White Rabbit Switch Calibration

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CERN

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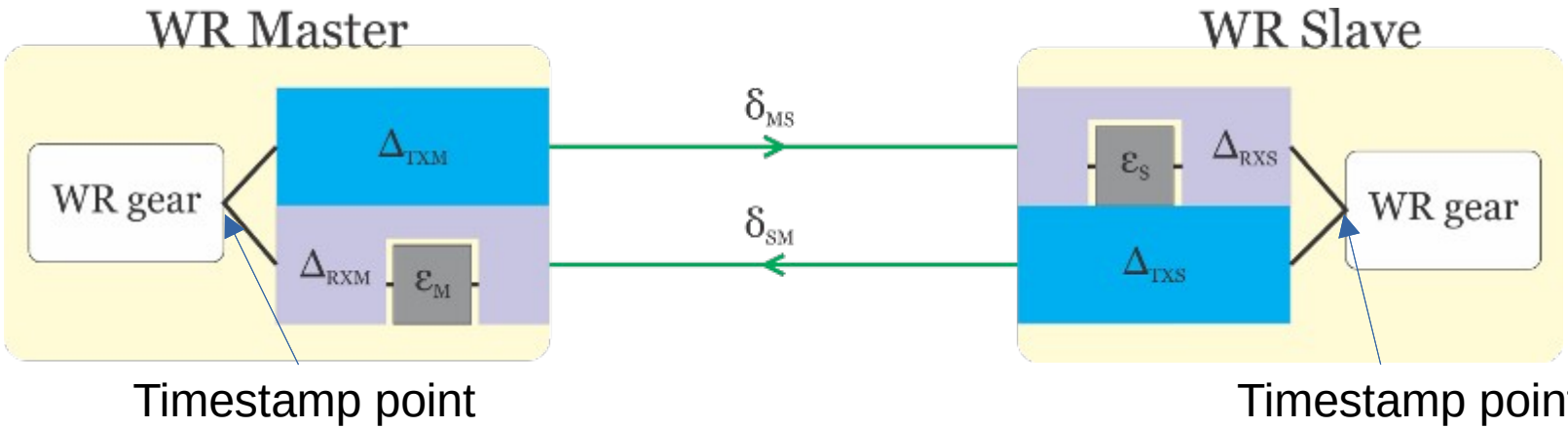
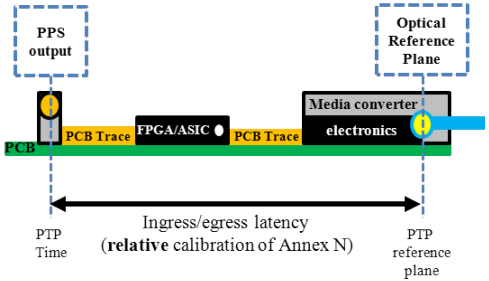
Collaboration

Calibration overview

- Do I need to calibrate my devices?
- It depends…
- WR devices should provide sub-ns accuracy out-of-the-box
- But one could use not officially support equipment (e.g., SFP)
- If better accuracy is needed then calibration may be required
  - WR switch
  - SFP modules
  - Fibers (also add/drop filters)
    - DelayAsymmetry (difference in ps) two fibers
    - delayCoefficient (difference as unit-less) one fiber
  - Coaxial cables

