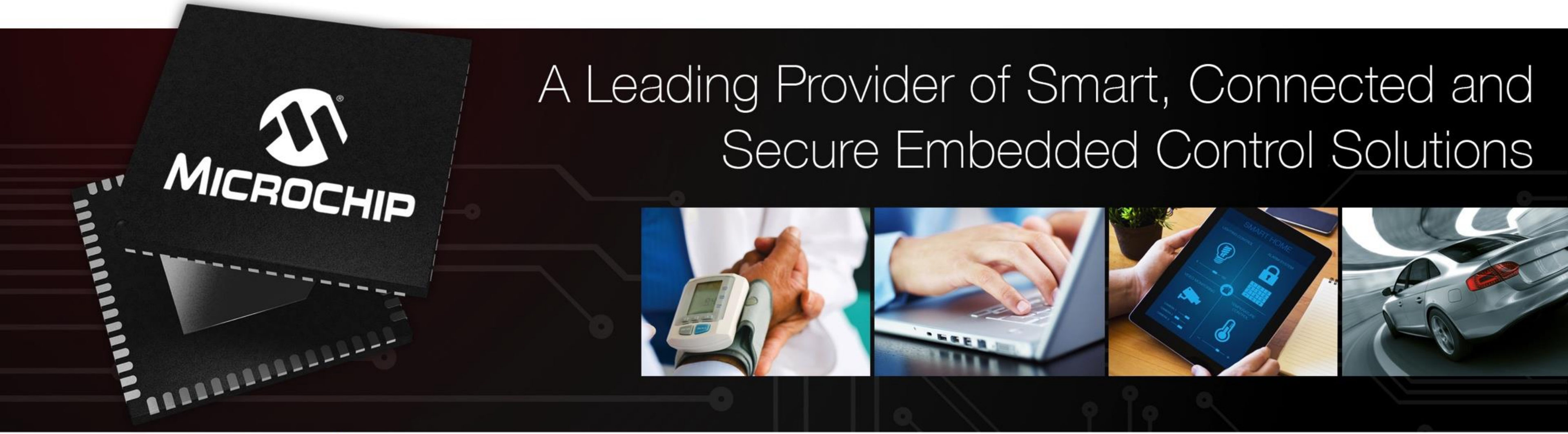

Resilient High Accuracy Optical Boundary Clocks

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ITSF 2019, November 6, 2019

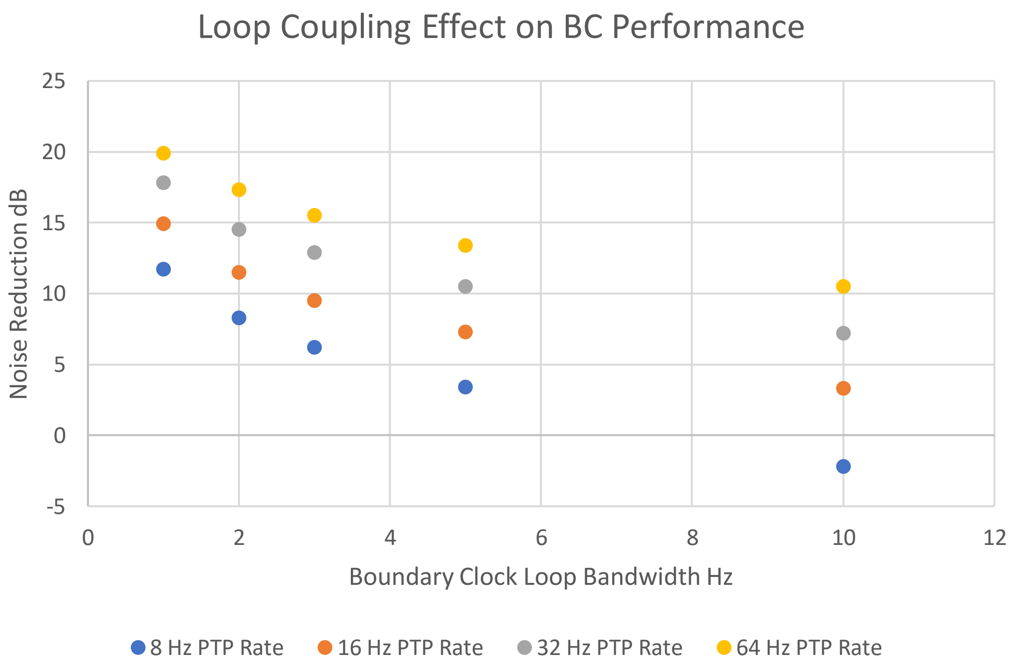
Overview of Topics

1. Servo Loop Coupling
2. Resilient Time to Digital Conversion Operation
3. Chromatic Dispersion Asymmetry Correct
4. Resilient Operation in Thermal Environment
5. Time Error Accumulation in Chain of Clocks
6. Resilient Node and Link Failure/Recovery Operation

