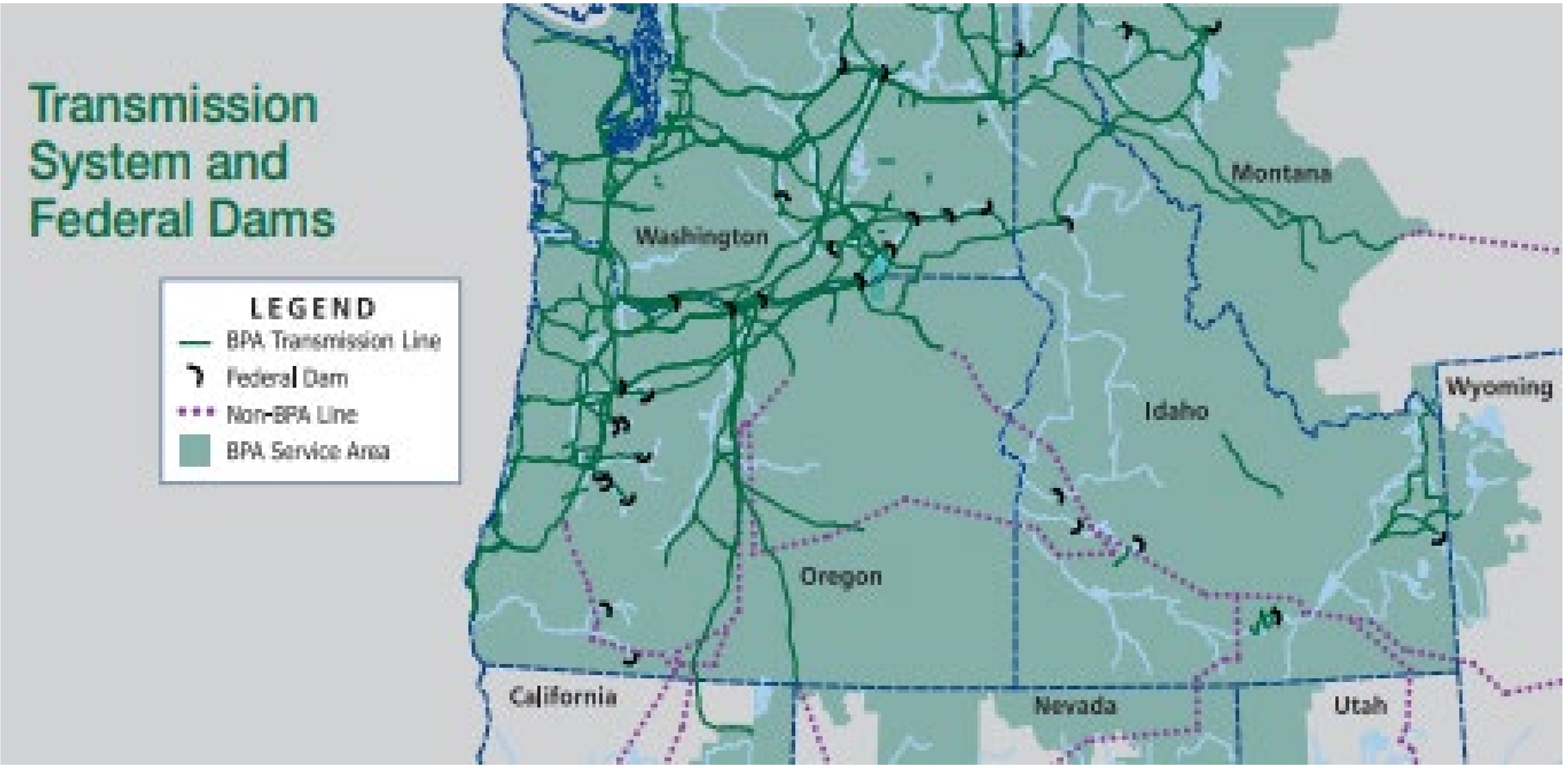
Phase 4 – Full Scale Field Testing – Worst Case

Late 2026 / Early 2027

Why is Testing on BPA's System Significant?

