Complementary Precise Timing Distribution in a Transmission Utility Environment

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Agenda

- Transmission System's Need for Precise, Synchronized Time
  - Basic Requirements
  - Denied/Degraded Environments
- Bonneville Power Administration's (BPA) Precision Time Distribution Project *
  - Overview and Significance
  - Methodology and Test Setup
  - Results
    - ✓ Fiber system
    - ✓ Point-to-Point Long-Haul Microwave
  - Next Steps

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

Timing Requirements for Bulk Electric System (BES) Functions

- Timing is everything!
  - PNT = pn**T**
- BES dependence on GPS timing
  - Requires Time of Day (ToD)
  - Most stringent in energy sector
  - IRIG-B derived from GPS for substations
- Disruptions
  - Natural/man-made; intentional or not
  - Solar flares
  - Jamming
  - Spoofing
  - Meaconing (delay or replay)

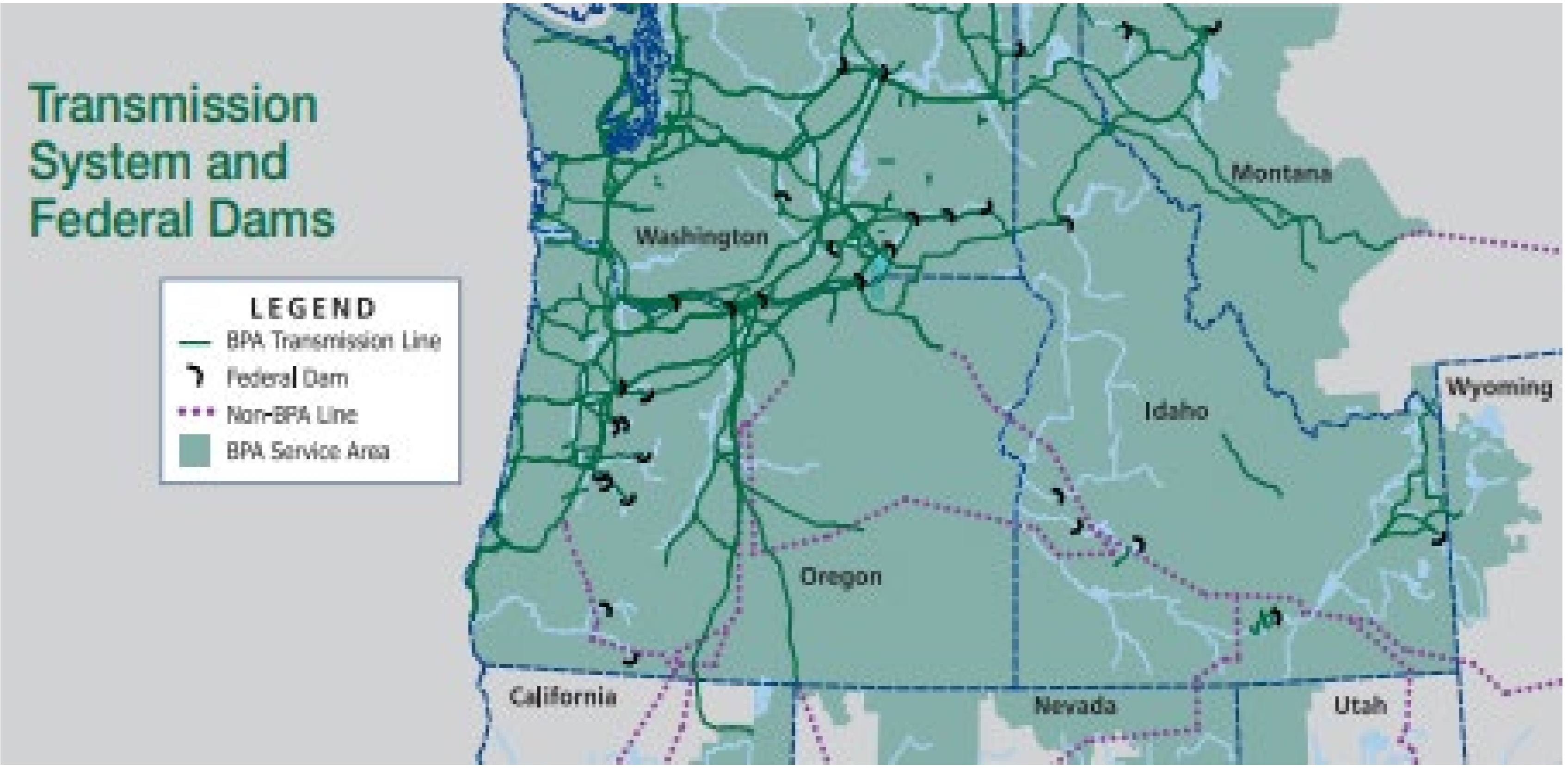
Grid Function	Timing Requirement
Regulatory Disturbance Reporting	±2 ms
Sequence of Events (SoE)	±1 ms
Line Current Differential Protection	±10 µs
IEC 61850 Sampled Values (~4kHz sampling synchronized at top of every second)	±1 µs
Synchrophasor Measurements	±1 µs
Traveling Wave Line Fault Location	±500 ns
Point on Wave switching	±100 ns

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

Why Test on BPA's System?