Resilient Loop Coupling

Key Observations:

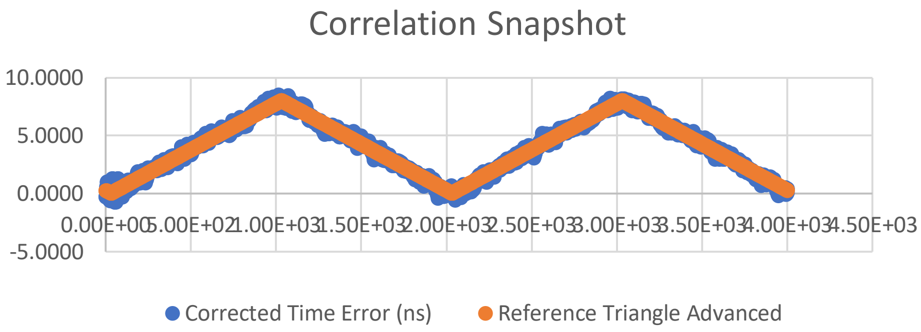
- For Resilient Operation loop bandwidth is a key parameter.
- The objective is to be “loosely coupled” to input to maximize detection and rejection of transients
- With proper design of critical components such as the local oscillator and synthesizer loose coupling can be achieved

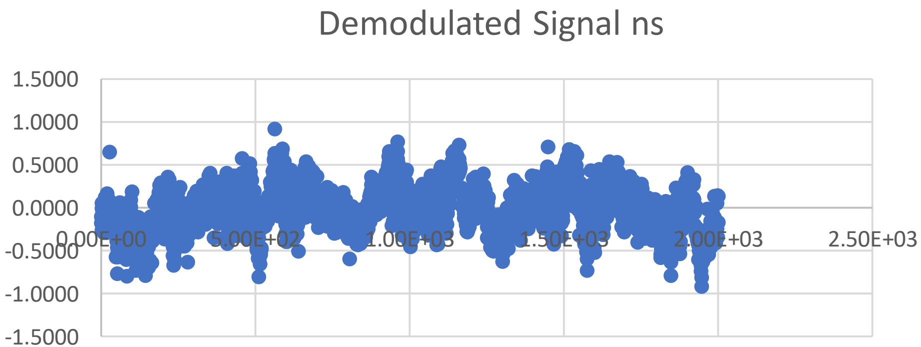


Time Digital Conversion TDC Resilient Operation

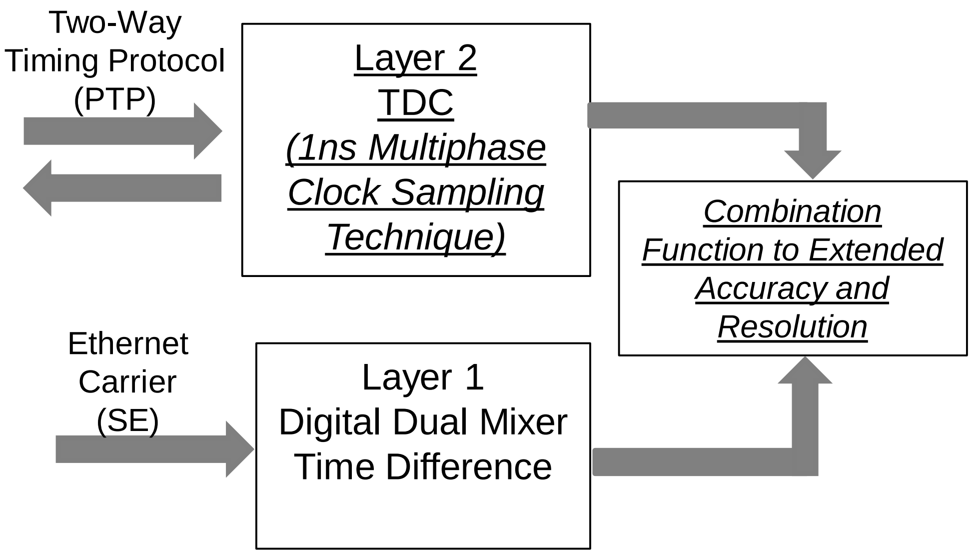
Key Observations:

- Ethernet Layer TDC is particularly sensitive to delay changes in the 8 ns (125 MHz related) range.
- A resilient High Accuracy implementation should achieve consistent results for all “fiber lengths”.
- A 8 ns sweep test is performed to ensure that consistent sub-nanosecond performance is achieved

