White Rabbit PTP for NMI time and frequency dissemination

SYRTE Seminar

Namneet Kaur

24th October 2022

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1. Introduction to White Rabbit PTP (WR-PTP)

2. WR Calibration
   - Sources of propagation asymmetry
   - Calibration techniques

3. Long haul WR links for:
   - Scientific applications
   - Industrial applications

4. Summary

The need for Time and Frequency signals

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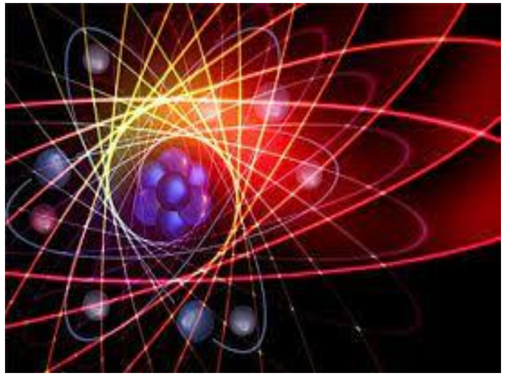
Telecom

Particle Accelerators

Radioastronomy

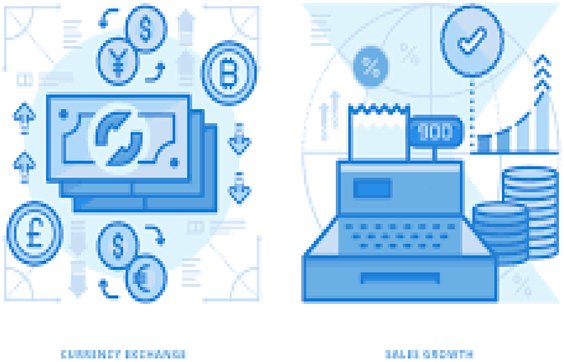
Quantum Technologies



Space

Navigation

Finance



Smart power grids

White Rabbit technology (WR-PTP)

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White Rabbit (WR) is a technology born at **CERN** which achieves **sub-nanosecond accuracy** in Ethernet based networks.

- Fully Deterministic low latency network.
- 10 years of expertise synchronizing large scientific facilities with WR.
- Validated by National Metrology Institutes (NMIs): VTT, OP, VSL, NIST, NPL, PTB, ROA, RISE…

CERN GSI Fermilab 50 Years of Discovery

Why White Rabbit?

- Based on open hardware and software
- Scalability to 1000s of nodes
- Cost effective
- Active WR community & adaptability to industry
- Standardization - High accuracy PTP profile (IEEE1588-2019)
- Impressive early results by NMI VTT, ADEV = $2x10^{-13}$@1000 s

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White Rabbit Add-ons to Precision Time Protocol (PTP):

Synchronous Ethernet (SyncE)

Digital Dual Mixer Time Difference (DDMTD)

Propagation asymmetry compensation

Sub-ns synchronization
< 1 ns !

Precision Time Protocol (PTP)