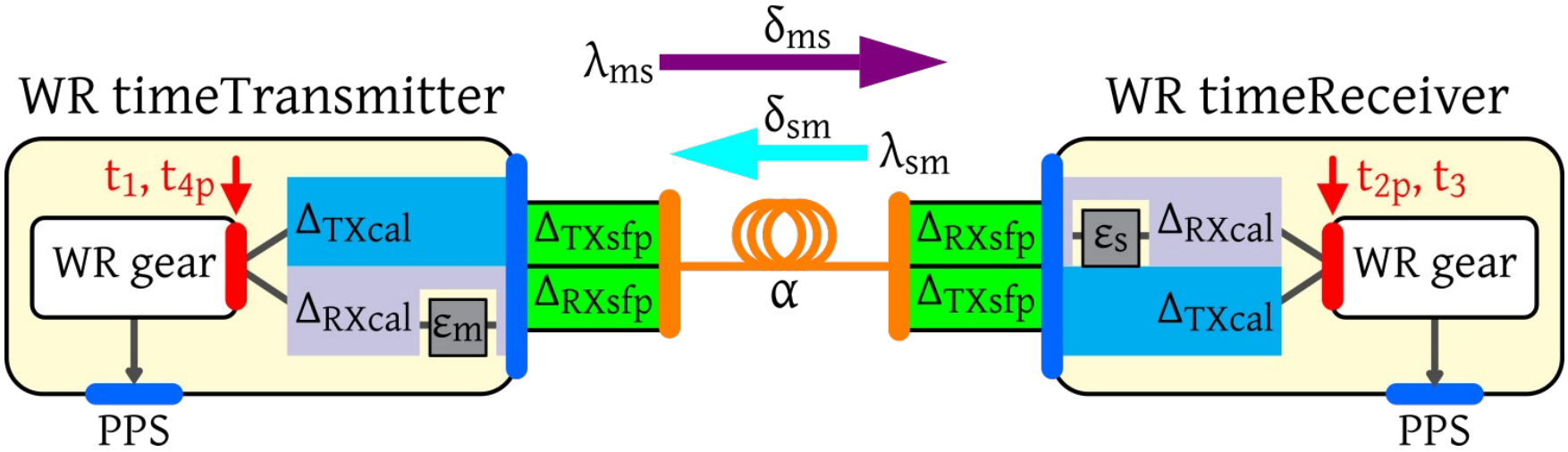
Link model





- δ_{MS} and δ_{SM} deepens on fiber length and used wavelength
- Difference in fiber length can be avoided with using single fiber
- For LPDC ports ε_m and ε_s (bitslide) are equal 0

Mapping of parameters to dot-config



- $(\delta_{MS}-\delta_{SM})/\delta_{SM}$ is alpha (delayCoefficient) stored in
  - CONFIG_PORT01_FIBER=0
  - CONFIG_FIBER00_PARAMS="alpha_1310_1490=0.0002743"
- Δ_{TXsfp}, Δ_{RXsfp} as tx=X, rx=Y in CONFIG_SFP00_PARAMS="vn=Axcen Photonics,pn=AXGE-3454-0531,vs=AX12390009629, tx=0,rx=0,wl_txrx=1490+1310"
- Δ_{RXM}, Δ_{RXS} – PORTXX_INST01_INGRESS_LATENCY
- Δ_{TXM}, Δ_{TXS} – PORTXX_INST01_EGRESS_LATENCY
- For LPDC ports ε_m and ε_s (bitslide) are equal 0, otherwise are read in runtime from HW

SFP database matching

- Why needed? To get relative calibration values of SFPs RX and TX
  - For absolute calibration, values will be read from SFPs EEPROM (see SFF-8472, rev 12.4.2)
- Entries in dot-config like:
  CONFIG_SFP00_PARAMS="vn=Axcen Photonics,pn=AXGE-3454-0531,vs=AX12390009629,
  tx=0,rx=0,wl_txrx=1490+1310"
  - vn – vendor name
  - pn – product name
  - vs – vendor serial
  - tx,rx – relative TX, RX delays (they may be negative!)
  - wl_txrx – TX and RX wavelengths in nm
- VN, PN, VS, TX wavelength are read from SFP's EEPROM
- Matching order:
  - TX wavelength, PN, VN, VS
  - TX wavelength, PN, VN
  - TX wavelength, PN
- After match, deltas are taken from tx= and rx=

