White Rabbit Calibration

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Outline

• WR link delay model
• Why and what to calibrate?
• Calibration procedure with hands-on
• Summary
WR link delay model

• fixed hardware delays: $\Delta_{TxM}, \Delta_{RxM}, \Delta_{TxS}, \Delta_{RxS}$
  • FPGA delay
  • PCB traces and components delay
  • Optical transceiver delay
• bitslides: $\epsilon_M, \epsilon_S$
• fiber propagation delays: $\delta_{MS}, \delta_{SM}$
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PTP synchronization

• PTP assumes that the link is symmetric:
  \[ \text{delay}_{MS} = \text{delay}_{SM} = \frac{1}{2} \text{delay}_{MM} \]

• PTP calculates clock offset using a one-way delay value:
  \[ \text{offset}_{MS} = t_1 - t_2 + \text{delay}_{MS} \]
Why to calibrate?

- Any non-compensated link asymmetry affects the clock offset calculation
- We need to characterize the total link asymmetry
- Only then WR can reach sub-nanosecond accuracy

If you don’t need sub-nanosecond timing, Just take default calibration values published on our wikis.
WR link asymmetries

- **Hardware asymmetry**
  - $\Delta_{TxM} \neq \Delta_{RxM}$
  - $\Delta_{TxS} \neq \Delta_{Rxs}$

- **Fiber asymmetry**
  - $\delta_{MS} \neq \delta_{SM}$

- **Different bitslides**
  - $\epsilon_{M} \neq \epsilon_{S}$

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What to calibrate?

• Fixed hardware delays ($\Delta_{Tx}, \Delta_{Rx}$)
• Fiber asymmetry coefficient

\[ \alpha = \frac{\delta_{MS} - \delta_{SM}}{\delta_{SM}} \]

• Bitslide is excluded from the calibration
• Is measured by the Phy (SerDes wrapper)
• Its exact value is known on each link up
Calibration methods

• **Relative calibration**
  • Defines a model for fixed hardware delays
  • Based on values calculated by PTP and 1-PPS skew measurement
  • All devices in a WR network calibrated to a single WR Calibrator
  • Calibration parameters published with stable firmware releases
    • [https://www.ohwr.org/projects/white-rabbit/wiki/Calibration](https://www.ohwr.org/projects/white-rabbit/wiki/Calibration)

• **Absolute calibration**
  • Measures the actual values of fixed hardware delays
  • Doesn’t require “golden calibration”
  • Work in progress
    • [https://www.ohwr.org/projects/wr-calibration/wiki](https://www.ohwr.org/projects/wr-calibration/wiki)
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Relative calibration

• Selects one WR device as a calibrator for the whole network
• Assumes the calibrator is symmetric ($\Delta_{TX} = \Delta_{RX}$)
• $\Delta_{TX}, \Delta_{RX}$ measured for WR devices contains also the calibrator asymmetry

• The calibrator’s asymmetry factor cancels
• ... provided two synchronizing WR devices were calibrated to the same WR calibrator.
Relative calibration steps

1. Reference fiber latency measurement
2. WR Calibrator pre-calibration
3. WR device calibration
4. Fiber asymmetry coefficient
Before we start...

The values of all parameters ($\Delta_{TX}$, $\Delta_{RX}$, $\alpha$) have to be configured to 0 for the WR Calibrator and all WR devices that will be calibrated.

All calculations in the calibration procedure are done using the round-trip-delay after subtracting the bitslide values:

$$delay'_{MM} = delay_{MM} - \varepsilon_M - \varepsilon_S$$
1. Reference fiber measurement

• Read the PTP round-trip delay for each of the setups

• Calculate the latency for both fibers:
  \[ \delta_1 = \text{delay}'_{MM3} - \text{delay}'_{MM2} \]
  \[ \delta_2 = \text{delay}'_{MM3} - \text{delay}'_{MM1} \]
2. WR Calibrator pre-calibration