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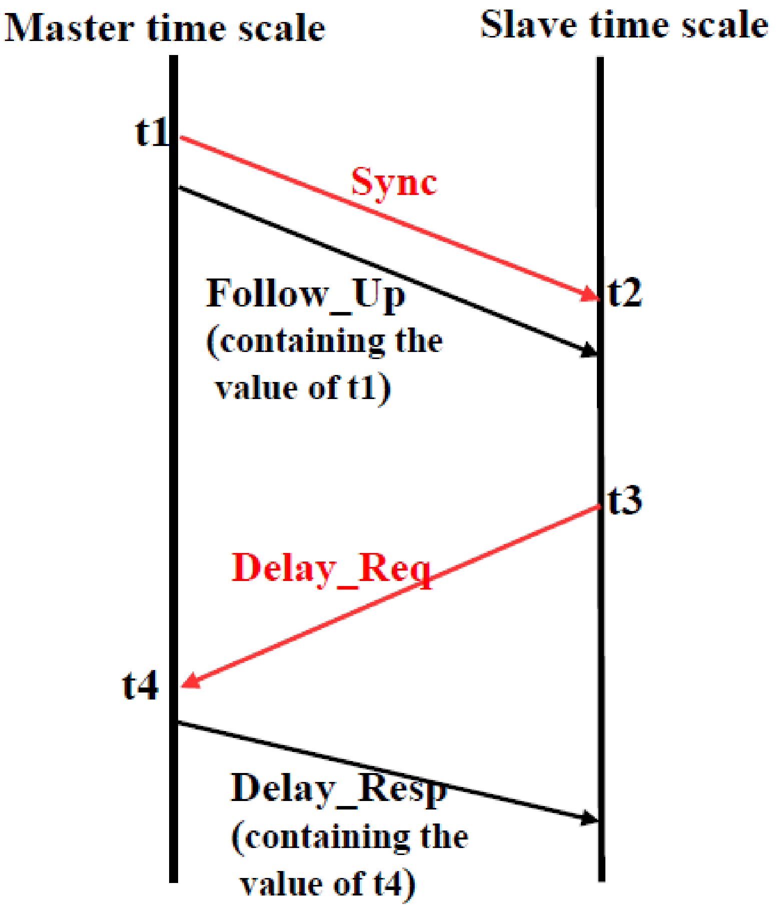
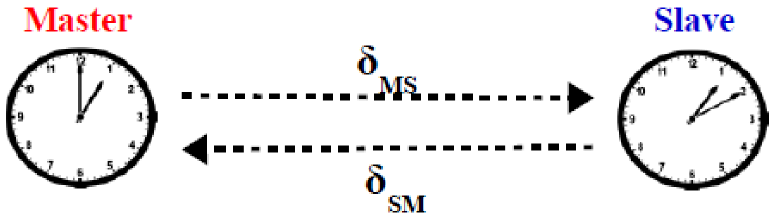
Two way time transfer technique





- Message exchange with transmission and reception timestamps.

$$\textit{Round trip time (RTT)} = (t2-t1) + (t4-t3)$$

$$\textit{Link latency } (\delta_{MS}) = RTT/2$$

$$\textit{Clock offset} = t2 - t1 - \delta_{MS}$$

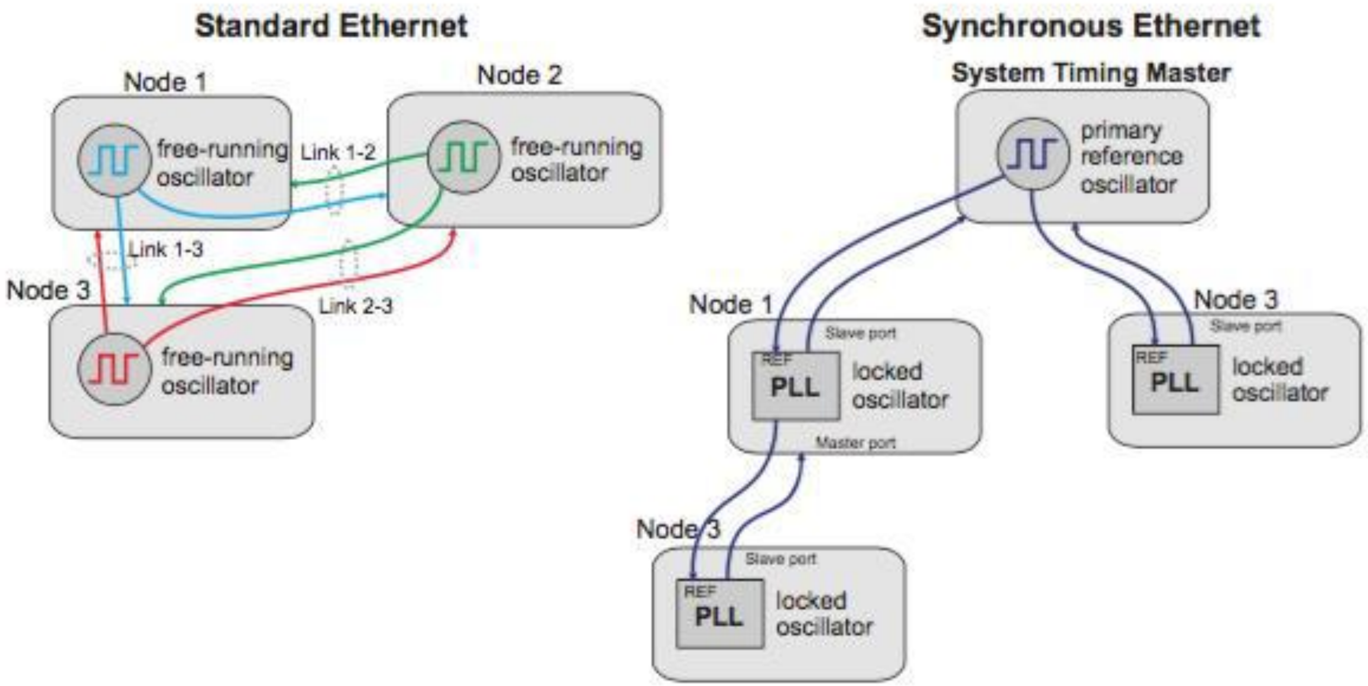
$$\textit{In case of asymmtery } (\delta_{MS} \neq \delta_{SM}):$$

$$\textit{error} = (\delta_{MS} - \delta_{SM})/2$$

- Instrumental delay asymmetries are taken into account.