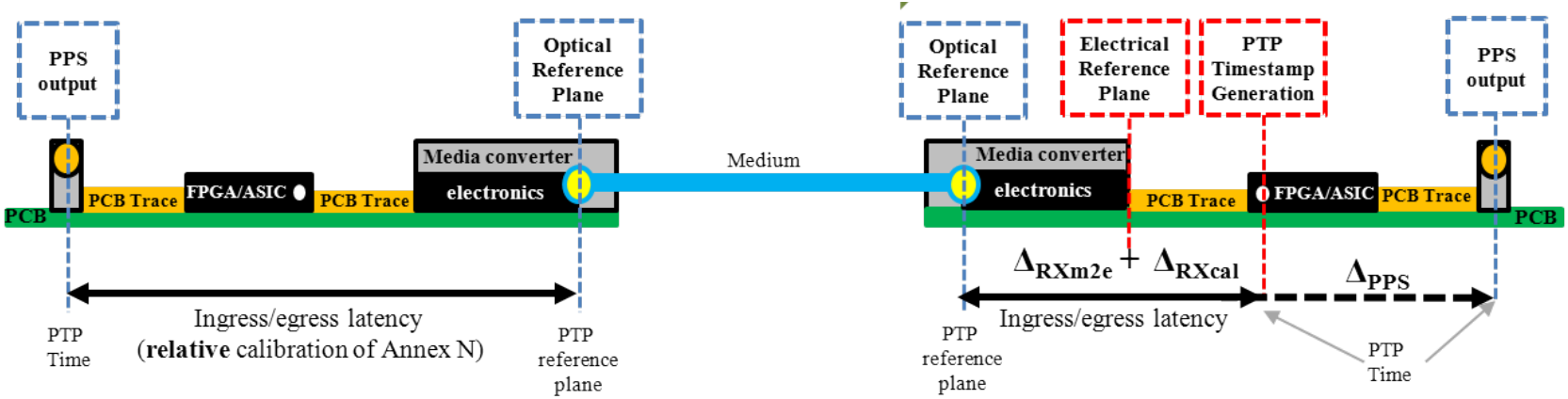
Fiber database matching

- Why needed?
  - To get delayCoefficient (alpha) of a fiber
  - Fiber has no memory that can store this value
- Entries in dot-config like:
  CONFIG_PORT01_FIBER=0
  CONFIG_FIBER00_PARAMS="alpha_1310_1490=0.0002743"
- Port has to define which fiber type is used (marked with gray)
- For matching alpha_XX_YY, values of XX and YY are taken from wl_txrx parameter of SFP DB entry. Like:
- CONFIG_SFP00_PARAMS="vn=Axcen Photonics,pn=AXGE-3454-0531,vs=AX12390009629, tx=0,rx=0,wl_txrx=1490+1310"
- If alpha_XX_YY is not matched, swapped XX and YY is tried (alpha_YY_XX)

Note alpha in the opposite direction is not -alpha, but: $\frac{1}{1+alpha}-1$ which is equivalent to: $-\frac{alpha}{1+alpha}$

Relative calibration

- Unable to measure all delays separately
- Use of the arbitrary value works pretty well



Golden calibrator

- Created once
- Kept as a reference for other devices
- Possible to create another Golden calibrator from original one (local Golden calibrator
- WR switch is not enough, needs pair of golden SFPs

- Can use independent golden calibrator
  - Device calibrated with one will show offset when connected to another

Calibration

Getting measurements

- Delays
  - wr_mon (try different options)
  - wrs_dump_shmem
- Oscilloscope/Time Interval Counter
  - PSS level at 850mV
- Make average over some time
- Be aware about temperature variations

Before starting the calibration

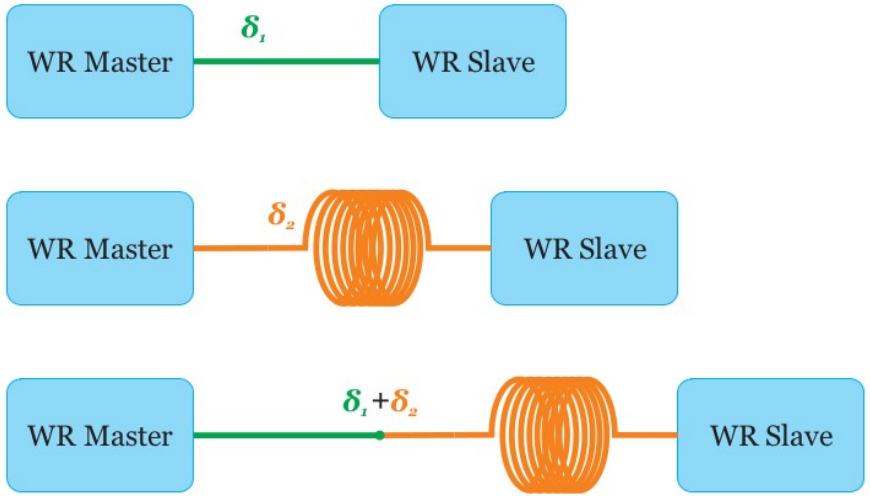
- Non-LPDC (13-18) ports can have up to ~70ps offsets between WRS reboots/linkup
- Make sure used calibration values are for a proper WRS HW version
- Make sure equal lengths of cables are used when necessary
- Precise enough measurement devices are used (Oscilloscope, Time Interval Counter)