- BPA transmission system
  - Service Area = 300,000 square miles in PNW
- BPA owns and operates a large private utility communications system
  - Use: operate and maintain the transmission grid
  - Challenging terrain; long paths
- Use "every tool in the belt" to carry grid traffic
  - Multiple media, technologies, and manufacturers interoperate in many combinations

- Onsite lab used for Phases 1 and 2–
  - Same equipment models as field locations (Substations / radio stations)
  - "Real-world" communications impairments



See Fact Sheets - Bonneville Power Administration: https://www.bpa.gov/about/newsroom/fact-sheets

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Methodology and Test Setup

- Current reliance on GPS (GNSS) for precise timing faces scrutiny due to security vulnerabilities.
- IEEE 1588 Precision Time Protocol (PTP) is investigated as a terrestrial alternative for "Time of Day" (ToD) precision timing.
- PMUs provide critical grid health information, requiring accurate time tags resolving to at least 1 μs for accurate synchrophasor measurements
- Tested over a geographically diverse segment of the network
- Test Setup:
  - Redundant identically-configured Phasor Measurement Units (PMUs) at selected substations – one on GPS, other on PTP
  - Compared PTP-synchronized vs. GPS-synchronized PMUs for phase angle differences
  - Analyzed Time Error (TE) between local PTP clocks and external GPS 1PPS references

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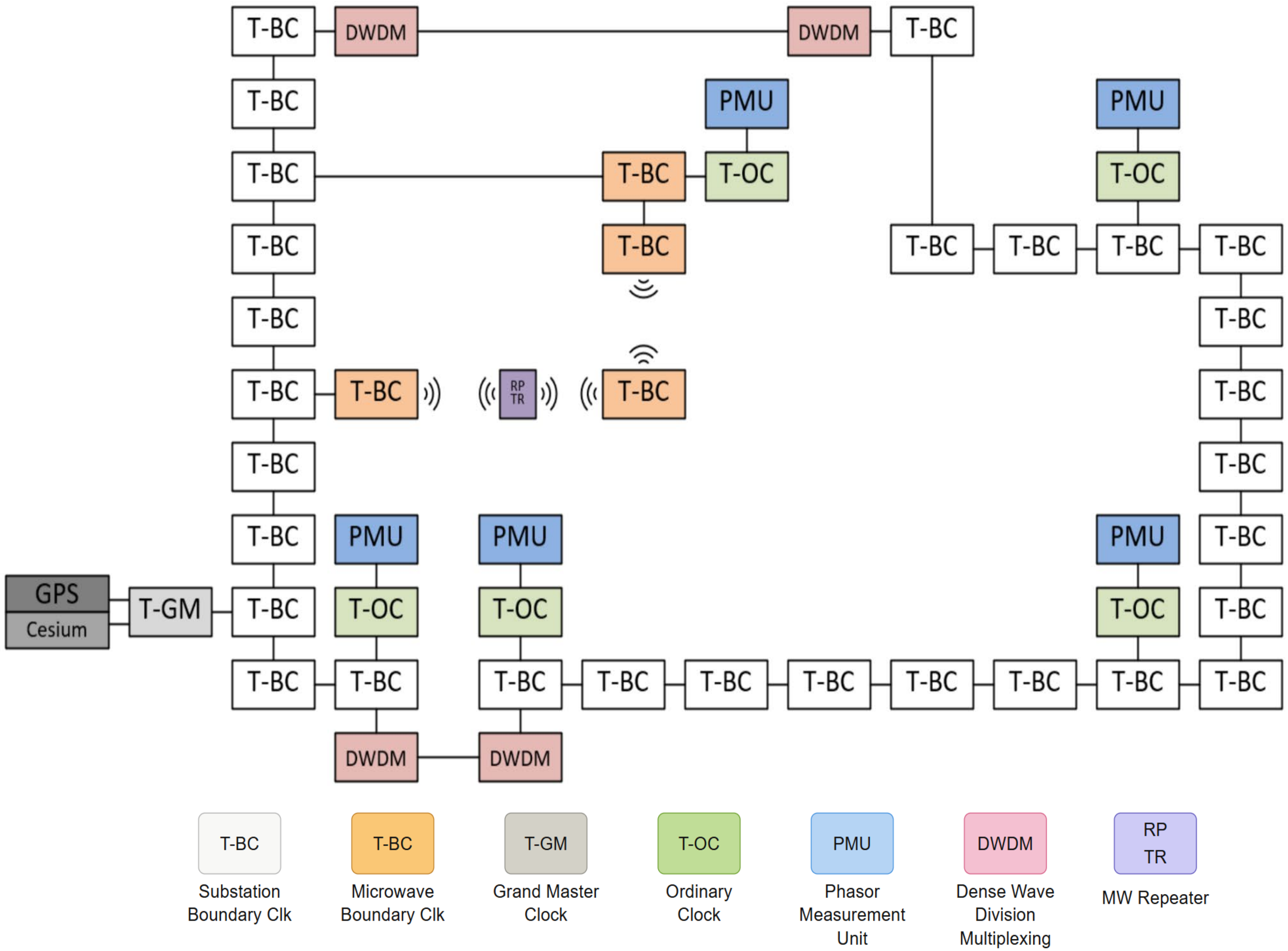
Overall Test System Topology