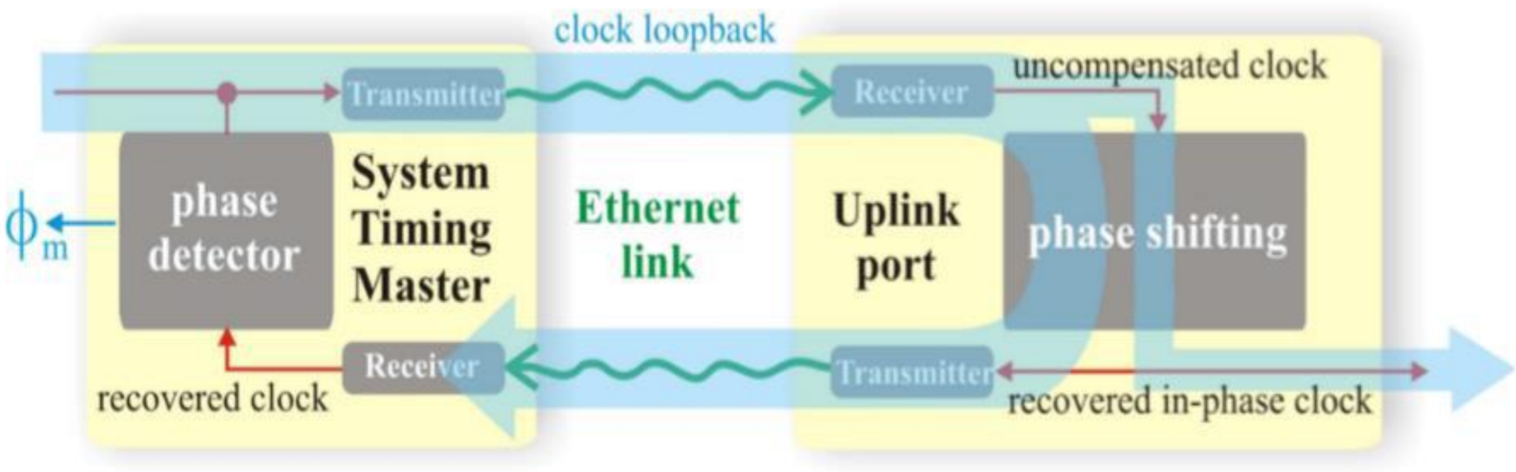
Synchronous Ethernet (Sync E)

A common clock frequency for the entire network - syntonization.