- BPA's 2-prong approach to reduce dependence on GPS
  - Complementary sources
  - **Optimizing source distribution**
    - ✓ High reliability and high accuracy
- 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

- BPA transmission system
  - Service Area = 300,000 square miles in PNW



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

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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**

Phases 1 and 2

- Same equipment models as field locations (Substations / radio stations)
- “Real-world” communications impairments

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

Methodology and Test Setup

- 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 within +/- 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, one on PTP
  - Compared PTP-synchronized vs. local GPS-synchronized PMUs for phase angle differences
  - Analyzed Time Error (TE) between local PTP clocks and external GPS 1PPS references

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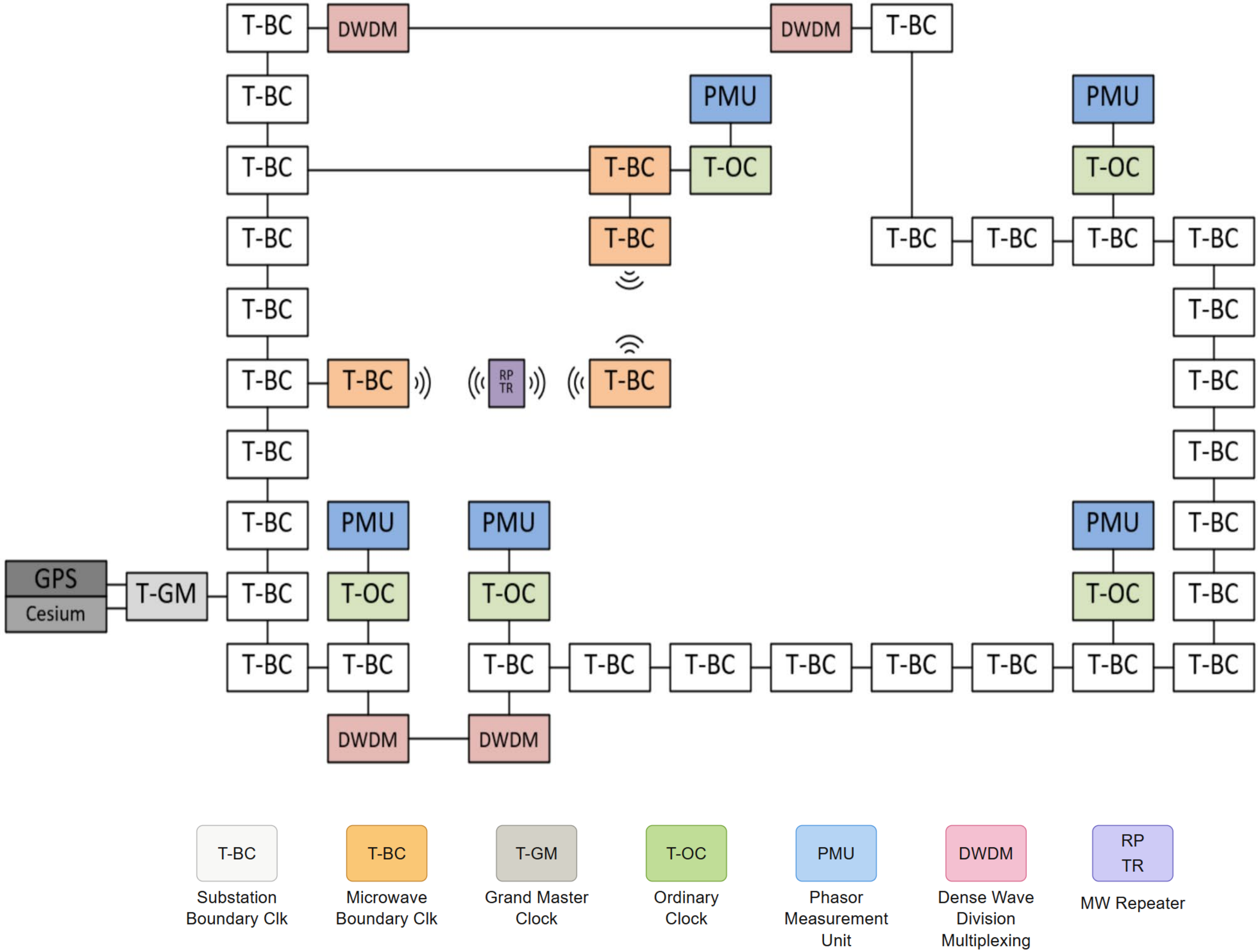
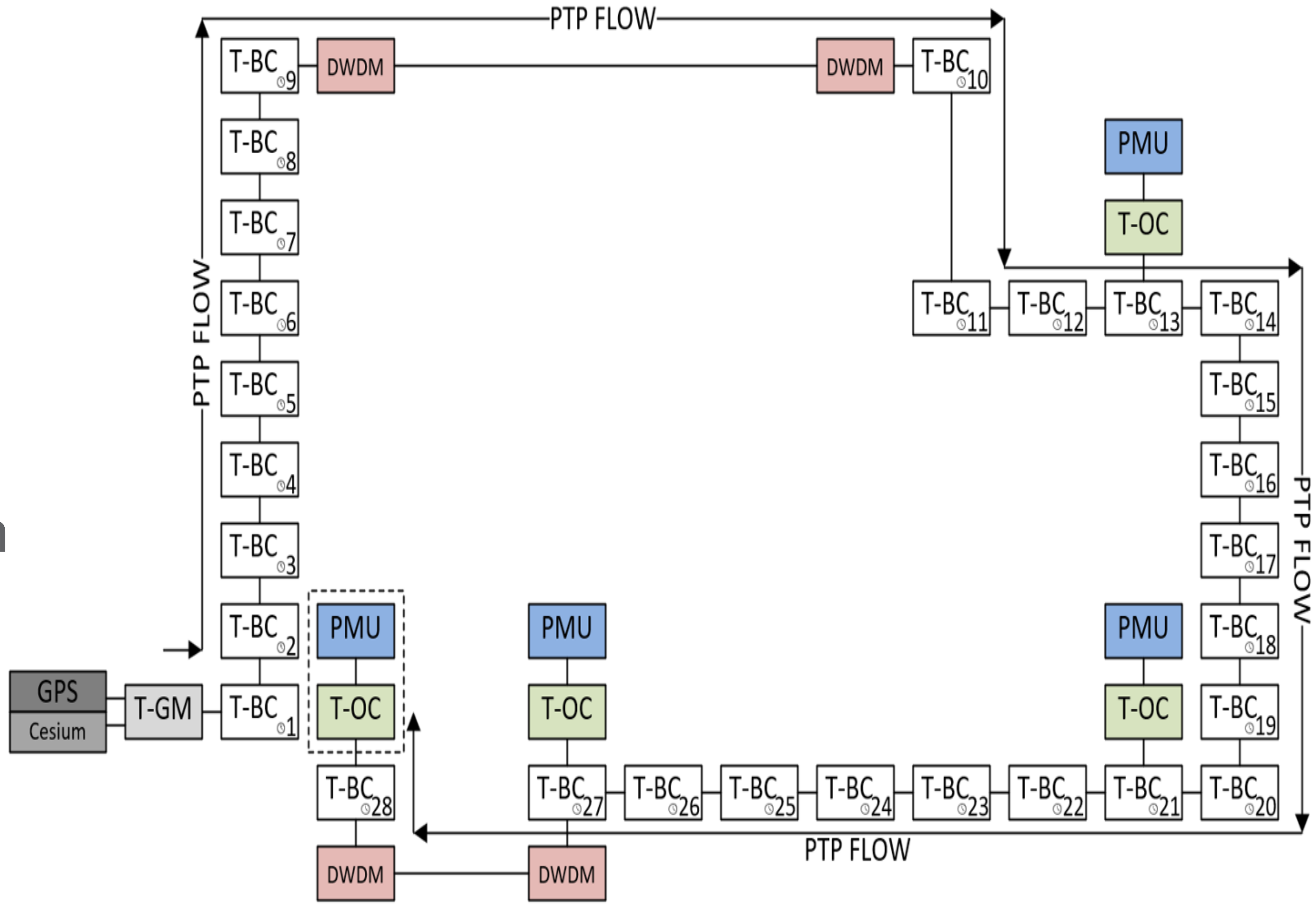
Overall Test System Topology