- Both long-haul fiber optic and point-to-point microwave systems
  - 32 substations
  - 1,240 km optical fiber
    - ✓ MPLS nodes
    - ✓ DWDM
  - 110 km microwave backhaul
    - ✓ SONET



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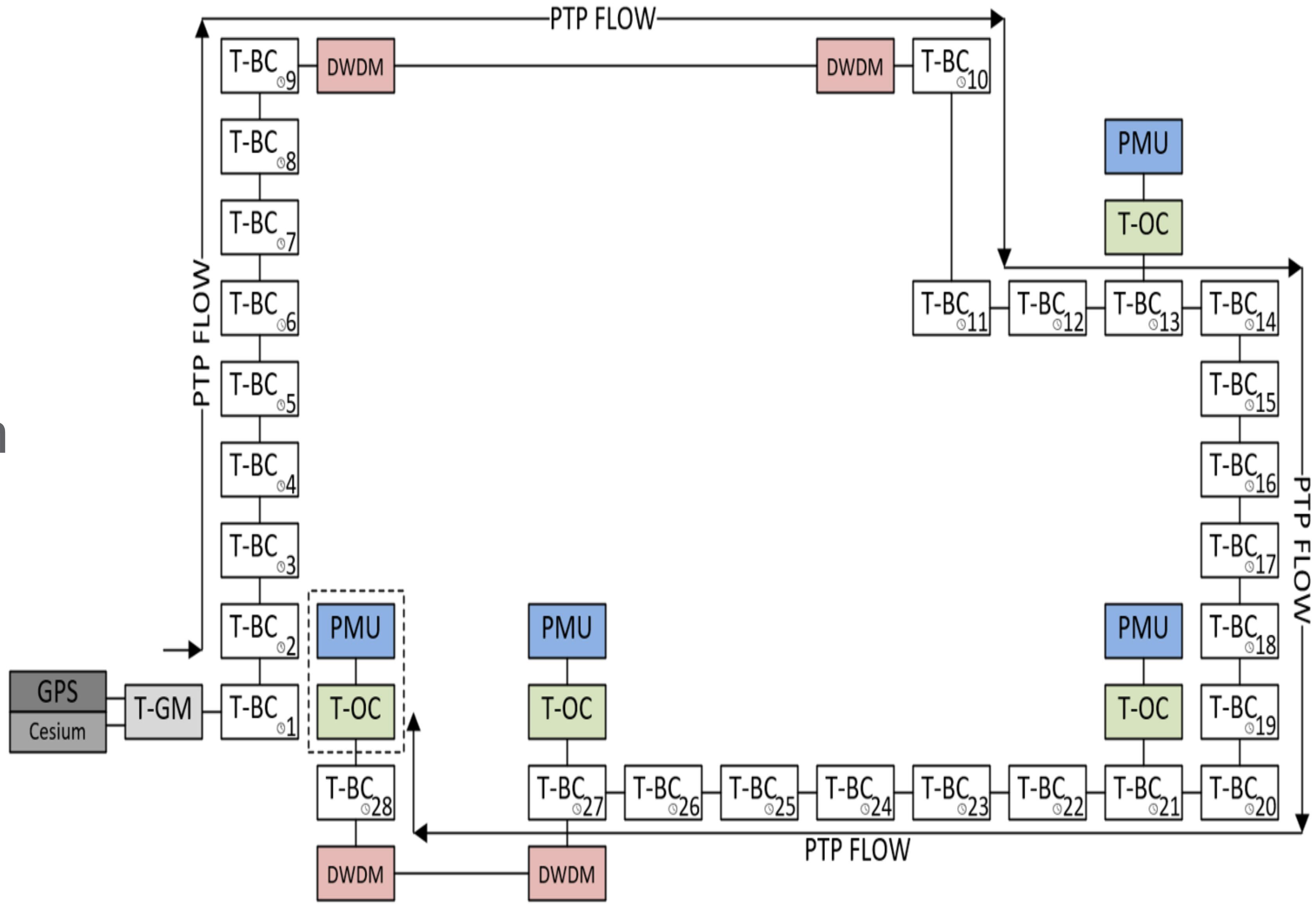
Phase 3 Profile Validations and Results:100G Fiber