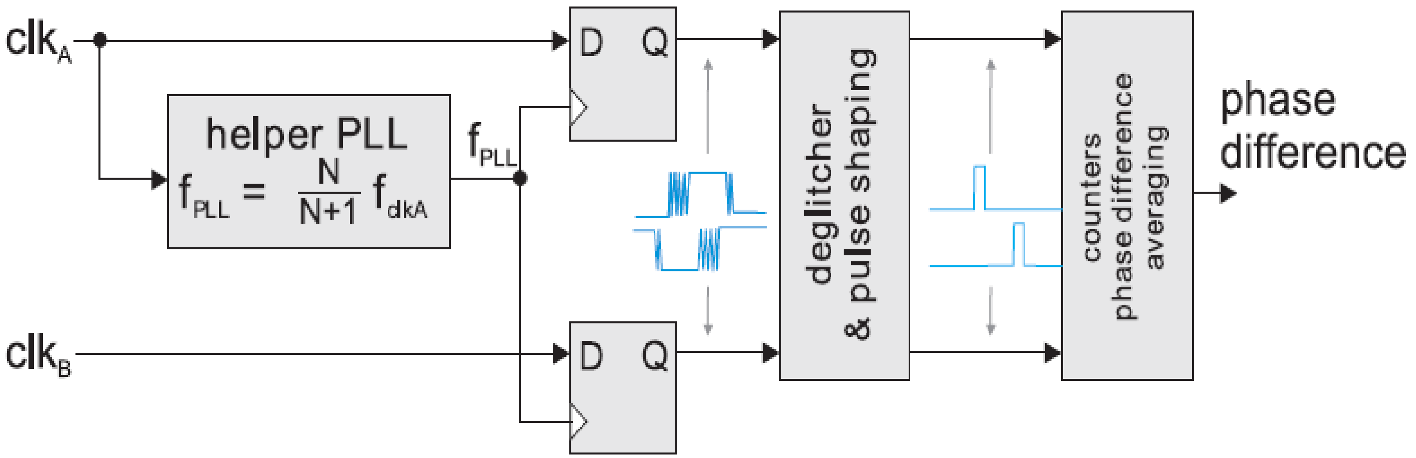
WR clock loopback

- All network devices use the same physical layer clock.
- Clock is encoded in data by master and recovered by slave.
- Clock loopback and phase detection allow **precise timestamps.**



Digital DMTD (DDMTD)

- Principle is based on the Analog version – Dual Mixer Time difference.
- Helper PLL is the common local oscillator signal.
- Down convert the input signals (by mixing with a common local oscillator signal).



