Timing, Synchronization and Software-Generated Beam Control at FRIB

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Introduction

- FRIB will require hundreds of devices throughout the linac to operate using synchronized timestamps and triggering events
- Accurate fault timestamps and time-dependent diagnostic measurements are accomplished with facility-wide fiber timing system
- Stable time is maintained using a GPS-disciplined 1pps Rubidium oscillator and distributed over the facility network via Network Time Protocol (NTP) and Precision Time Protocol (PTP)
- Complex and varying beam pulse patterns are accomplished using software-generated 'beam scheduling'

Timing Architecture

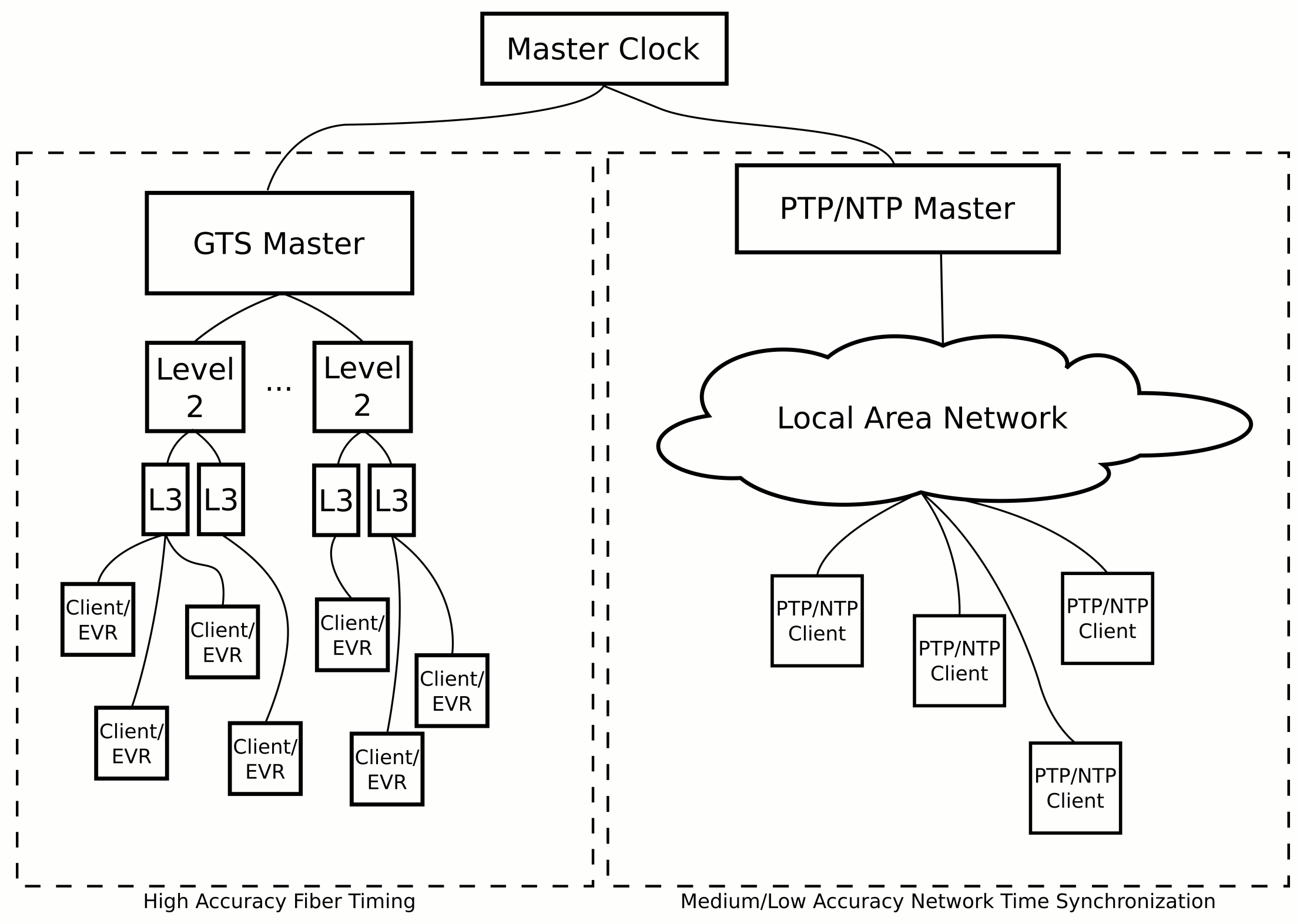


Figure 1: FRIB timing network topology. Phase-sensitive diagnostic devices such as faraday cups utilize the high-precision fiber timing, while networked devices requiring less accuracy (~10 μs) use NTP or PTP, if supported.

- Grandmaster consists of commercial off-the-shelf GPS receiver with NTP/PTP capability and 1 PPS output
- Global Timing System (GTS) Master consists of Micro Research Finland CPU card and Event Generator
- Level 2 nodes distribute events to level 3 nodes; some directly connected to a few client devices
- Level 3 nodes connect exclusively to client devices in their operating area, transmitting events and timestamps
- Devices not capable of, or requiring fiber timing may synchronize their onboard clocks using older but widely-supported NTP, or less-supported and more accurate PTP