- 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
- ePRTC source – GPS/Cesium



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 ≤ 0.0135 degrees
  - **Well within +/- 0.1 degree tolerance**



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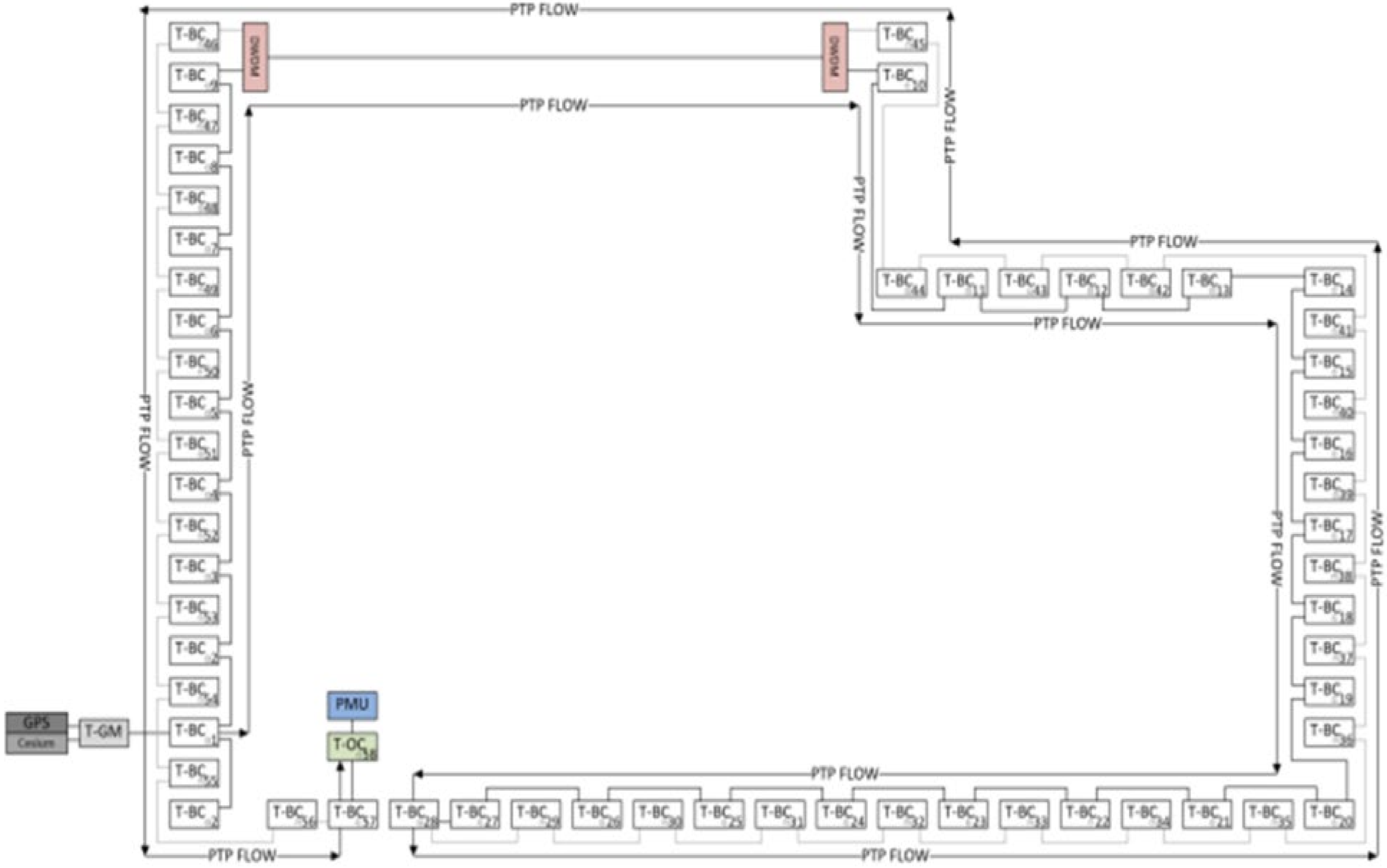
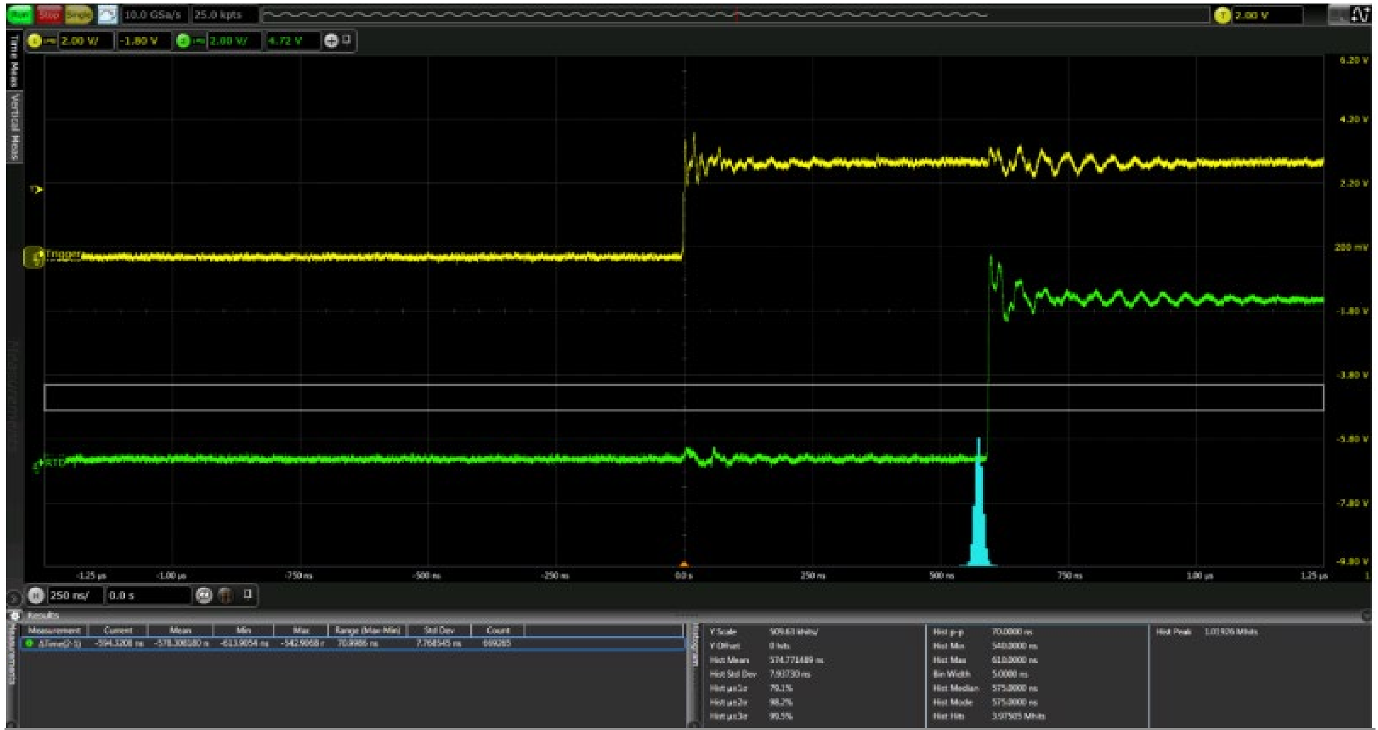
Pushing the Hop Limit on 100G Fiber Backbone