Equipment requirements

- Fibers
  - One short (few meters)
  - One long (few kilometers)
  - Adapter to connect two fibers
- WRS devices
  - Golden calibrator+device to be calibrated
  - Or two identical devices to make golden calibrator
- Two oscilloscope cables with the same length (or known lengths)
- Oscilloscope or Time Interval Counter
- Stable 1PPS and 10MHz source

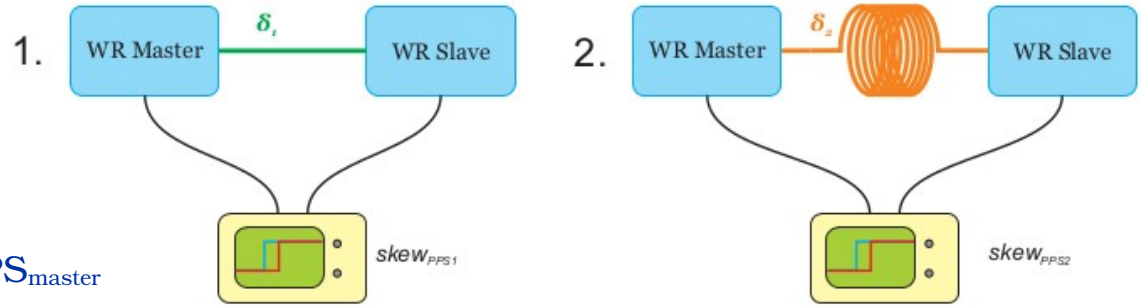
Reference fiber latency

- Set all delays and alpha to 0
  - PORT01_INST01_EGRESS_LATENCY=0
  - PORT01_INST01_INGRESS_LATENCY=0
  - CONFIG_FIBER00_PARAMS=""
- Measure $delay_{MM}$ of (e.g., read from wr_mon)
  - Short fiber ($delay_{MM1}$)
  - Long fiber ($delay_{MM2}$)
  - Short+long connected with adapter ($delay_{MM3}$)
  - For LPDC, bitslide can be skipped (is 0)
- $\delta_1 = delay_{MM3} - delay_{MM1}$
- $\delta_2 = delay_{MM3} - delay_{MM1}$



Fiber asymmetry

- Set all delays and alpha as 0
- Measure PPS skew of
  - Short fiber ($skew_{PPS1}$)
  - Long fiber ($skew_{PPS2}$)
  - Skew is positive if PPS_{slave} follows (right side) PPS_{master}



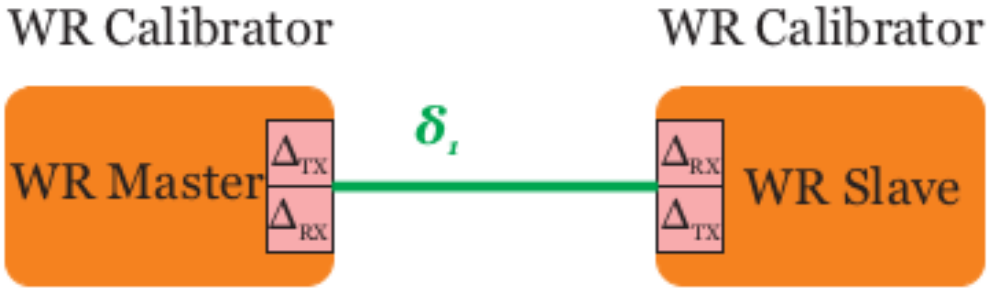
- Calculate α (delayCoefficient) with the formula:

$$\alpha = \frac{2(skew_{PPS2} - skew_{PPS1})}{\frac{1}{2}\delta_2 - (skew_{PPS2} - skew_{PPS1})}$$