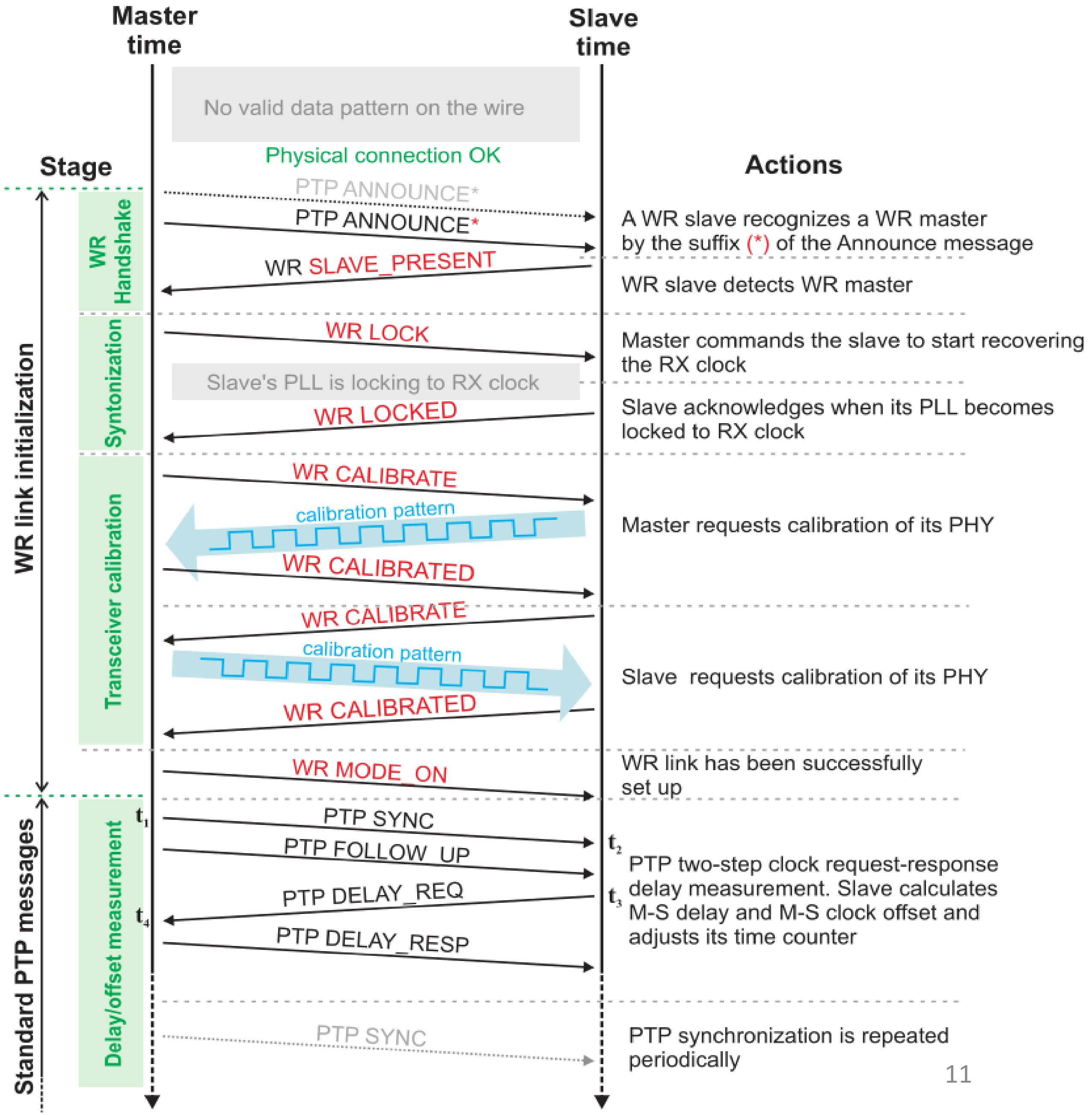
Unification of WR with PTP

WR Master – Slave recognition

Syntonization

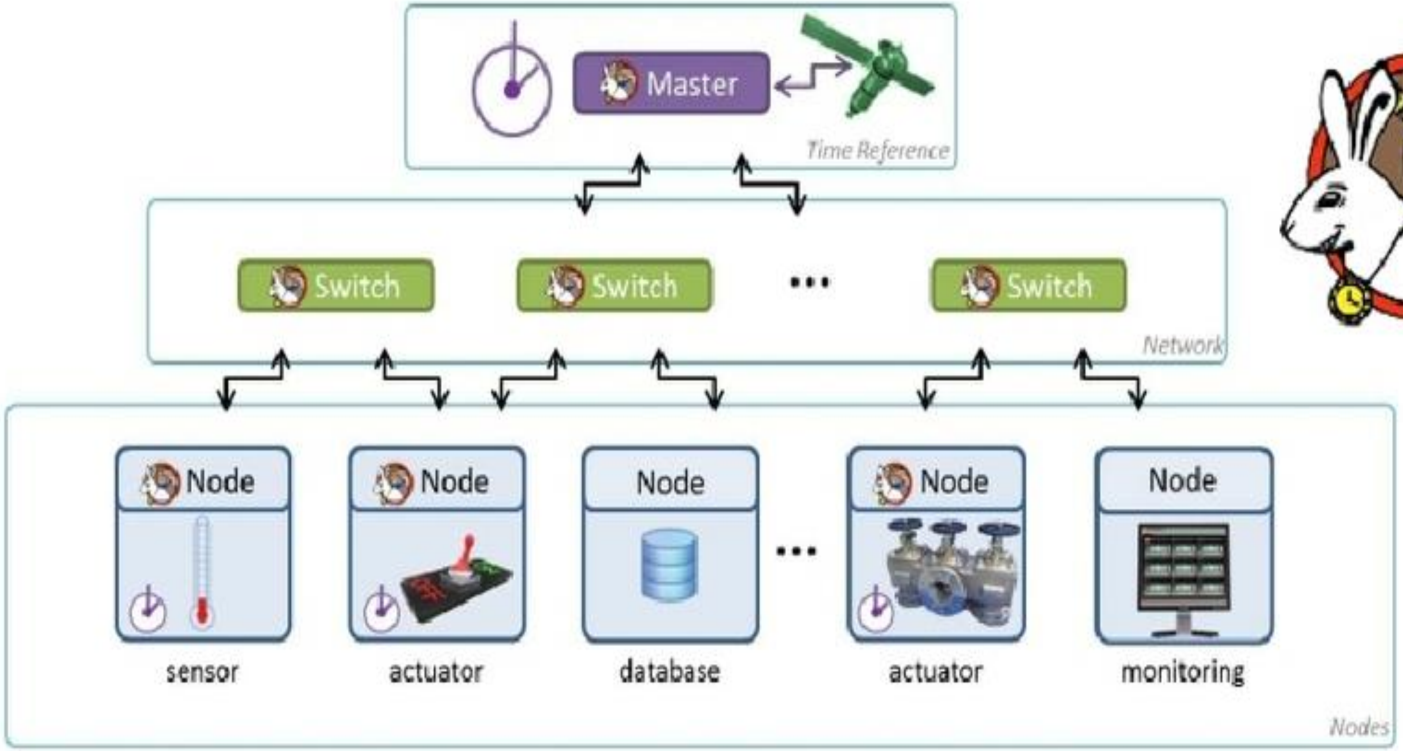
Transceiver calibration

Standard PTP message exchange - synchronization



A typical White Rabbit network

Hierarchial network consisting of Switches and Nodes.