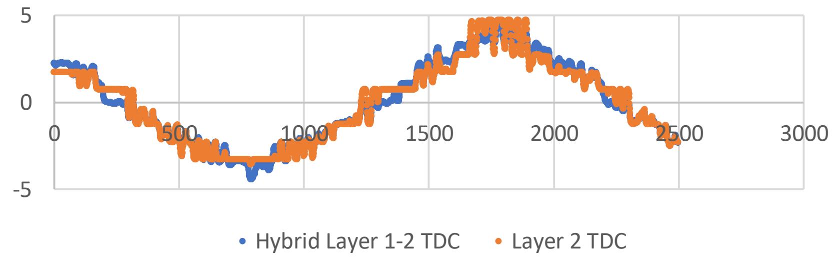




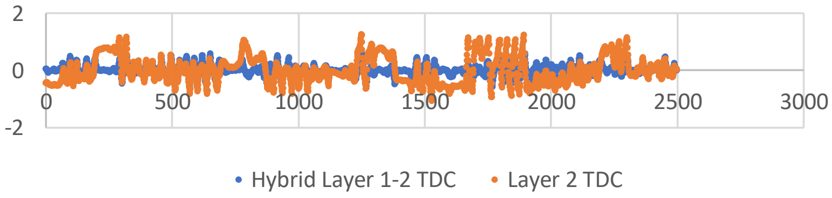
Time Digital Conversion TDC Resilient Operation Hybrid Layer 1-2



TDC Measure Sweep Results



TDC Noise Estimate
Layer 2: 458 ps Hybrid 1-2: 187 ps



** Note TDC Noise Estimate includes additional control loop noise*

Bi-Directional Optical Asymmetry Correction

Objective: observe the chromatic dispersion and correction over the fiber optic path.

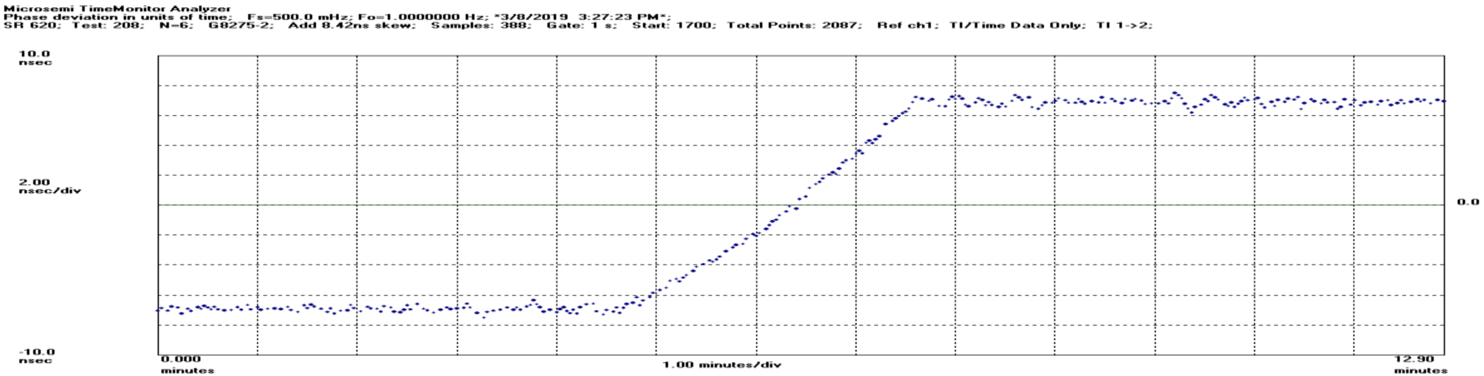
The path is supported with:

1) 83.633 km of single mode Corning G.652.D Fiber
2) Bi-Directional SFPs Investigated
   - Case 1: 1605/1615 nm Bi-Directional SFPs
   - Case 2: 1290/1350 nm Bi-Directional SFPs

The test sequence is:

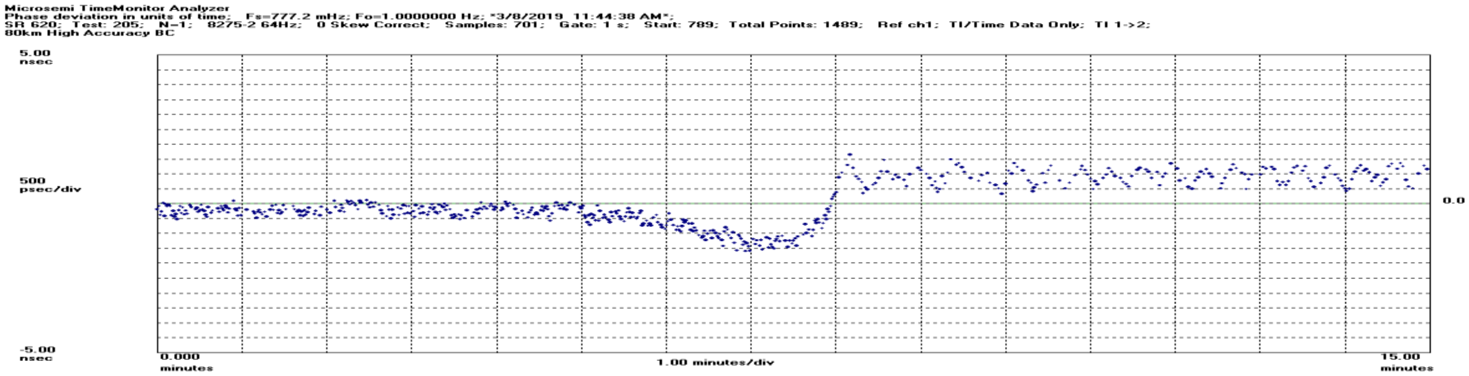
1) Start system with the PRTC GM operating with:
   - Case 1: 1605 transmit SFP.
   - Case 2: 1290 transmit SFP.
2) Collected data for nominally 15 minutes
3) Disconnect Fiber and SFPs and swap the SFPs so that the GM now transmits longer wavelength.