- Original 100G fiber test extended to
  - **58 T-BCs**
  - **2050 km of fiber**
    - ✓ MPLS nodes
    - ✓ DWDM

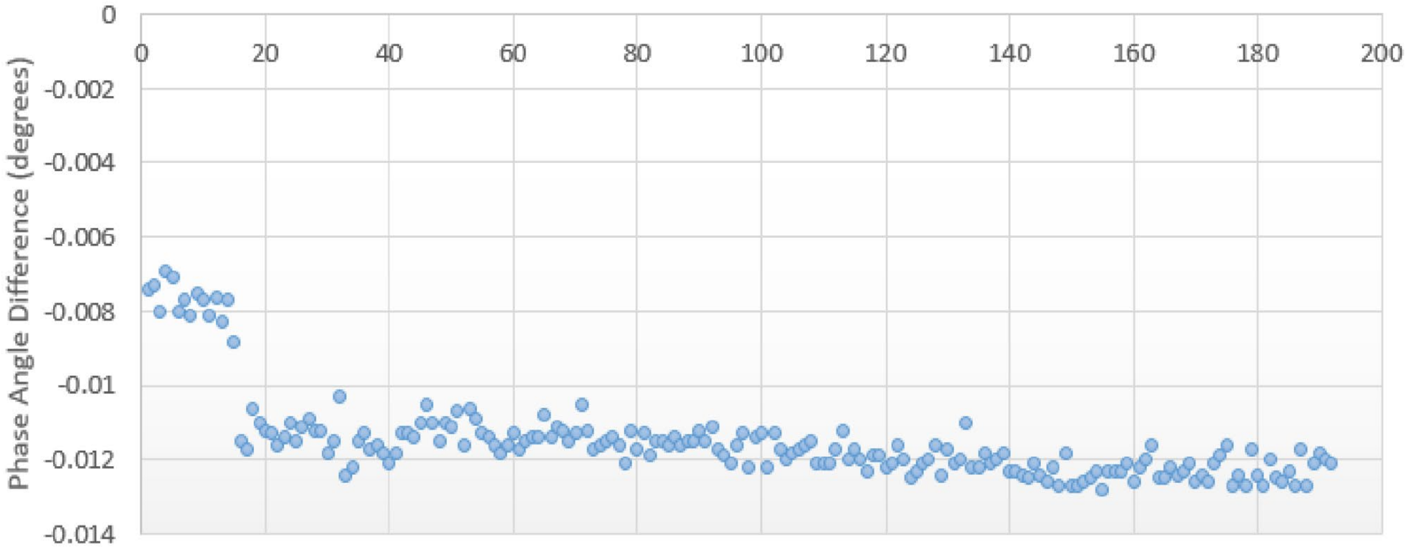


Impact on Time and Phase Error Through 58 Boundary Clocks