- ITU-T G.8275.1 profile used across 28 telecom boundary clocks (T-BCs) with the Grand Master at site zero
  - Mean TE was ~ 452.7 ns
  - Standard deviation of 6.4 ns
  - **Well within the +/- 1 µs target**
- PMU angle differences between test and reference PMUs
  - Average = 0.00878 degrees
  - All deviations $\leq$ 0.0135 degrees
  - **Well within +/- 0.1 degree tolerance**



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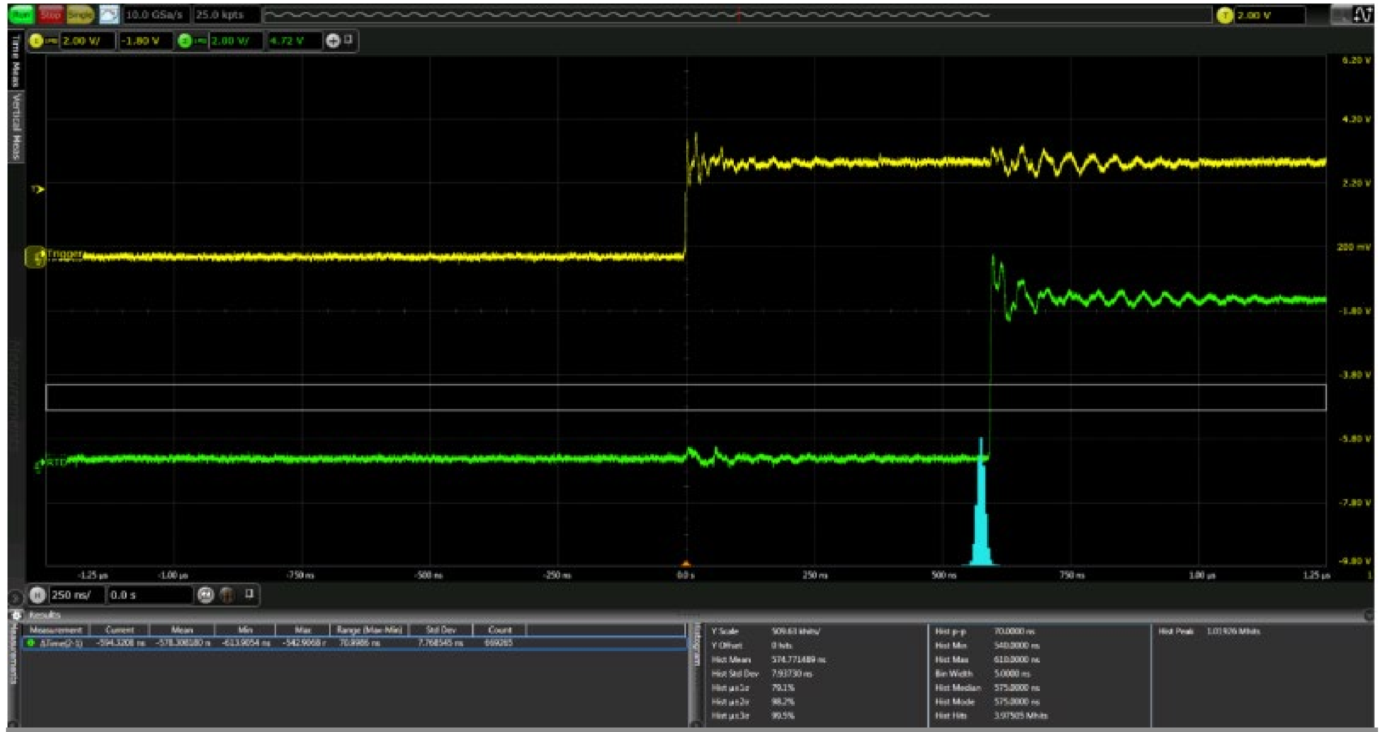
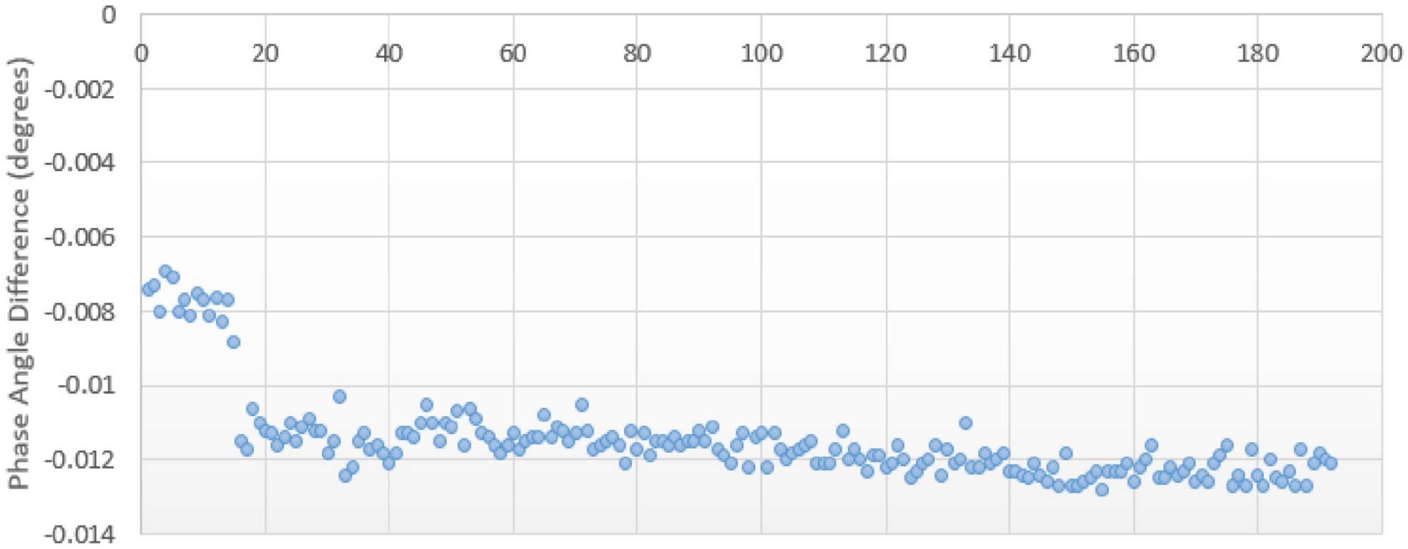
Pushing the Hop Limit on Fiber Backbone

