Synchronization for Interferometry through White Rabbit

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White Rabbit
Interferometry
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White Rabbit

White Rabbit is an open source (OHWR) project to distribute accurate timing and deterministic control traffic. It originated at CERN as an effort to improve and simplify the LHC beam control. It offers 1 ns accuracy, and much better stability.

It makes use of some COTS Ethernet parts, and several existing networking standards:
- Synchronous Ethernet (SyncE)
- Precision Time Protocol (PTP)
- Bi-directional use of single fiber (1Gbase-BX10 SFP, 1310 nm / 1490 nm)
- Carries regular Ethernet data traffic as well

WR is now also part of PTP (IEEE 1588-2019) as High Accuracy Profile
A WR link transports the input 10 MHz clock, and PPS, and TIA
- Compensates for the unknown, and variable, delay in the fiber
- System measures the RTT at ps resolution
- Before use: Calibrate out all the fixed delays ($d_{TX}$, $d_{RX}$)
- Removing the fixed delays leaves the fiber RTT
- Dispersion calibration: $\alpha = v_g(\lambda_s)/v_g(\lambda_m) - 1$
- WR calculates the one-way fiber delay, and corrects for it
Interferometry

The science (and art) of measuring the amplitude and phase structure over a field, in order to reconstruct the incoming wavefront, and from that an image of the source. In radio astronomy we use arrays of antennas, and measure the phase difference between each pair of receptors. Phase is usually measured against a reference phase at each of the antennas.

Left: Very Large Array (Image: NRAO)

Right: Square Kilometre Array (Image: SKAO)
Interferometry

- Over integration time $\tau$, calculate complex cross correlation on all baselines:
  \[ f \star g = \int_\tau \bar{f} \cdot g \]
- Inverse 2D transform, advanced imaging methods
- Sky brightness distribution (i.e. image)

SagA*, EHT Collaboration
Coherence and Coherence Loss

Given one perfect sinusoid, and one with phase noise $\varphi(t)$,

$$V_a(t) = V_0 \cos 2\pi \nu_0 t$$

$$V_b(t) = V_0 \cos(2\pi \nu_0 t + \varphi(t))$$

The coherence $C$ over an integration time $T$ due to phase error $\varphi(t)$

$$C(T) = \left| \frac{1}{T} \int_0^T e^{i\varphi(t)} \, dt \right|$$

Coherence Loss

$$L_C(T) = 1 - \sqrt{\langle C^2(T) \rangle}$$

Coherence loss results in reduced sensitivity

SKA1 design limit: $< 2\%$ coherence loss (clock distribution)

B. Alachkar e.a., Frequency Reference Stability and Coherence Loss in Radio Astronomy Interferometer Applications for the SKA

Journal of Astronomical Instrumentation, DOI 10.1142/S2251171718500010
Calculating Coherence

Assuming stationarity, Gaussian phase noise: Express clock behaviour as Allan Variance $\sigma_y^2(\tau)$

$$\langle C^2(T) \rangle = \frac{2}{T} \int_0^T \left(1 - \frac{\tau}{T}\right) e^{-\left(\pi \nu_0 \tau\right)^2 \left[\sigma_y^2(\tau) + \sigma_y^2(2\tau) + \sigma_y^2(4\tau) + \cdots\right]} \text{d}\tau$$

Analytic solutions for two cases:

- **White Phase Noise**: ADEV slope $= -1$ (AVAR slope $= -2$)
  $$\lim_{k \to \infty} \sum_{n=0}^{k} \left(\frac{1}{4}\right)^{-n} = \frac{4}{3} \quad \Rightarrow \quad L_C = 1 - \sqrt{e^{-h_2 f_h \nu_0^2}}, \quad \sigma_y^2(\tau) = \frac{3 h_2 f_h}{(2\pi)^2 \tau^2}$$

- **White Frequency Noise**: ADEV slope $= -\frac{1}{2}$ (AVAR slope $= -1$)
  $$\lim_{k \to \infty} \sum_{n=0}^{k} \left(\frac{1}{2}\right)^{-n} = 2 \quad \Rightarrow \quad L_C(T) = 1 - \sqrt{\frac{2(e^{-aT} + aT - 1)}{a^2 T^2}}, \quad a = \pi^2 \nu_0^2 h_0$$
Clock Characterization: Allan Deviation (fractional frequency stability)

Flicker and White Phase Noise
slope = -1

White Frequency Noise
slope = -1/2

Flicker Frequency Noise, slope = 0

Frequency Drift
slope = 1

Random Walk
slope = 1/2

ADEV: $\sigma_y$

AVAR: $\sigma_y^2$

$\tau$ (s)

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Interferometry through White Rabbit
GNU Radio Days 2023, Paris 9 / 16
Due to phase lock, ADEV slope stays at -1

Graph: ADEV, 50Hz ENBW
Red: Standard White Rabbit
Blue: White Rabbit + Low Jitter Daughterboard
Green: above, + clean-up oscillator
Brown: two free-running clean-ups
Grey: System noise floor

van Tour & Koelemeij, ngVLA memo #22
Coherence Loss (%)
Observing Frequency $\nu_0$

WR
WR-LJD

2% loss
$\sigma_y(1s) = 2 \times 10^{-11}$
$\sigma_y(1s) = 2 \times 10^{-12}$
Connecting your SDR to WR

- Your atomic clock: 10 MHz and PPS rising edge is aligned to UTC
- Your SDR, and WR switch:
  - PPS indicates that the next 10 MHz edge starts the second
  - PPS must be stable during the 10 MHz edge
- Setup time: PPS signal must be stable $T_S$ ns before clock edge
- Hold time: PPS signal must stay stable $T_H$ ns after the clock edge
- If these are violated: wrong data in Flip Flop, or even metastability
- Ettus publishes (published?) these with their devices. So does WR.
- Delay the 10 MHz signal by a few ns, using a few m of coax.
- Don’t simply use the falling edge of the 10 MHz or 1 PPS!
Extending White Rabbit

- Original spec: 1Gbase-BX10 optics, 10 km reach, 1310 nm / 1490 nm
- Links can be cascaded a few times
- 80 km reach BiDi optics: 1490 nm and 1550 nm (less attenuation)
- Higher dispersion (17 ps/nm/km) and longer links
  - Wavelength drift (e.g. temperature) causes timing offsets
- Solution: use stabilized (DWDM) optics, COTS
  - With external diplexers to use single fiber link
- Built a 35 km dark fiber link
- And a 169 km WR link, running over existing SURFnet DWDM network
  - Uses out-of-band wavelengths for WR
  - Uses bi-directional Silicon Optical Amplifiers
  - Co-exists with production 100 G network traffic
Extending White Rabbit: The ASTERICS Project

C. van Tour, ASTERICS Deliverable 5.7, 5.14
- Observing 3C84 for 90 minutes
- At 1330 MHz
- Dwingeloo and WSRT
- Using WSRT H-maser via WR
- SNR > 200
- Same ADEV for 35 km and 169 km
- Two separate observations
- Diverges for $\tau > 300$ s, due to ionosphere
Conclusions

- White Rabbit is a useful way to distribute a reference clock for interferometry
- For signals up to 2.5 GHz - with LJD up to 25 GHz
- For distances up to at least 169 km, likely much longer
- Can co-exist with other fiber users
- Successful VLBI observations using 35 km and 169 km links