- 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**



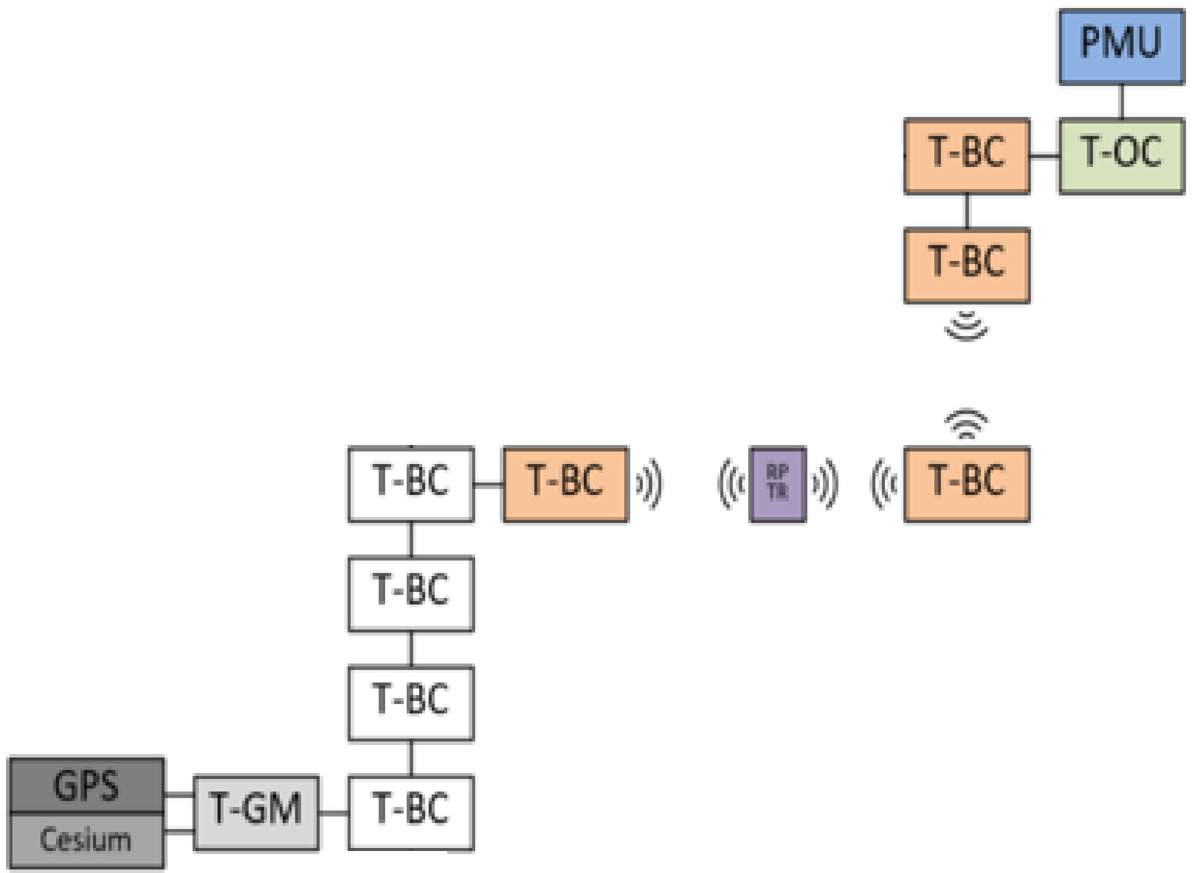
Time Error Histogram – 58 BC



PMU Phase Angle – 58 BC

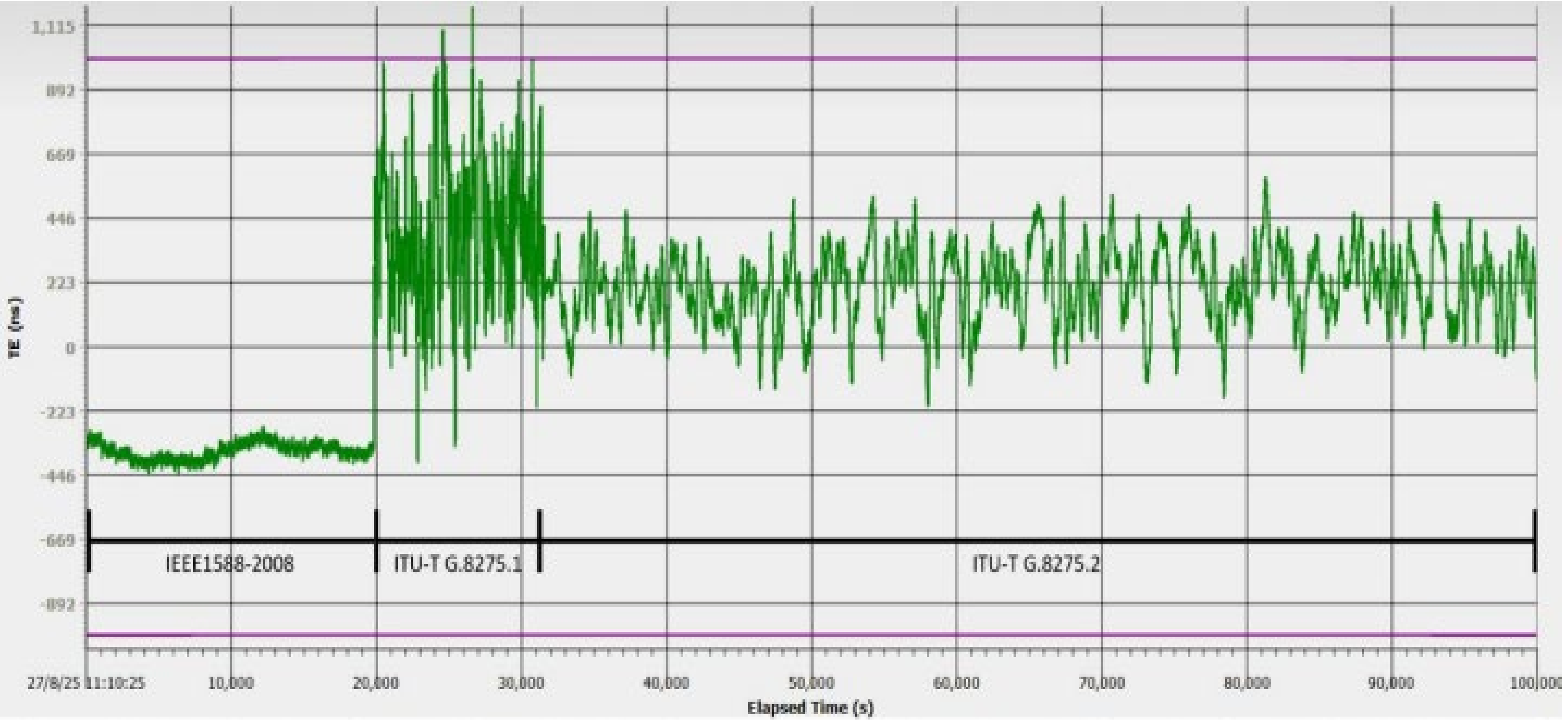
Performance Over SONET Microwave Radio Paths