• Two WR devices of the same hardware and gateware version

• Assuming the calibrator is symmetric, calculate its fixed hardware delays:

\[
\Delta_{Tx} = \Delta_{Rx} = \frac{(delay_{MM} - \delta_1)}{4}
\]

• Write these delays to the WR Calibrator configuration
3. WR device calibration

- Calculate the coarse fixed delay for the WR device:

  \[ \Delta_c = \frac{1}{2} (\text{delay}_{MM} - \Delta_{TxM} - \Delta_{RxM} - \varepsilon_S - \delta_1) \]

- Write it to the WR device configuration as \( \Delta_{Tx} \), \( \Delta_{Rx} \)

- Restart synchronization with the new values.
3. WR device calibration

• Measure 1-PPS skew

• Calculate final Tx and Rx delays for the WR device:
  \[ \Delta_{Tx} = \Delta_c - skew_{PPS} \]
  \[ \Delta_{Rx} = \Delta_c + skew_{PPS} \]
Remote configuration of WR node

- SNMP requests can be used to update the calibration values
  - `SNMP_OPT="-c public -v 2c -m WR-WRPC-MIB -M \n   +/var/lib/mibs/ietf:lib 192.168.1.20"

- Read the SFP database
  - `snmpwalk $SNMP_OPT wrpcSfpTable`

- Update the values in the database
  - `snmpset $SNMP_OPT wrpcPtpConfigDeltaTx.0 = <value>`
  - `snmpset $SNMP_OPT wrpcPtpConfigDeltaRx.0 = <value>`
  - `snmpset $SNMP_OPT wrpcPtpConfigApply.0 = \n    writeToFlashCurrentSfp`

- Restart PTP daemon to use new values
  - `snmpset $SNMP_OPT wrpcPtpConfigRestart.0 = restartPtp`
4. Fiber asymmetry coefficient

- Measure 1-PPS skew for short and long fiber synchronization
- Calculate $\alpha$ for the long fiber: $\alpha = \frac{2(\text{skew}_{PPS2} - \text{skew}_{PPS1})}{\frac{1}{2}\delta_2 - (\text{skew}_{PPS2} - \text{skew}_{PPS1})}$
- Convert $\alpha$ to a natural number representation for the WR PTP Core:
  $$\alpha_N = 2^{40} \left( \frac{\alpha + 1}{\alpha + 2} - \frac{1}{2} \right)$$
Remote configuration of WR node

- SNMP requests can be used to update the calibration values
  
  ```
  SNMP_OPT="-c public -v 2c -m WR-WRPC-MIB -M 
  +/var/lib/mibs/ietf:lib 192.168.1.20"
  ```

- Update the value of $\alpha$ in the database
  
  ```
  snmpset $SNMP_OPT wrpcPtpConfigAlpha.0 = <value>
  ```

- Restart PTP daemon to use new values
  
  ```
  snmpset $SNMP_OPT wrpcPtpConfigRestart.0 = restartPtp
  ```
Calibration is done!
Summary

- You don’t need to calibrate when start playing with WR
- We publish calibration values for WR Switch firmware and WR Node reference designs

- You need to calibrate when making your own WR node
- The whole WR network has to be calibrated to the same WR calibrator to ensure sub-nanosecond synchronization

https://www.ohwr.org/projects/white-rabbit/wiki/Calibration
Backup
Recovering the calibrator

- Calculate the coarse fixed delay for the WR device:
  \[ \Delta_c = \frac{1}{2} (\text{delay}_{MM} - \Delta_{TXM} - \Delta_{RXM} - \Delta_{RXS} - \delta_1) \]
- Measure 1-PPS skew
- Calculate final Tx and Rx delays for the new WR Calibrator:
  \[ \Delta_{TX} = \Delta_c - \text{skew}_{PPS} \]
  \[ \Delta_{RX} = \Delta_c + \text{skew}_{PPS} \]
\(\alpha\) for a deployed fiber

- It’s problematic to measure 1-PPS skew
- Use any other fiber link for 1-PPS transmission

\[
skew_{PPS} = \frac{1}{2} (skew_{PPS1} + skew_{PPS2})
\]