- Original 100G fiber test extended to
  - **58 T-BCs**
  - **2050 km of fiber** through MPLS nodes
- Resulting TE increased to ~578.7 ns while remaining stable
  - **Well within the +/-1 µs tolerance**
- PMU phase angle differences averaged 0.01147 degrees
  - **Still well within the +/- 0.1 degree tolerance.**



Time Error Histogram – 58 BC



PMU Phase Angle – 58 BC

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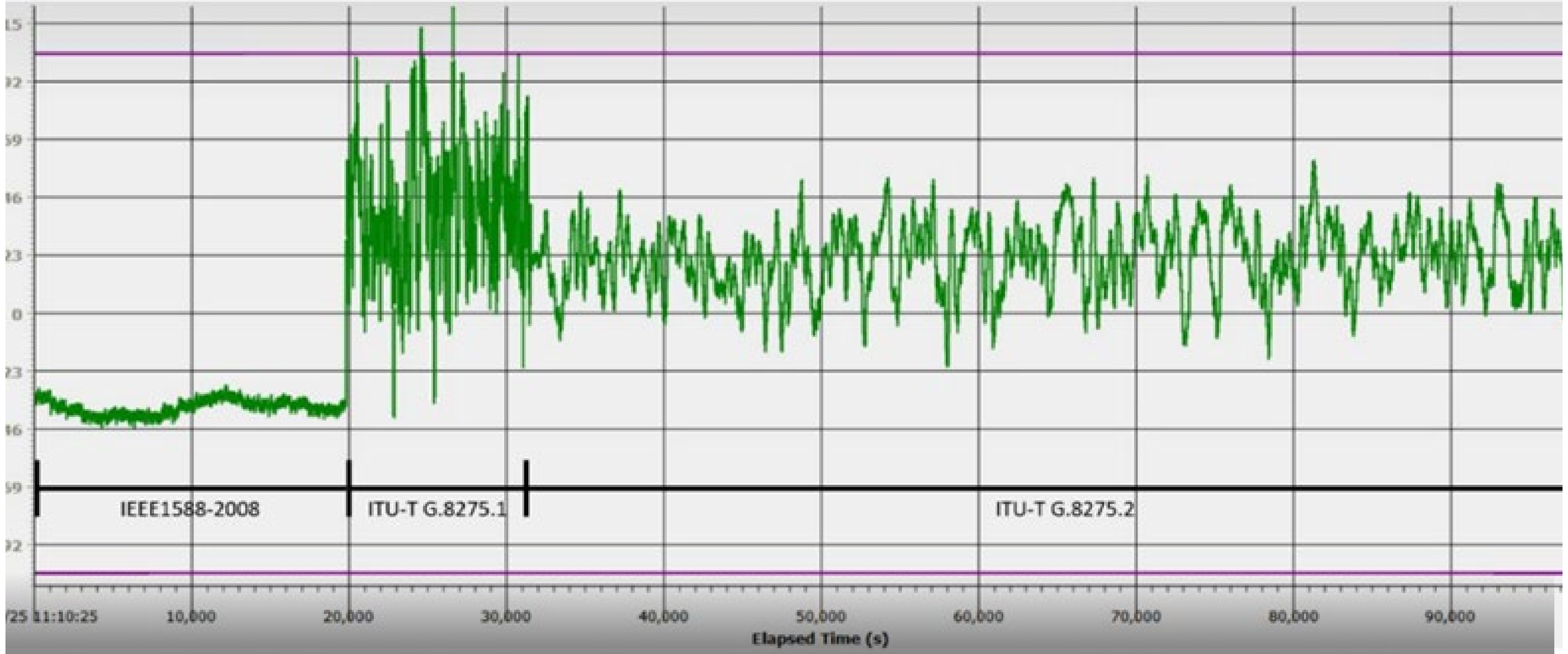
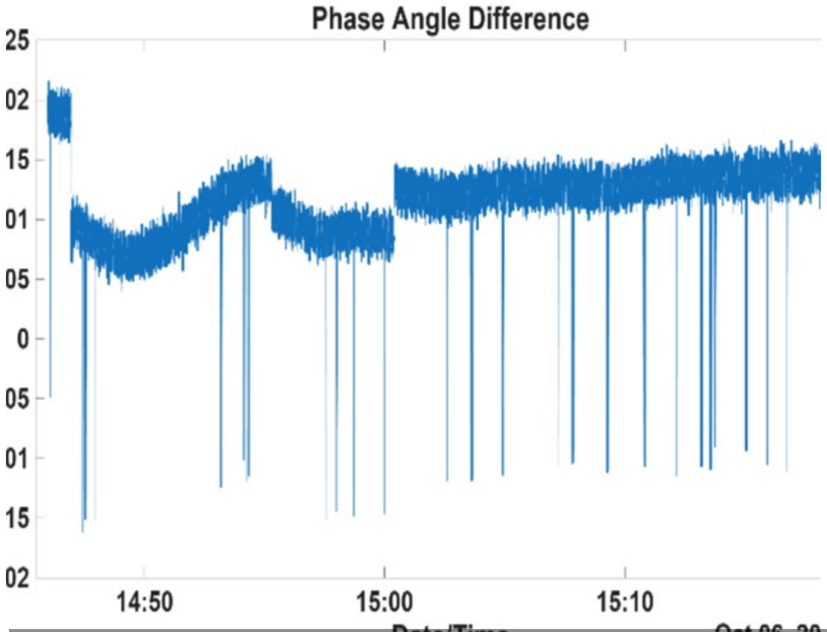
Performance Over SONET Microwave Radio Paths