- Tested across a 114 km subset of the initial topology
- Microwave segments present challenges due to atmospheric conditions and path geometry affecting synchronization
- SONET is not a packet technology
  - Point-to-point layer 2 service was used to bridge between MPLS nodes at each end



Time Error Over SONET Microwave Radio Paths

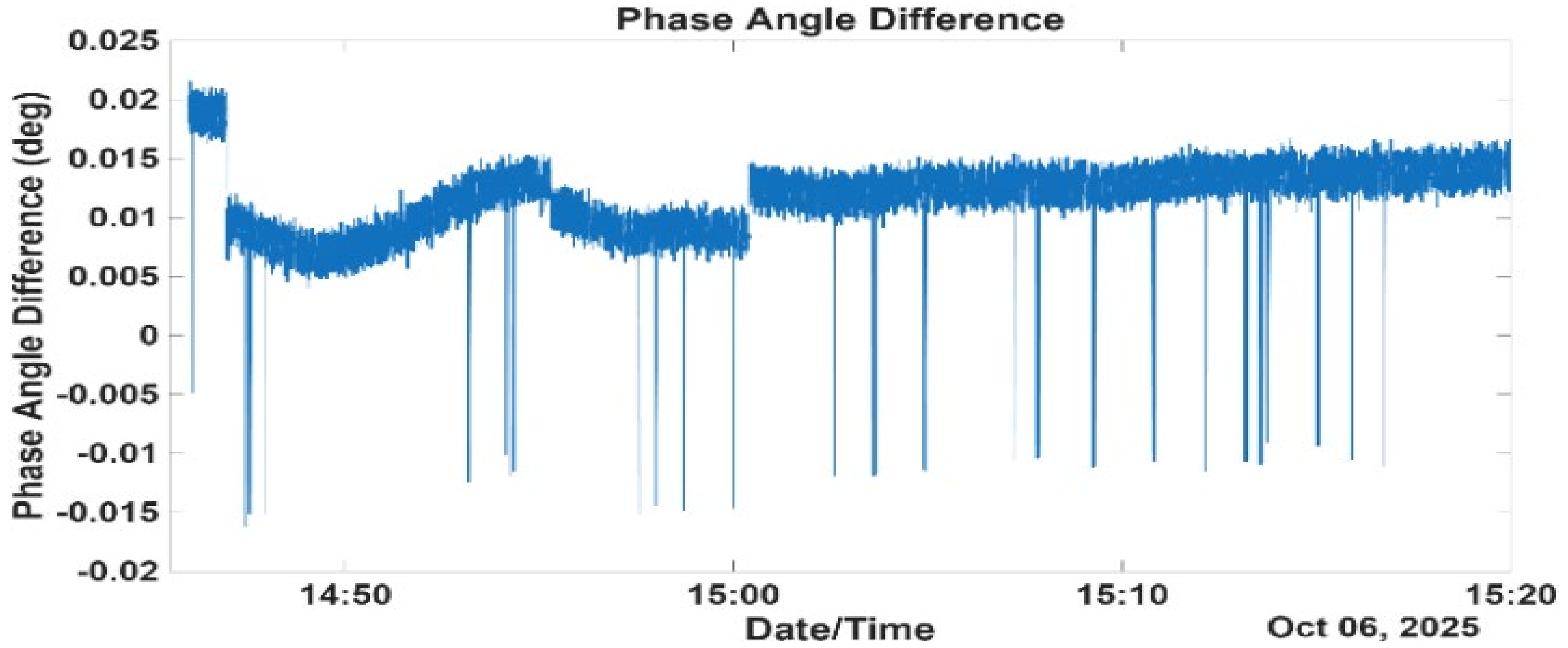
- Testing with ITU-T G.8275.2 and G.8275.1 profiles showed high-frequency jitter, irregular adjustments, and holdover at the T-OC clock
  - ITU-T G.8275.2 profile had significant high frequency jitter and irregular adjustments
  - ITU-T G.8275.1 profile was the worst - large time excursions, never reached sync lock, and stayed in holdover
- Using IEEE 1588-2008 default profile significantly improved performance
  - Greatly reduced high frequency jitter
  - Time error reduced by approx. 50% as compared to G.8275.2
  - No large time excursions
- Gradual delay drifts were found, aligning with expected delay variability for microwave