Case 1: Optical Asymmetry 1605/1615 nm



The time error average before and after the switch is +/- 6.92 ns.
The total excursion of 13.84 ns is the measured delay difference.
What is the simple first order predicted asymmetry?
The dispersion effect at 1600 nm is nominally 17 ps/km/nm: 17e-12*83.633*10 = 14.22 ns
The error using this simple first order correction term is: 0.5(14.22-13.84) = 0.19 ns
The error is less than 1 ns with an application of the chromatic dispersion compensation.

Case 2: Optical Asymmetry 1290/1350 nm

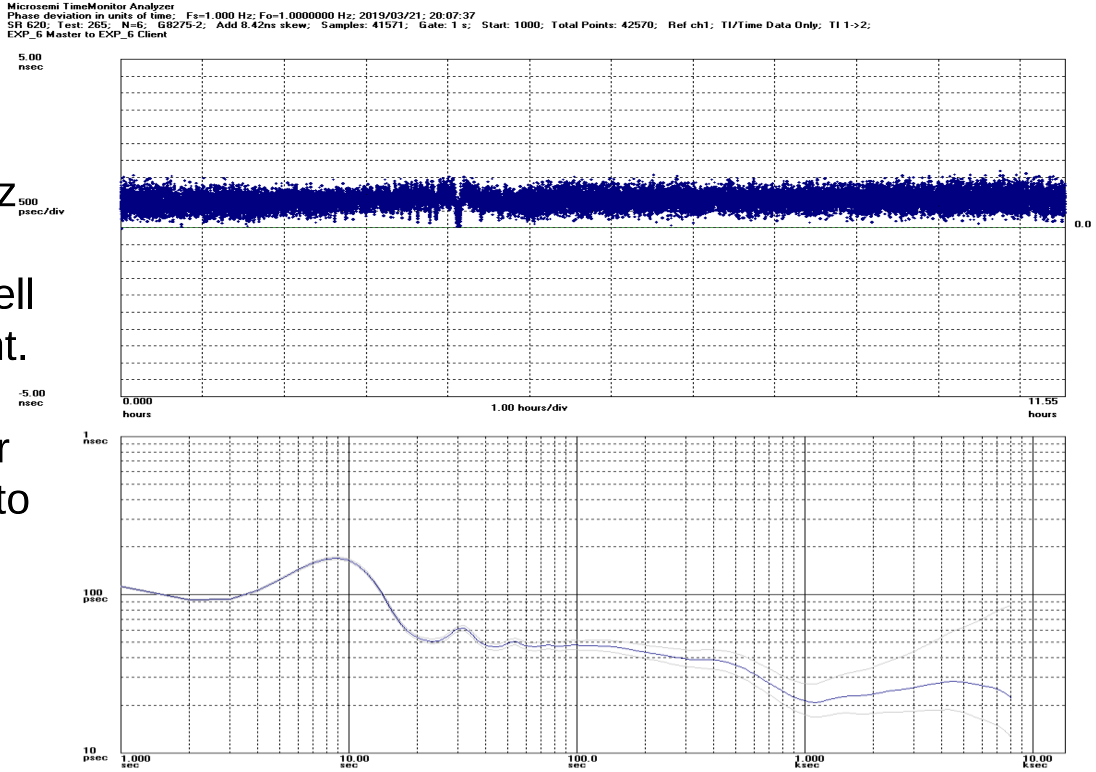


The time error average before and after the switch is +/- 0.56 ns.
The total excursion of 1.12 ns is the measured delay difference.
The dispersion effect at 1300 nm is nominally +/-1 ps/km/nm (zero dispersion point for the fiber).
For the sake of simplicity, we'll assume the Bi-Di SFP is close to 0 dispersion effect:
The error using this simple first order correction term is: 0.5(1.12 – 0) = 0.56 ns
The error is less than 1 ns with an application of the chromatic dispersion compensation.

