Time Transfer in a Wide Area White Rabbit Network

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White Rabbit

- Timing & Control of the LHC @ CERN: Deterministic data transfer and accurate clock synchronization
- Open Hardware & Software
- Up to 10 km link length
- < 1ns time offset between more than 1000 nodes

![Diagram](link)

**Problem** | **Solution**
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$k_A = k_B$ syntonization | Synchronous Ethernet at 1.25 GPS
$b_A = b_B$ synchronization | Precision Time Protocol (PTP) + DMTD

“I’m late, I’m late, for a very important date! No time to say hello, goodbye…”
White Rabbit Algorithm

(Step 0: SyncE provides syntonized clocks)

Step 1.
Hardware time-stamping of $t_1$-$t_4$
Gives coarse (8 ns) RTT


delay\_coarse = (t_4 - t_1) - (t_3 - t_2)

Step 2: Enhance $t_2$, $t_4$
With a phase-measurement

- Syntonization and physical layer calibration
- Measure coarse delay = PTP
- Measure phase
- Add phase information to PTP timestamps $t_2$, $t_4$
- Calculate one-way delays and offset
- Steer slave clock
- Measure phase

Phase tracking
Phase measurement using DMTD = Dual Mixer Time Difference

FPGA Implementation in WR-node

\[ f_{PLL} = \frac{N}{N+1} f_{dKA} \]

\[ 124.99 \text{ MHz} \]

\[ 125 \text{ MHz} \]

\[ \sim 10 \text{ kHz} \]

[T. Włostowski]
Fiber asymmetry not known beforehand, must be calibrated

\[ n^2(\lambda) = 1 + \frac{B_1 \lambda^2}{\lambda^2-C_1} + \frac{B_2 \lambda^2}{\lambda^2-C_2} + \frac{B_3 \lambda^2}{\lambda^2-C_3} \]

\[ \alpha = \frac{\delta_{ms}}{\delta_{sm}} - 1 = \frac{n_{1550}}{n_{1310}} - 1 \]

+680 ppm, typically

- New SFPs claim up to 160 km reach (with new bidir-amplifiers even further)
- White Rabbit works with duplex (two-strand) SFPs also
Many point-to-point links: WR Network

WR Node:
- SFP + FPGA + FMC front-end
- Open hardware
- Open firmware/software
Espoo-Kajaani time-transfer experiment in FUNET

- 1000 km Espoo-Kajaani light-path in FUNET
- 10% of fiber is in DCF spools
- Duplex (two-strand) SFPs on ITU-T #60 (196 THz)
- GrandMaster node in Espoo locked to UTC(MIKE)

Details on FUNET fiber-spans and amplifiers not shown. Information available from CSC on request.
Independent verification by GPS-PPP

1. Receivers colocated, common-clock calibration (5 days)
2. Receivers at Espoo/Kajaani, Fiber-asymmetry calibration (1 day)
3. Data collection (100 days)
Initial problems with 8 ns RTT jumps
Link operation started 2013 September

Collaborative testing during 2013 autumn allowed WR-team at CERN to produce firmware that copes with 10.4 ms RTT and eliminated "8ns jump" problems

RTT varies strongly with temperature:
- Seasonal +/- 200 ns or more
- Daily +/- 50 ns in spring/autumn
- WR asymmetry parameter is ca. -800 ppm (uplink is 4 us shorter than downlink)
Link Error vs. Round-Trip-Time

![Graph](image)

- **cold (-15 C)**
  - 2 ns
  - 100 days

- **warm (+20 C)**
  - 200 ns

Network Maintenance!

**alpha** = 788 ppm (before maintenance)
**alpha** = 849 ppm (after maintenance)
Time Deviation

WR Link Error, Time Deviation, Updated 2014-01-31T07:34Z

- WR(Espoo-Espoo)
- WR_PPP(Espoo-Kajaani)
- BIPM TWSTFT(NIST-PTB)
- BIPM TWSTFT(OP-PTB)
- TTTOF_PPP(Braunschweig-Hannover), 73km
- TTTOF(Braunschweig-Hannover), 73km
- UTC(TP)-UTC(IPE), 550km

Long-haul, limited by GPS-PPP instability
Short-haul common-clock
Outlook / Challenges

1. Short-term stability

- Improve PLL between external clock and GM-node
- PLL tuning between Master and Slave
- Better local-oscillator (OCXO) on SPEC (?)

2. Measuring fiber-asymmetry

Reverse asymmetry by:
- Exchanging Tx/Rx fibers (two-strand)
- Exchanging Tx/Rx wavelengths (single-strand)
[Huang, China Mobile]

3. Additional Phase-servo inputs
  e.g. Temperature (Fiber, DCFs, Nodes)

4. Fiber-Fiber comparisons
   Not limited by satellite technique
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