  - Take δ_2 from Reference fiber latency calculations

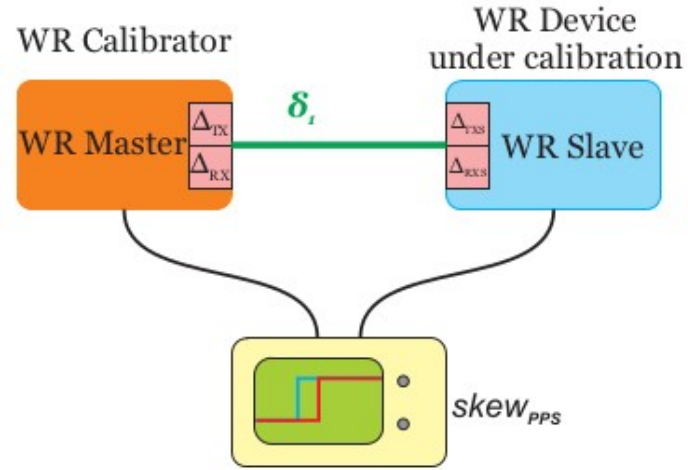
Calibrator pre-calibration

- Assume that both devices are identical
  - (We already know that SFPs used in both directions are different, but let's ignore it)
- $\Delta_{TXM} + \Delta_{RXM} = \Delta_{TXS} + \Delta_{RXS}$
- Then: $delay_{MM1} - \delta_1 = 2(\Delta_{TX} + \Delta_{RX})$
- When we assume that golden calibrator has no asymmetry
  - $\Delta_{RX} = \Delta_{TX}$
  - This assumption is why we have „relative calibration"
  - $delay_{MM1} - \delta_1 = 4(\Delta_{TX}) = 4(\Delta_{RX})$
  - In other words: $\Delta_{TX} = (delay_{MM1} - \delta_1)/4$



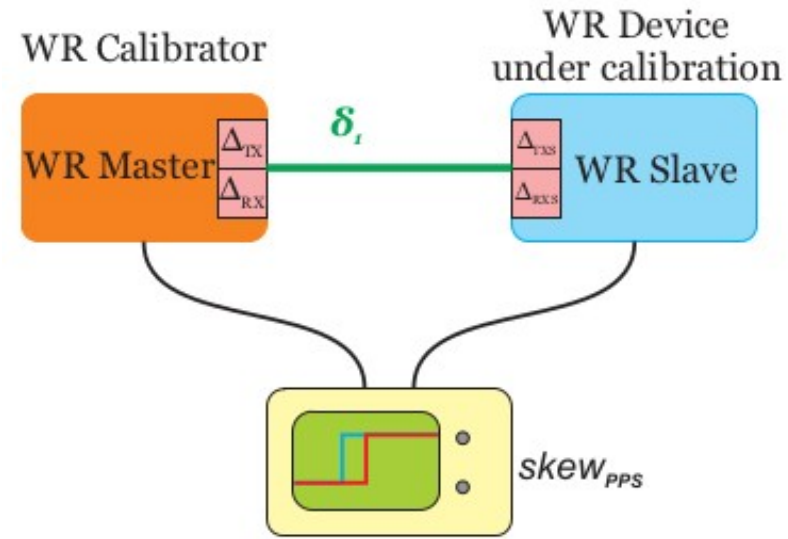
WR Device calibration

- Set delays on golden from “Calibrator pre-calibration”
- Set correct alpha measured in “Fiber asymmetry”
- Restart devices to apply changes
- Connect devices
- Read $delay_{MM}$ from slave
- Calculate: $\Delta_{TXS} = \Delta_{RXS}$
- $\Delta'_{TXS} = \Delta'_{RXS} = ½ * (delay_{MM} - \Delta_{TXM} - \Delta_{RXM} - \delta_1)$
- Save deltas on slave, restart it
- Measure $skew_{PPS}$ on oscilloscope and correct $\Delta'_{TXS} = \Delta'_{RXS}$
- Calculate:
  - $\Delta_{TXS} = \Delta'_{TXS} - skew_{PPS}$
  - $\Delta_{RXS} = \Delta'_{RXS} + skew_{PPS}$
- Save new values on slave, restart WRS
  - Repeat measurement of $skew_{PPS}$ and last calculation if needed (use Δ_{TXS} as Δ'_{TXS} and Δ_{RXS} as Δ'_{RXS})
- Repeat this slide for all ports