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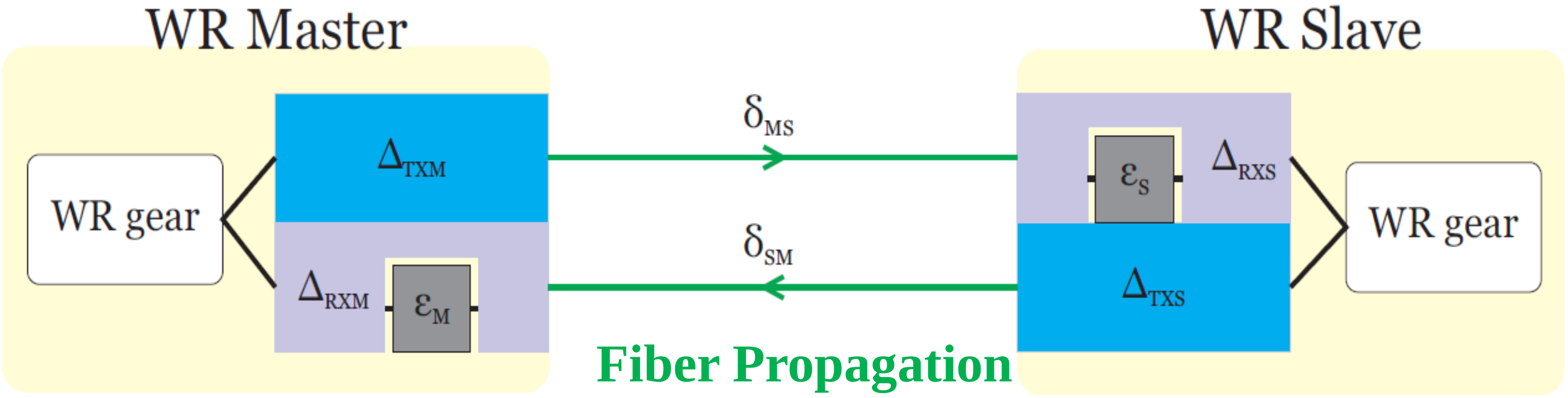
WR calibration – Link delay model



Fiber Propagation delays
$(\delta_{MS}, \delta_{SM})$

Master Transmission and Reception delays
$\Delta_{TXM}, \Delta_{RXM}$

Slave Transmission and Reception delays
$\Delta_{TXS}, \Delta_{RXS}$

Bitslide values $(\varepsilon_M, \varepsilon_S)$

WR calibration – Link delay model

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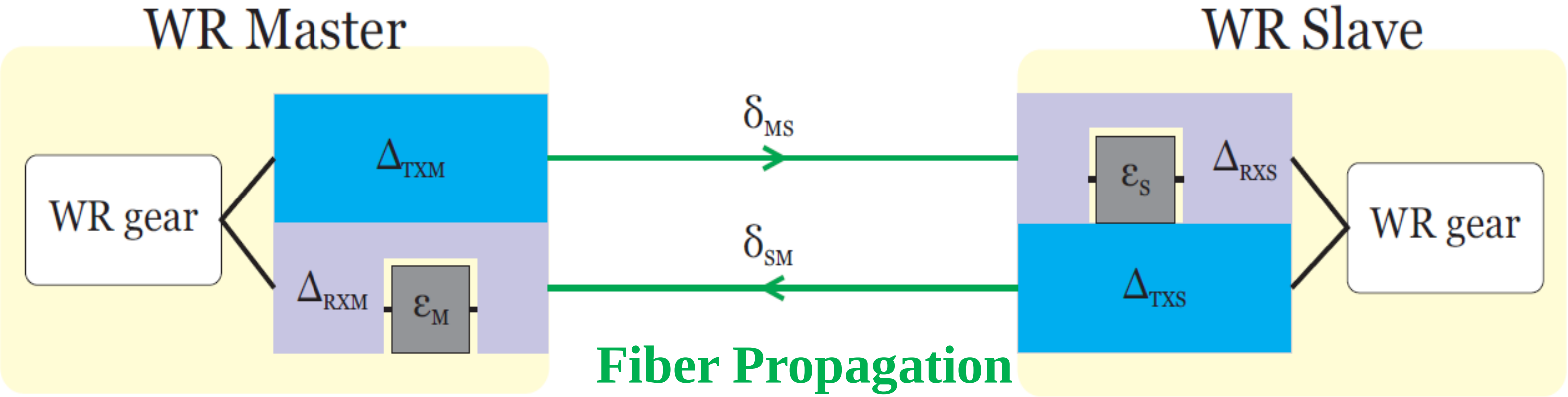