Time Synchronization

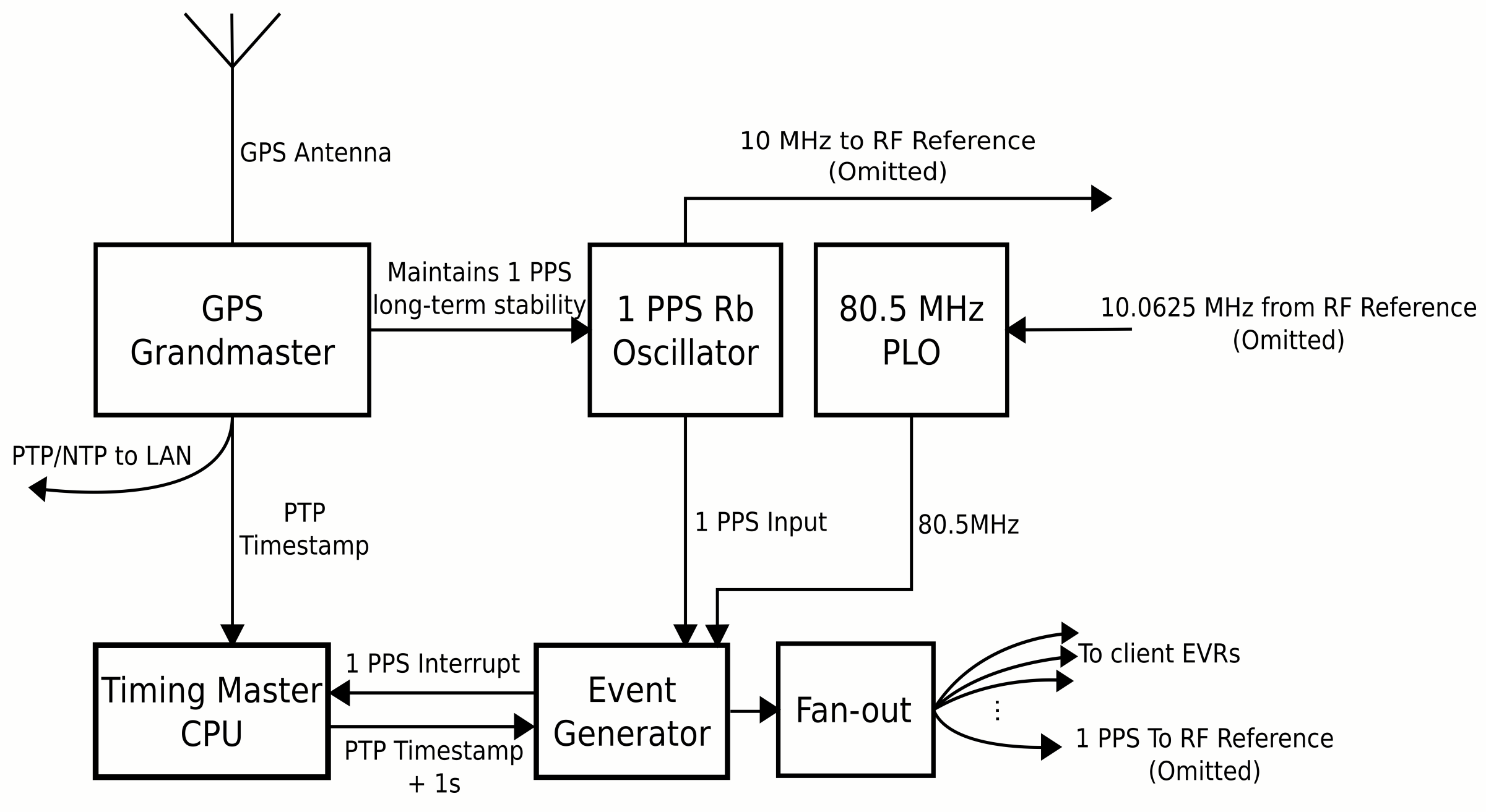
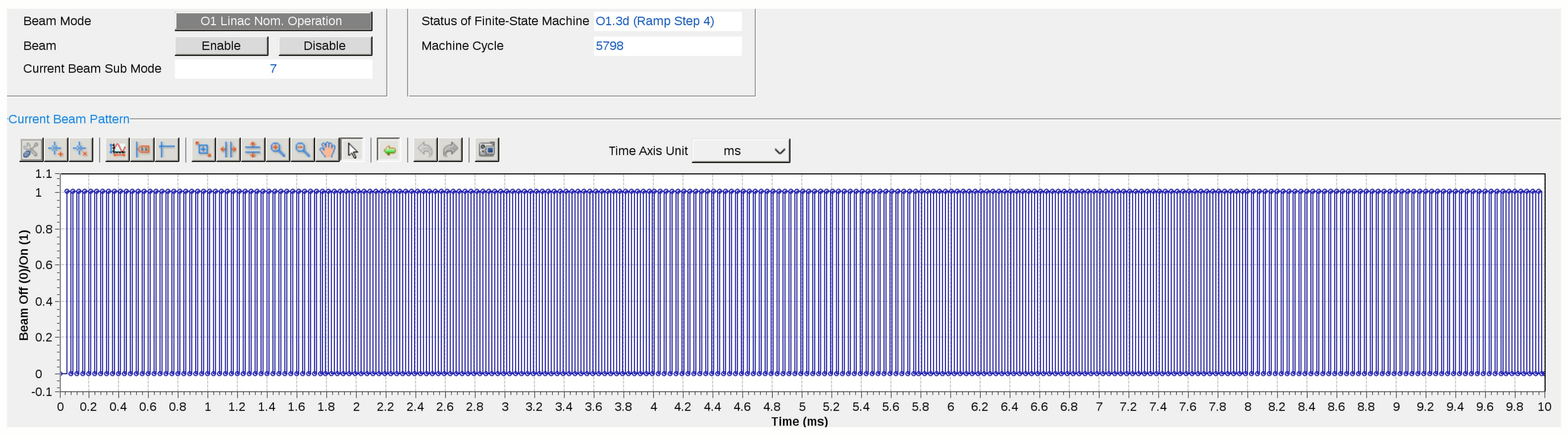


Figure 2: A detailed schematic of the timing master synchronization design. The Rubidium oscillator and RF signal provide exact 1-second ticks and an 80.5 MHz event carrier signal in phase with the rest of the machine.