Case 1: 84 km High Accuracy 12 Hour Test Run

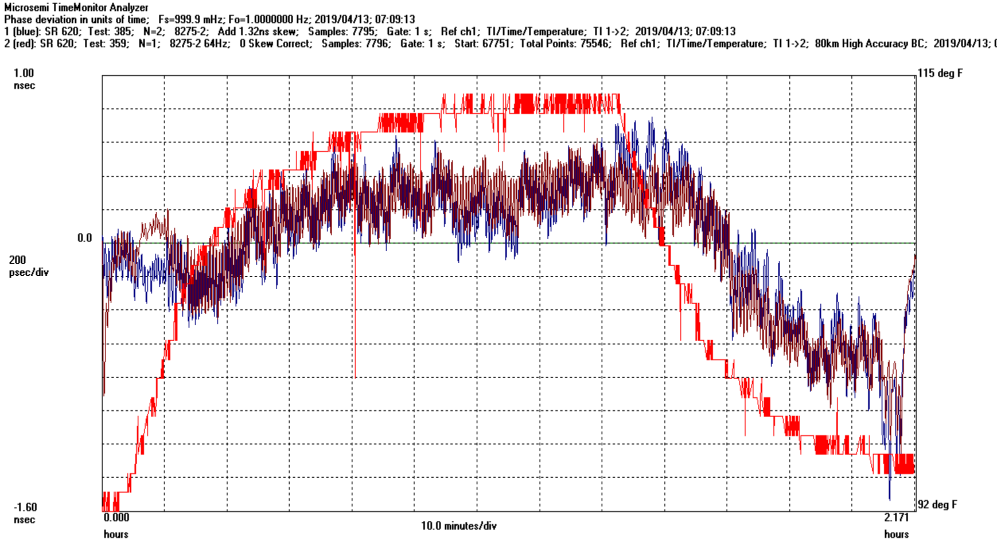
Key Observations:

- Time Error graph include 0.1 Hz proposed filter
- Measured MAX|TE| = 1.7 ns well within 5 ns Class D requirement.
- This test includes both the high accuracy BC and 85 km of fiber optic link which is not required to pass Class D!
- TDEV stability characteristic is shown below. Floor is 30 ps.



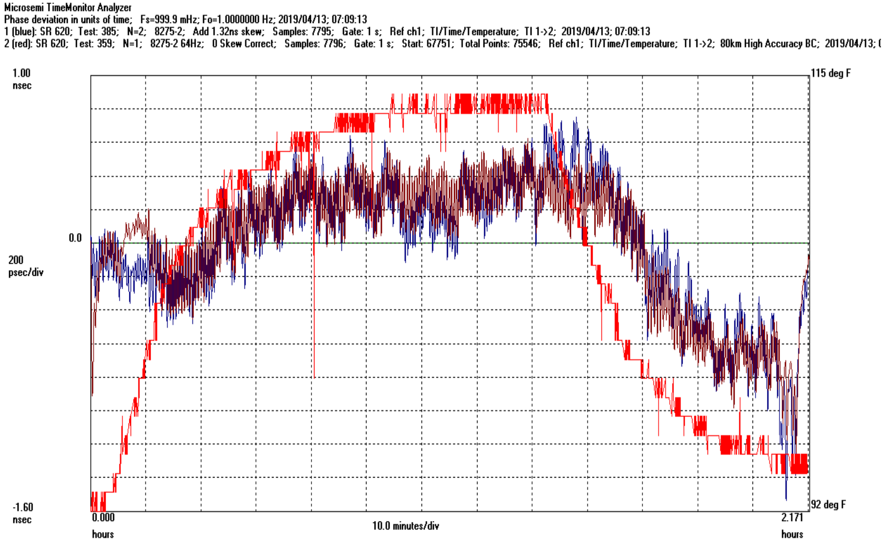
Resilient Operation in Thermal Environment

A distributed heat source is coupled top of the unit under test and supply 50W heat loading for 1 hour and then removed.
The red graph shows the 12.8 degree rise and fall of the chassis temperature.
The PPS outputs of the clock directly heated (blue) and the next clock in the chain (light red) are observed.



Resilient Operation in Thermal Environment (Continued)

The rate of change of the temperature exceeds anticipated rates.
The observed steady state change in delay is nominally 600 ps (there is an overshoot seen in the falling temperature related to loop dynamics. The effective temperature sensitivity is 50 ps/C based on the test results.
Note that we see effectively the same effective on the unit under stress (first BC in the chain) as well as the next unit down.