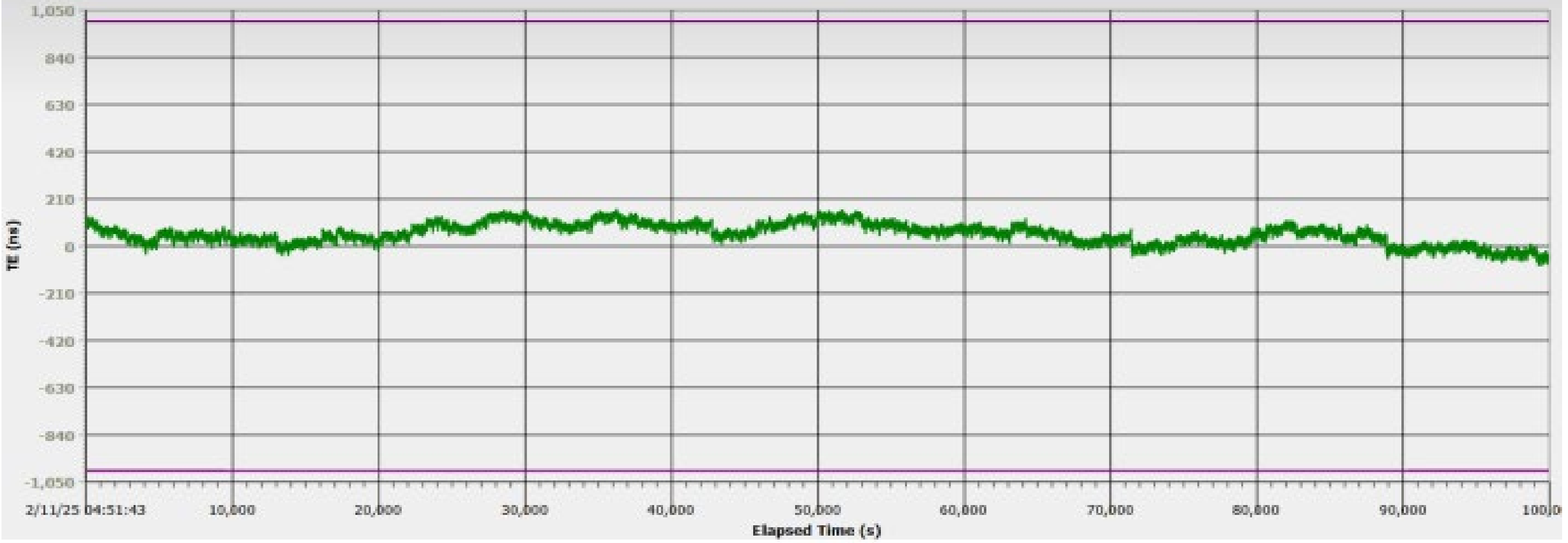
TE Comparison of tested PTP profiles

Performance Over SONET Microwave Radio Paths

- T-OC time quality bits showed less stability over many months
  - Alarm logs showed 85 holdover events
  - Holdover was keeping phase angles within tolerance
- Increasing the SYNC and DEL_REQ rate from 64 to128 packets/sec eliminated holdover events and improved TE
  - This does decrease available bandwidth on low-capacity links

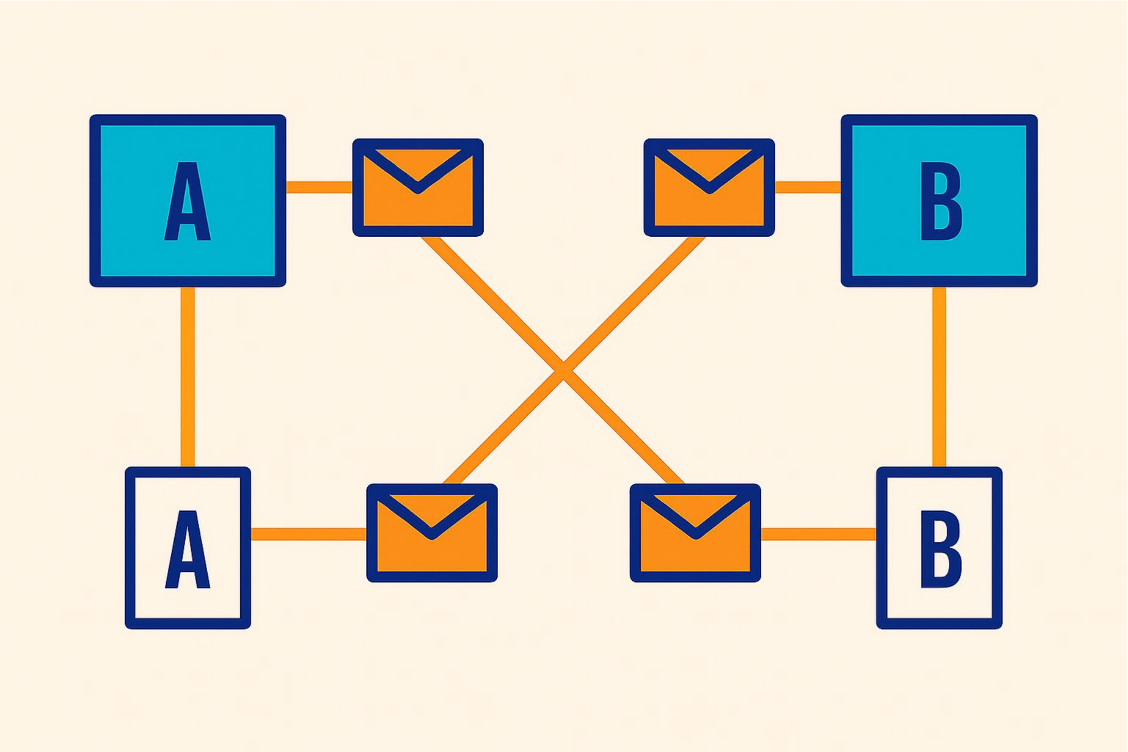


PMU phase comparison during holdover



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

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

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/complement** 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 to address this!

Questions?

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