- Event clock is closed loop with global RF reference
- 1 PPS Rb oscillator is wired to EVG, which triggers heartbeat/start-of-second event, and interrupt on CPU
- Oscillator also provides stable 10MHz output to 10.0625 reference clock
- CPU provides incremented PTP timestamp for attachment to event stream
- Fan-outs broadcast fiber event stream to any number of clients

Software-generated Beam Control


Beam Mode: O1 Linac Nom. Operation

Beam: Enable Disable

Current Beam Sub Mode: 7

Status of Finite-State Machine: O1.3d (Ramp Step 4)

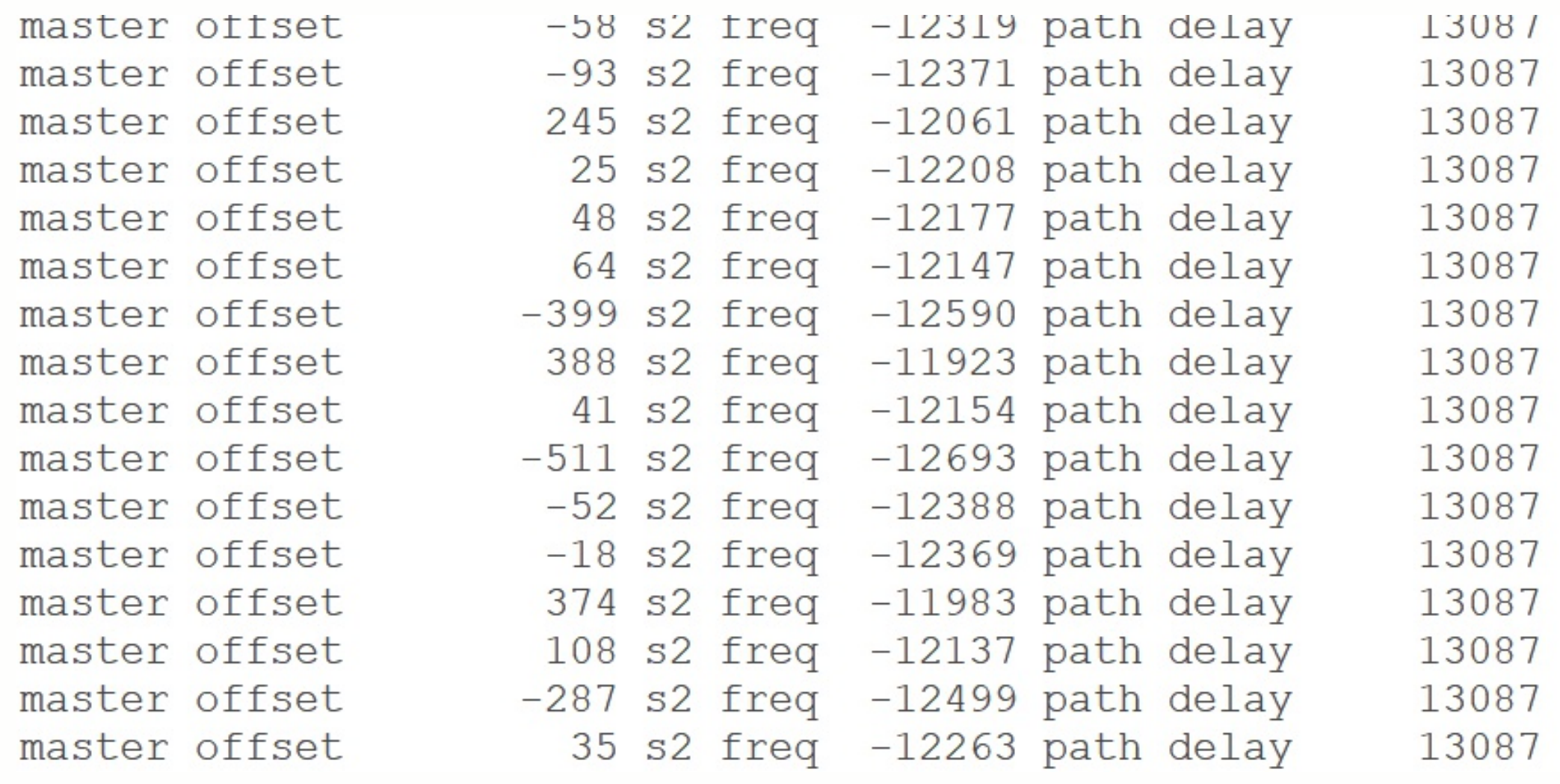
Machine Cycle: 5798

Time Axis Unit: ms

Figure 3: 'Beam scheduling' operator interface. Time scale in pictured graph is 1 machine cycle, equal to exactly 10 ms. 9 operating modes, some with variable pulse width, are defined for different beam power and use cases.