SFP calibration

- Keep the setup from the previous slide
- Measure $skew_{PPS}$ on oscilloscope
- Calculate:
  - Δ_{TXSfp} = - $skew_{PPS}$
  - Δ_{RXSfp} = $skew_{PPS}$
- Save new values on slave, restart WRS
  - Repeat measurement of $skew_{PPS}$ and last calculation if needed
    (subtract or add the new value of skewPPS to Δ_{TXSfp} and Δ_{RXSfp})

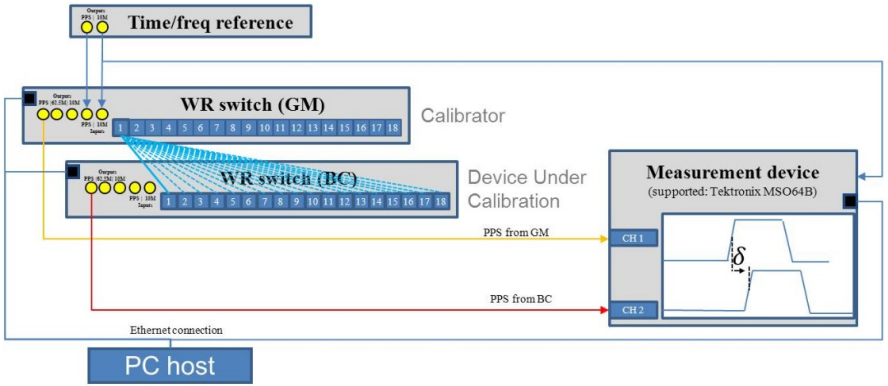


Calibration automation

- As today, only WR switch is supported (no node)
- Some steps can be automated
  - Data collection from measurement device
    - Supported Tektronix MSO64b and LeCroy WaveRunner 8104
    - More can be easily added
    - Possible manual input
  - Re-configuration of WR Switch
  - Calculations
- Needs some manual interactions, e.g., fiber changing

Calibration automation, requirements

- 2x WR Switch
  - One local calibrator
  - Or two the same to make golden calibrator
- Optional Oscilloscope (manual input supported)
  - Tektronix MSO64b
  - LeCroy WaveRunner 8104
- 1-2 fibers depends if golden calibrator is available
- Pair of SFPs
- PC with installed python to run script
- Optional time/freq reference to improve calibration