Fiber Propagation delays $(\delta_{MS}, \delta_{SM})$

Master Transmission and Reception delays $\Delta_{TXM}, \Delta_{RXM}$

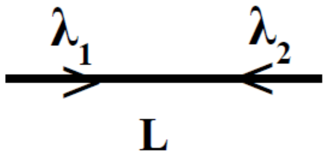
Slave Transmission and Reception delays $\Delta_{TXS}, \Delta_{RXS}$

Bitslide values $(\varepsilon_M, \varepsilon_S)$

- Transmission & Reception delays = PCB trace + SFP transceiver + component delays + FPGA internal delays
- Fiber Propagation Delays $(\delta_{MS}, \delta_{SM})$
- Round trip delay RTT = TX and RX + Fiber propagation delays + bitslide values.

Types of WR links

Bi-directional link



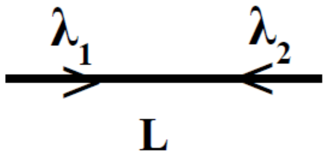
Chromatic Dispersion

$$n(\lambda_1) \neq n(\lambda_2)$$

- Single fiber
- Different Transmission and Reception wavelengths
- Time offset arises due to Chromatic dispersion (different wavelengths travel at different speeds)
- CWDM/DWDM

Types of WR links

Bi-directional link



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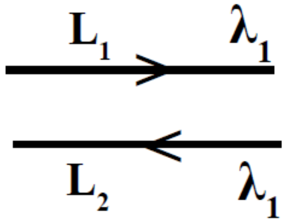
Uni-directional link



Unequal fiber length

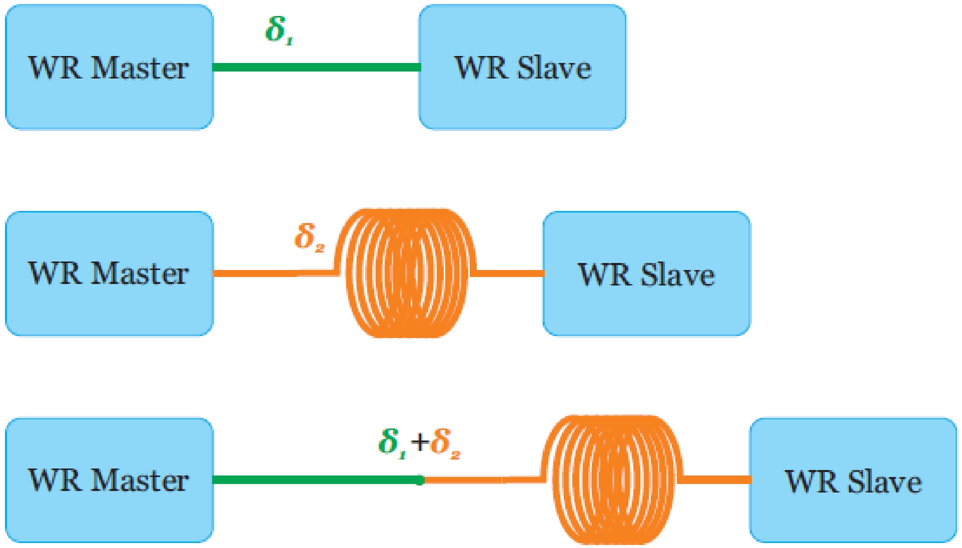
$(L_1 \neq L_2)$

and Chromatic Dispersion

- Dual fiber
- Same Transmission and Reception wavelengths
- Time offset arises due to physical fiber length imbalance
- CWDM/DWDM

WR calibration – Fiber latency

1. Measure the RTT with fiber f1.
2. Measure the RTT with fiber f2 .
3. Measure the RTT with fiber f1 + f2.
4. Subtract measure 1 or 2 from the combined RTT to obtain the required latencies.