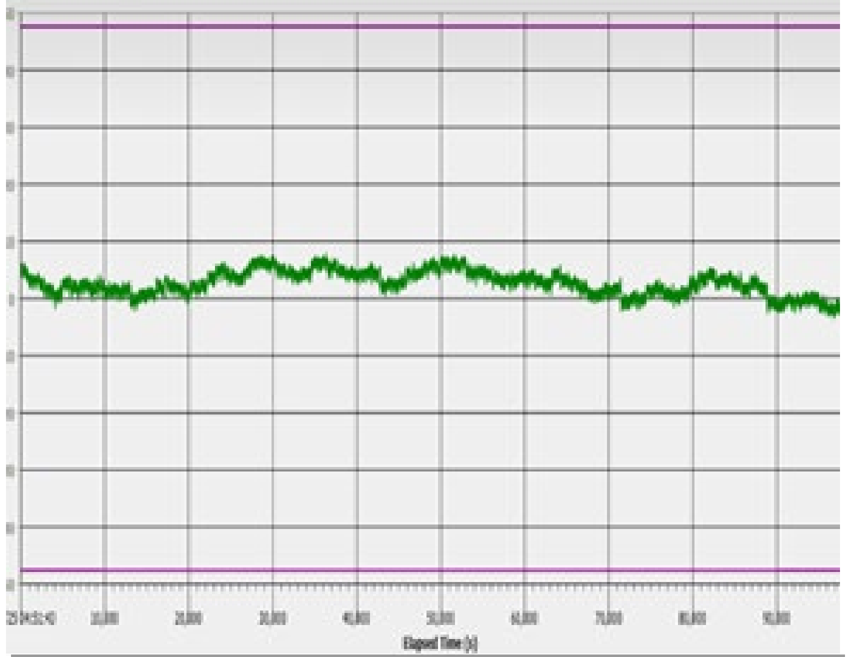
- Testing with ITU-T G.8275.2 and G.8275.1 profiles showed high-frequency jitter, irregular adjustments, and holdover
- The IEEE 1588-2008 default profile significantly improved performance
- Increasing the SYNC and DEL_REQ rate from 64 to 128 packets/sec. eliminated holdover events and improved TE



TE Comparison of tested PTP profiles



PMU phase comparison during holdover



TE plot, IEEE 1588-2008 default with 128 packets/sec

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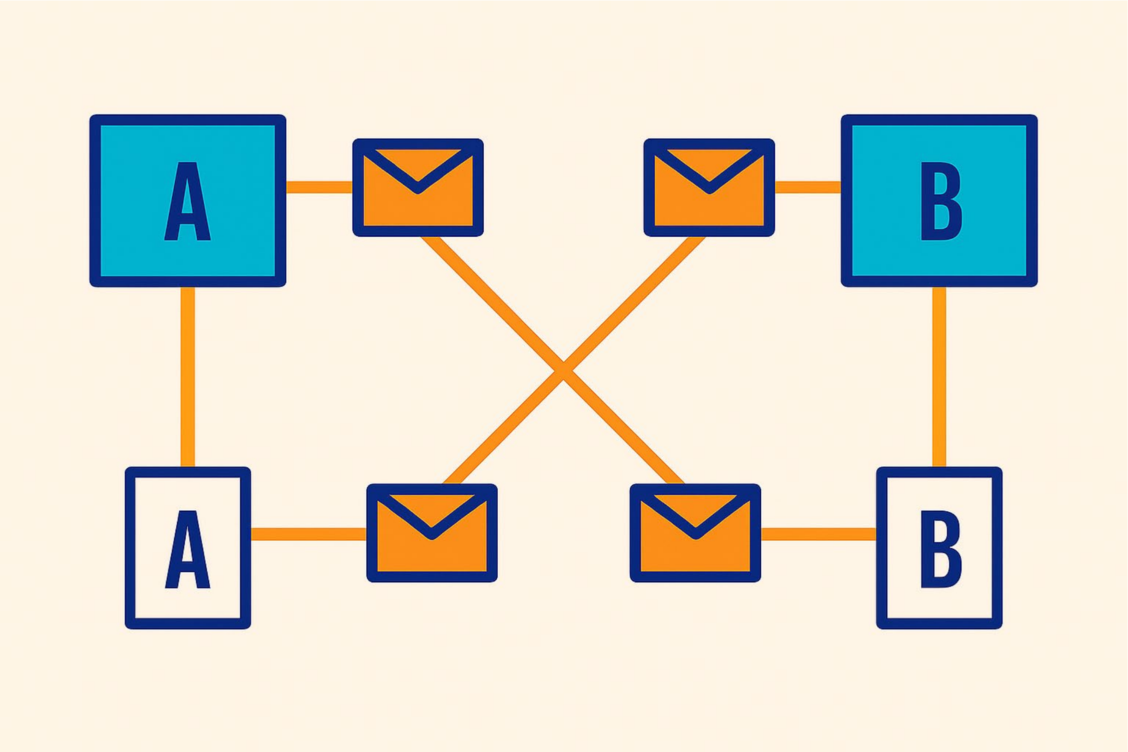
Network Rearrangement Resilience