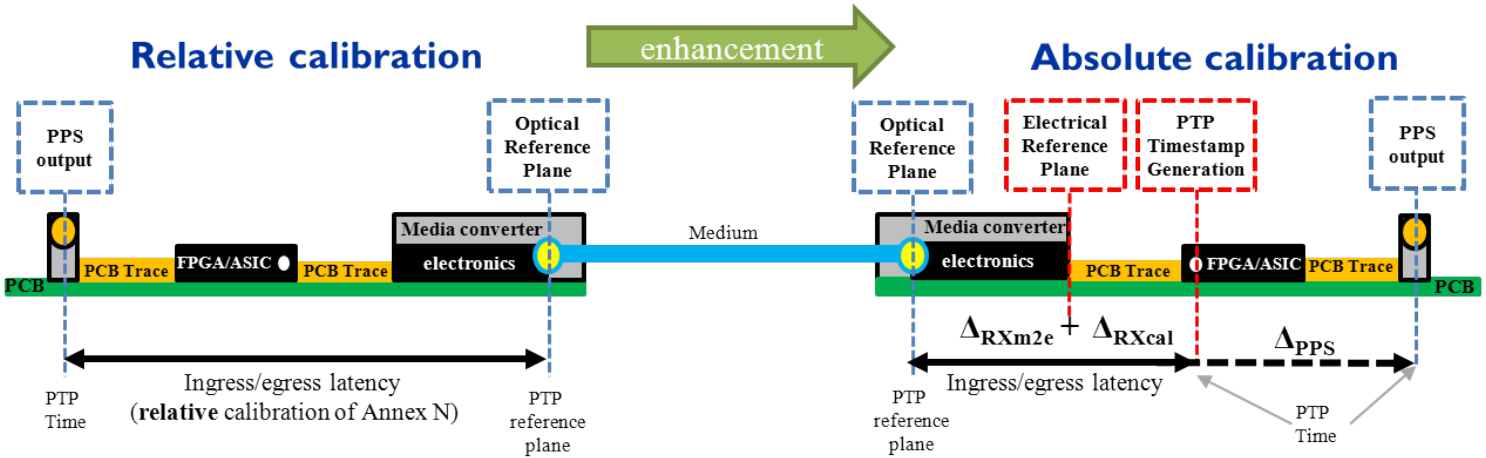
Calibration automation

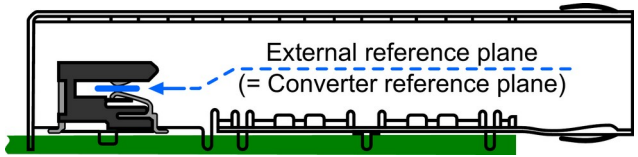
- Supported Calibration Scenarios
  - Full calibration
    - Create new calibrator
    - Calibrate against the new calibrator
    - Measure delays of reference fibers
    - Calculate delay asymmetry coefficient (alpha)
  - Partial calibration
    - Create new calibrator
    - Calibrate against the new calibrator
    - Provide delays of reference fibers
  - Normal calibration
    - Calibrate against already existing calibrator
  - Calibration of SFPs is included

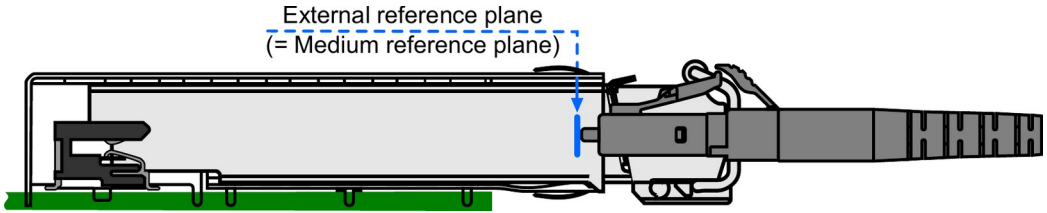
  - See https://ohwr.org/project/wr-switch-sw/-/tree/master/userspace/host_tools/calibration
  - wrs-user-manual Appendix 5
    https://ohwr.org/project/wr-switch-sw/-/wikis/uploads/d1f78666704fb292982453e1429b9f10/wrs-user-manual-v7.0.pdf

Absolute calibration (future)

- Electrical
- Electrical to Optical (SFP)
- In-situ Fiber calibration (as alternative to lab measurements)