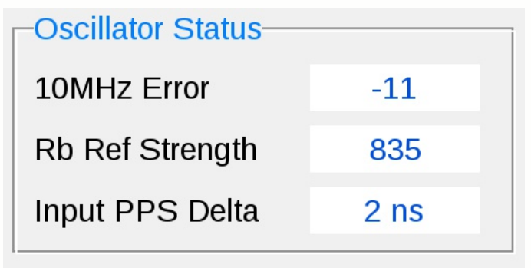
- Broad options for beam pattern are possible with software beam scheduling
- Beam pattern is loaded into hardware in 10ms 'machine cycles', consisting of event code and timestamp arrays
- Designed to be fail-safe: beam is guaranteed to turn off after 1 machine cycle if events stop transmitting for any reason

Performance



```
master offset         -58 s2 freq  -12319 path delay     13087
master offset         -93 s2 freq  -12371 path delay     13087
master offset         245 s2 freq  -12061 path delay     13087
master offset          25 s2 freq  -12208 path delay     13087
master offset          48 s2 freq  -12177 path delay     13087
master offset          64 s2 freq  -12147 path delay     13087
master offset        -399 s2 freq  -12590 path delay     13087
master offset         388 s2 freq  -11923 path delay     13087
master offset          41 s2 freq  -12154 path delay     13087
master offset        -511 s2 freq  -12693 path delay     13087
master offset         -52 s2 freq  -12388 path delay     13087
master offset         -18 s2 freq  -12369 path delay     13087
master offset         374 s2 freq  -11983 path delay     13087
master offset         108 s2 freq  -12137 path delay     13087
master offset        -287 s2 freq  -12499 path delay     13087
master offset          35 s2 freq  -12263 path delay     13087
```

Figure 4: Excerpt of PTP logging on a test machine with hardware timestamping support. Timestamping error from master is shown after 'master offset' in nanoseconds. In a 1-minute sample from this time frame, the machine reported a mean error of 2.43 ns, with a standard deviation of 232.6 ns.


Oscillator Status

10MHz Error	-11
Rb Ref Strength	835
Input PPS Delta	2 ns

Figure 5: Rubidium oscillator statistics (Error in Hz)

Start-of-cycle Timing	SoC Min	10.000 msec
	SoC Max	10.000 msec
	Tics Per Second	80500000

Figure 6: Diagnostic EVR receiving 10.000 ms machine cycles and 80.5MHz event carrier

- Sub-μs network timestamping accuracy achieved between PTP-aware PHYs, even if network equipment is not PTP-aware
- Fiber timing provides machine cycles at exactly 100 Hz, with 80.5MHz event clock required by diagnostics equipment
- 400+ devices currently utilizing fiber event link

Challenges

- Central timing master results in single failure point - redundancy greatly increases cost
- In practice, 100Hz machine cycle rate aliases out 5th harmonic of 60Hz line noise, making it impossible to filter from diagnostic measurement
- Fiber hardware tends to be more delicate than fiber - have lost connections to single client devices
- Our fiber distribution chassis power supplies are prone to getting very hot and failing prematurely; however, they are inexpensive and redundant
- Not all network hardware is PTP-aware, this precludes some nicer features of PTP such as peer-to-peer delay negotiation
- Not all PTP-capable hardware supports attaching timestamps on PHY; software timestamping reduces accuracy from <1 μs to <100 μs offset

Hardware Diagram

Figure 7: Timing master hardware. 1) GPS/PTP/NTP grandmaster, 2) 1 PPS/10MHz Rb oscillator, 3) cPCI CPU card running real-time Linux kernel, 4) Master event generator with 1 PPS and 80.5MHz inputs, 5) Fan-out distribution to facility; yellow cables are 10Gb/s single-mode fiber, cyan cables are 1Gb/s multi-mode.

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