Chain of Boundary Clocks Operation

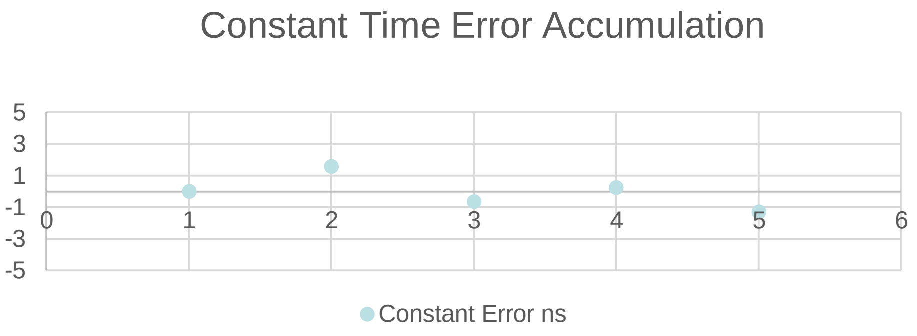
Objective: to observe the time error accumulation over a chain of High-Performance Boundary Clocks:

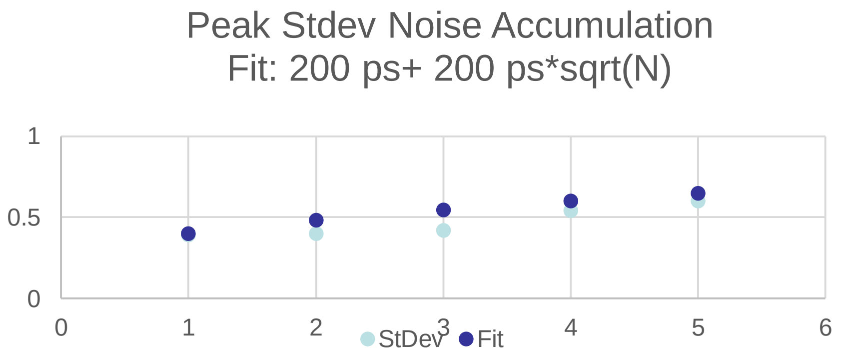
The path is supported with:

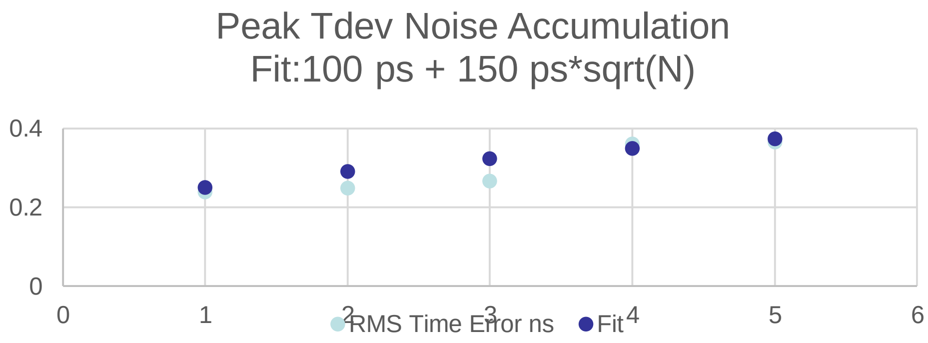
- High-Performance Boundary Clock key parameters:
  - OCXO (SC cut)
  - 1 ns Multiphase Clock Sampling Technique
  - G8275.1(16 Hz) and G8275.2(64 Hz) (With OCXO results are essentially equivalent)
  - 33 ps controlled phase stepper-based synthesizer
- Path originates with a PRTC level GM clock
  - GM clocks has same 1 ns Multiphase Clock Sampling Time Stamper.
  - GM is driven by GNSS simulated ideal signal that is locked to the house timescale.

Chain of Boundary Clocks Operation

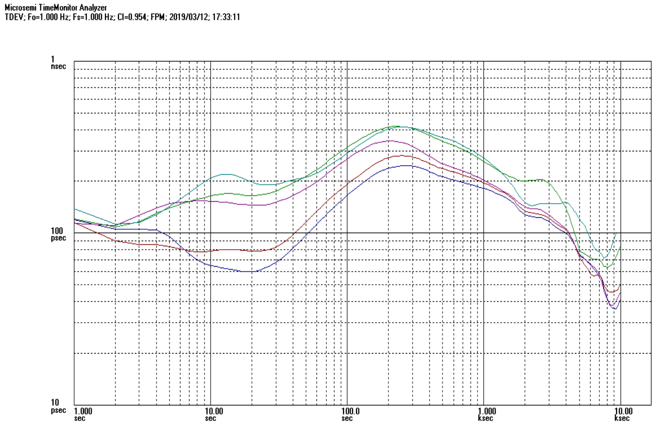
- No appreciable growth in constant time error.
- Dynamic noise accumulation shows modest growth well bounded by sqrt(N) bound.
- Class D performance maintained over 6 nodes.