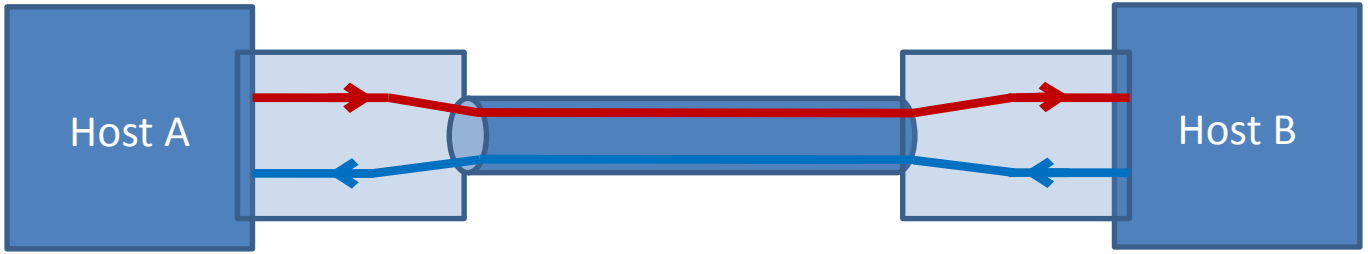




In-situ fiber calibration

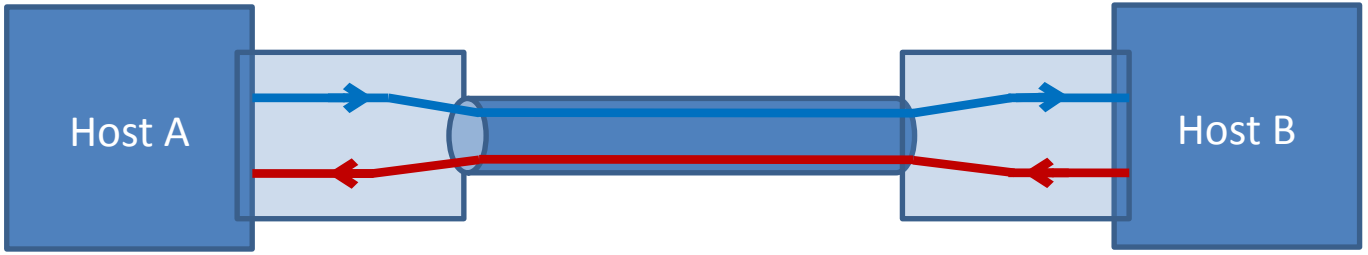
- Swapping of one-way delays

Step 1: Host A transmits with wavelength X, Host B with Y



Measure:
Clock offset against stable source d1

Step 2: Host A transmits with wavelength Y, Host B with X



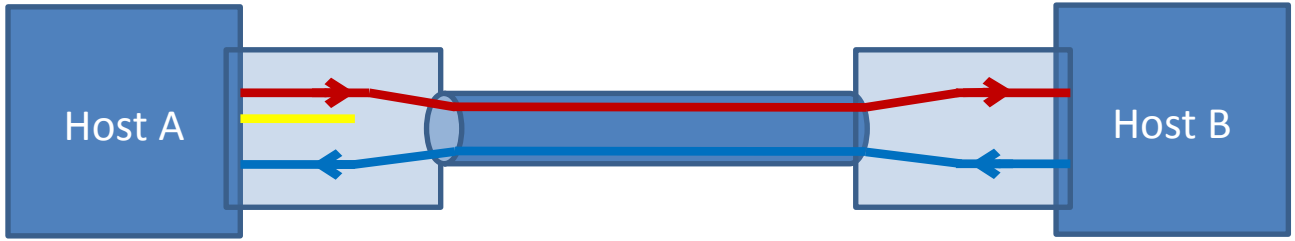
Measure:
Clock offset against stable source d2

(d2-d1)/2 is the delayAsymmetry

In-situ fiber calibration

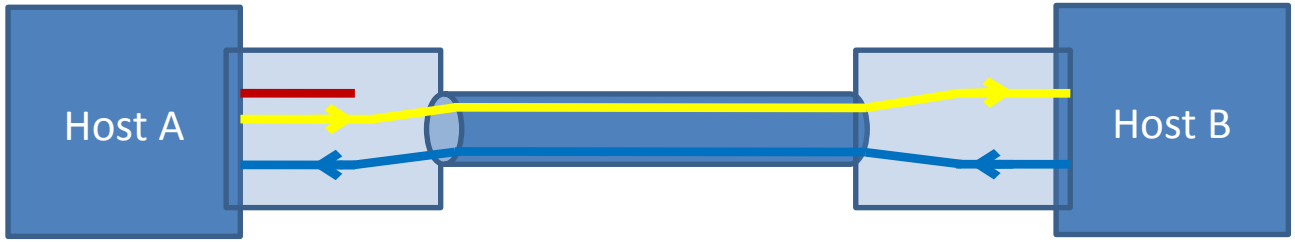
- Three one-way delays (with tunable SFP)
- Host B transmits with wavelength X all the time, Host A with a help of tunable SFP transmits two different wavelengths

Step 1: Host A transmits with wavelength Y1



Measure:
Round_Trip_Time1

Step 2: Host A transmits with wavelength Y2



Measure:
Round_Trip_Time2

Based on wavelength X, Y1, Y2, Round_Trip_Time1, Round_Trip_Time2 it is possible to calculate delayCoefficient (alpha) for X, Y1

Future work

- Characterize changes with temperature changes
  - delayCoefficient
  - Port delays
  - SFP delays
- Apply corrections in runtime

More info

WR Calibration procedure v1.1

https://ohwr.org/project/white-rabbit/uploads/76cdbdbadccc9d6c54d5caf246550fbf/WR_Calibration-v1.1-20151109.pdf

WR Calibration Application Note1:

https://ohwr.org/project/white-rabbit/-/wikis/uploads/11f29675590d6d62b296064bd4e87921/WR_Calibration-Application_Note_1_v0.4.pdf

WRS: User Manual, Appendix 5:

https://ohwr.org/project/wr-switch-sw/-/wikis/uploads/d1f78666704fb292982453e1429b9f10/wrs-user-manual-v7.0.pdf