- Fiber core protection switching –
  - No change to reported time quality by the T-OC
  - Rapid convergence of phase adjustments.
- Microwave network rearrangements -
  - Introduced larger transient phase excursions and extended holdover periods (Average: 20m 56s)
  - PMU phase angle difference reached 0.2496 degrees before normalizing
- Despite these challenges, PTP architecture proved operationally robust during worst-case topology changes, with PMU phase deviations remaining bounded.

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Conclusions and Key Takeaways

- **ITU-T G.8275.1 is highly stable for 100G fiber MPLS backbones**, even with extended hop counts and network rearrangements.
- **For SONET microwave links, the IEEE 1588-2008 default profile with increased message rates is necessary** to mitigate path asymmetry and environmental variability to achieve the 1 µs requirement.
- **PTP-based timing remains robust during protection switching events, with** fiber paths showing rapid convergence and **microwave paths relying on disciplined oscillator holdover**.
- **With appropriate profile selection and tuning**, IEEE 1588 **PTP is a viable and resilient alternative** to GNSS-based timing for both Time of Day and critical grid monitoring and protection functions.
- Further testing is needed for SONET and Ethernet microwave radio paths under various environmental conditions – Phase 4 is coming soon!

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IEEE Standards Activities

- IEEE P1952
  - Resilient Position Navigation and Timing User Equipment (PNT UE)
  - Focuses on the PNT-related resilient capabilities of the User Equipment (e.g., GNSS receiver)
    - ✓ Not the input signals or end-use applications
    - ✓ Several areas out of scope (e.g., power requirements, physical environment, GNSS satellite availability, network connectivity for PTP)
  - Five resilience levels defined – **Resist (3) and Withstand (4) most applicable for electricity sector**
  - Adversities detectable by PNT UE equipment
  - Use Cases focus applicability of resiliency parameters in real-world applications
  - PNNL leads the effort to develop a **timing use case for electric system operations**
    - ✓ Participates in other topical areas
  - Standard *should* go to ballot by the end of this year

IEEE Standards Activities

- IEEE P2030.101
  - Guide for Designing Time Synchronization Systems for Electric Power Systems
  - Revision to existing 2018 standard
  - Developed under the Power System Relay and Control (PSRC) Committee
  - Expand scope from “within substation fence boundary” to include wide-area timing networks
  - Specific focus on applicability to electricity sector – substations, generation plants, control centers
    - ✓ Design guidelines to allow meeting accuracy and precision required by the sector
  - Address new and emerging threats and capabilities
  - Address emerging time distribution sources
- Requirements for Time Sources in Protection and Control Systems Whitepaper
  - Discusses application requirements for clocks and time sources
  - Developed by the PSRC Committee
  - Intended to be available at no cost on the PSRC resources webpage

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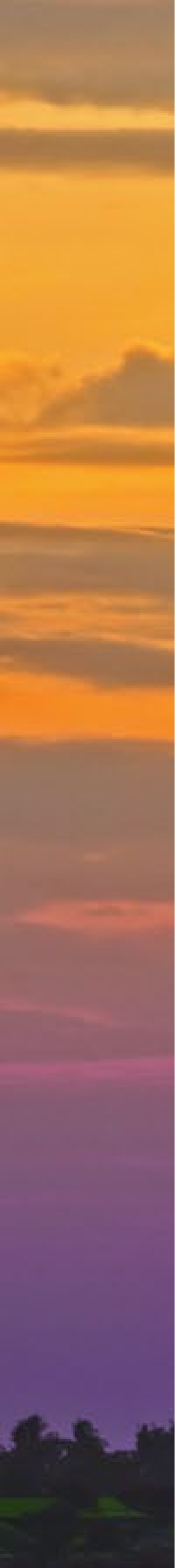

THANK YOU

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