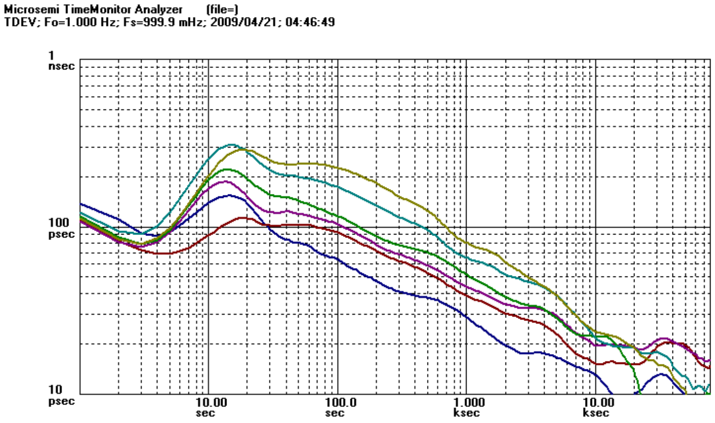




Chain of High-Performance Boundary Clocks TDEV Stability



March 2019 TDC

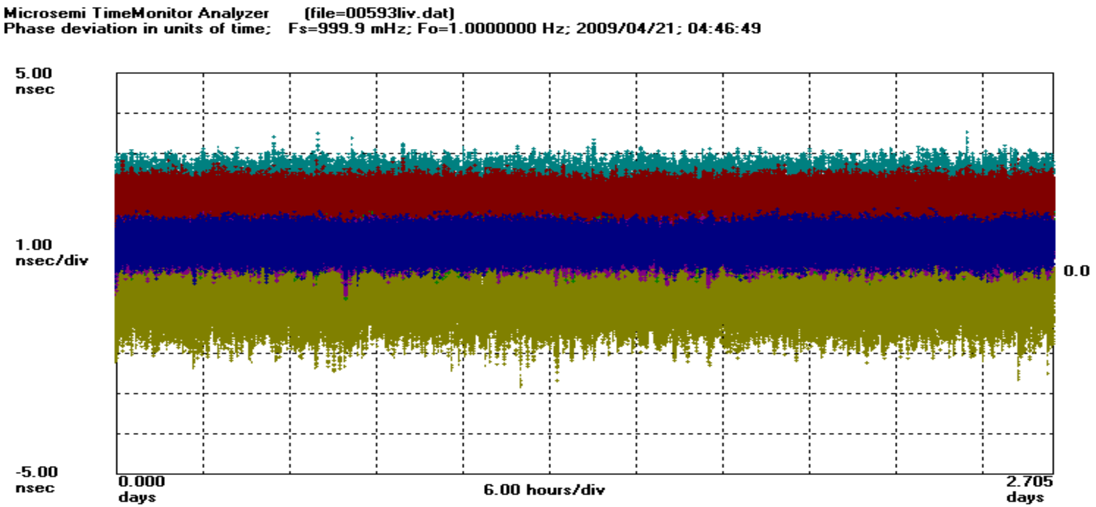


September 2019 TDC

Observations:

- The overall stability performance for the entire chain of clocks is better than 1 ns.
- The same test was repeated with our improved TDC system (September 2019) showing significant improvement (~4 dB).

Chain of High-Performance Boundary Clocks September 2019



Observations:

September 2019 TDC

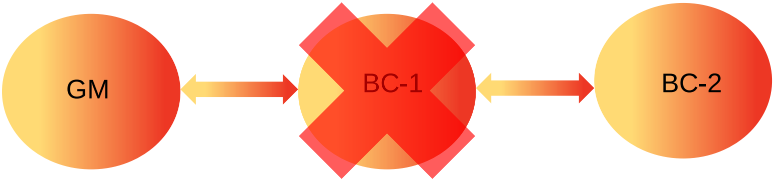
- The scatter plot shows the time error for each of the six clocks in the chain (blue is the first, green the last).
- Not only does the first clock in the chain (blue) meet the class D 5 ns requirement but the entire chain meets Class D performance for a single clock!

Chain of High-Performance BCs Failure Scenario Loss of Node

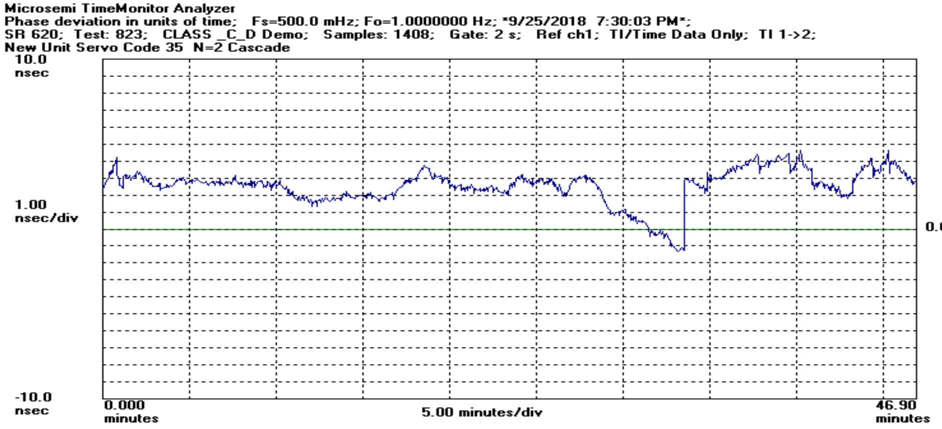
- PRTC GM provides a direct fiber connection to BC-1
- BC-1 provides a direct fiber connection to BC-2.

Procedure:

- Warmup for nominally 30 minutes
- Remove power for 30 seconds from BC-1 and then restored.

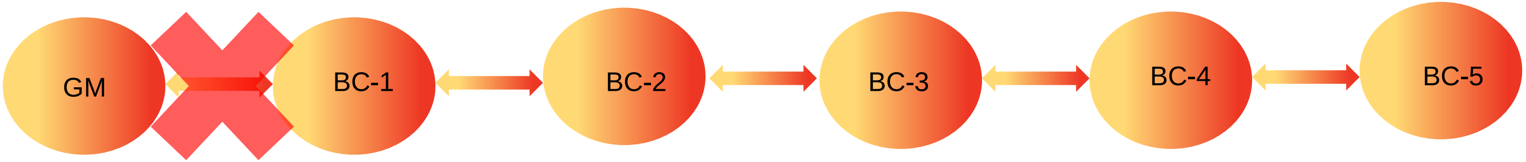


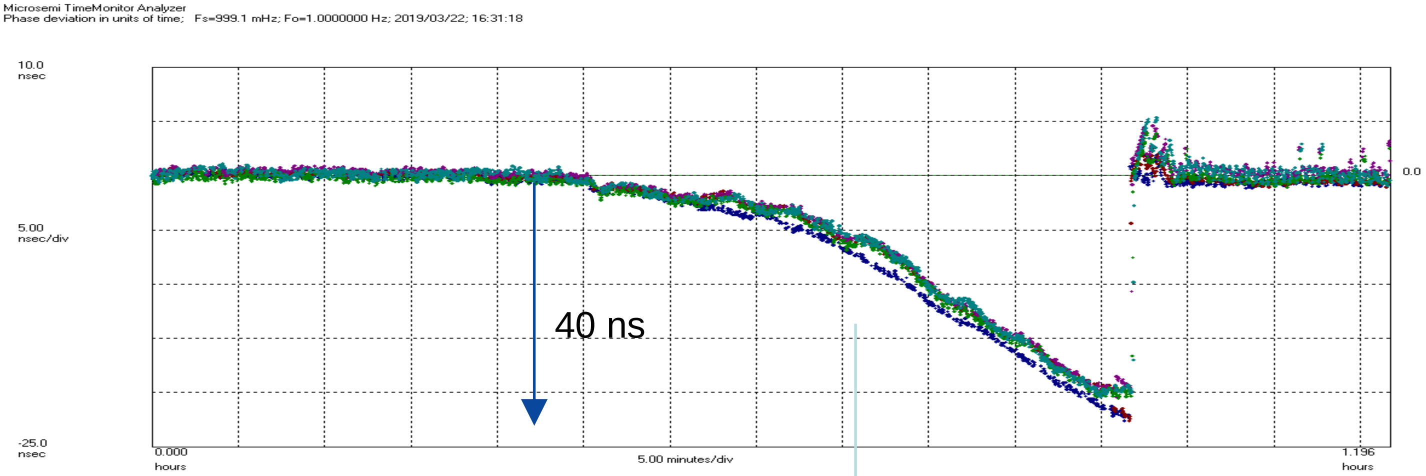
The timing performance of BC-2 is observed during this failure scenario. The external time error graph starts about ten minutes prior to the power cycle fault introduced at BC-1. Keep in mind that this is the output of the second boundary clock in the chain so strictly speaking the Class D limits do not directly apply. Also the constant time error is not corrected in this test. The high-performance BC is able to maintain these accuracy limits in this test case.



Chain of High-Performance BCs Failure Scenario Loss of Link

In this test the fiber link is disconnected to BC-2 through BC-6 and then reattached nominally 30 minutes later.





Summary

1. Resilient High Accuracy operation of a Chain of Boundary Clocks requires that all operational areas of stress be properly addressed.
2. Reliable sub-nanosecond Time to Digital Conversion accuracy is already being achieved without Layer 1 extensions such as White Rabbit.
3. Fiber optical path asymmetry (chromatic dispersion) can be addressed well within Class D proposed requirements.
4. Operational Issues such as Fiber and Node Loss and Intermittent effects are addressable with proper "loosely coupled" design.