✓ **Calibrate Optical multiplexers, Optical Amplifiers and Fiber patches and spools**

WR calibration – Fiber asymmetry

The fiber asymmetry is defined by alpha (α) as:

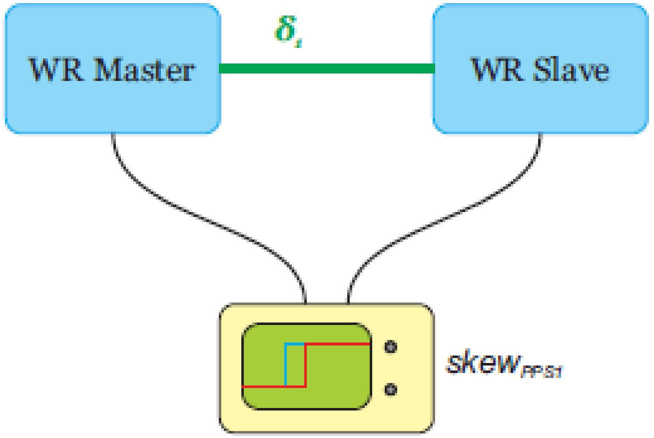
$$\alpha = \frac{\delta_{MS} - \delta_{SM}}{\delta_{SM}}$$

For a Bi-directional link:

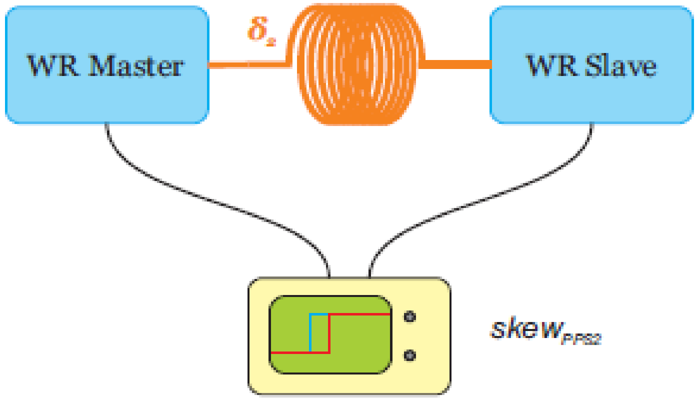
1. Measure Skew1 for a link with fiber f1 with a TIC.
2. Measure Skew2 for a link with fiber f2 with a TIC.
3. Calculate the α value as:

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

1.



2.



Only for Lab tests – when Master and Slave are at the same site

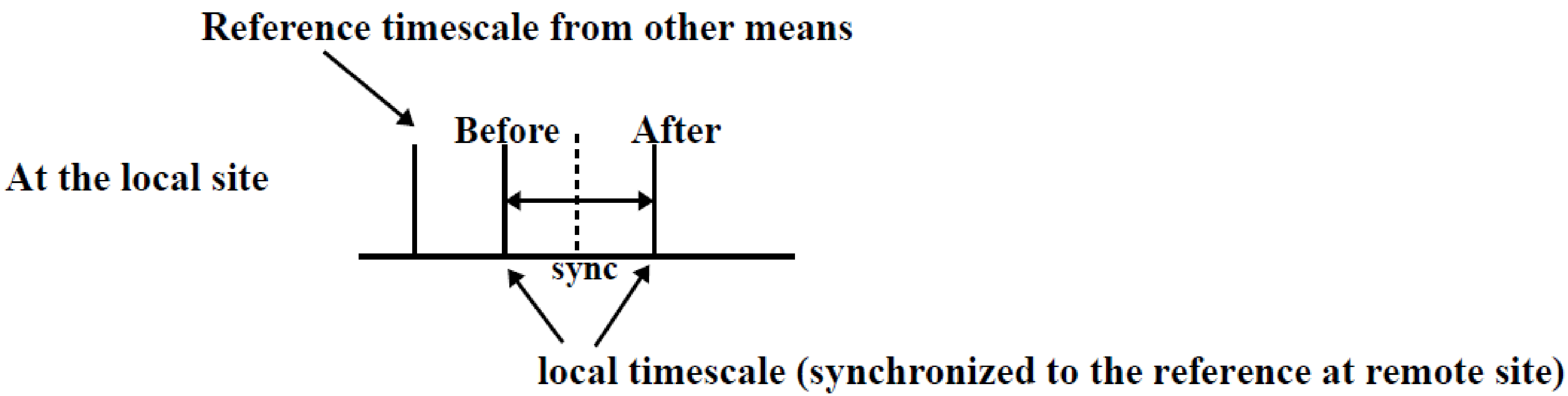
Calibration of Deployed links

Fiber swapping method

Estimating the propagation asymmetry of a Uni-directional link

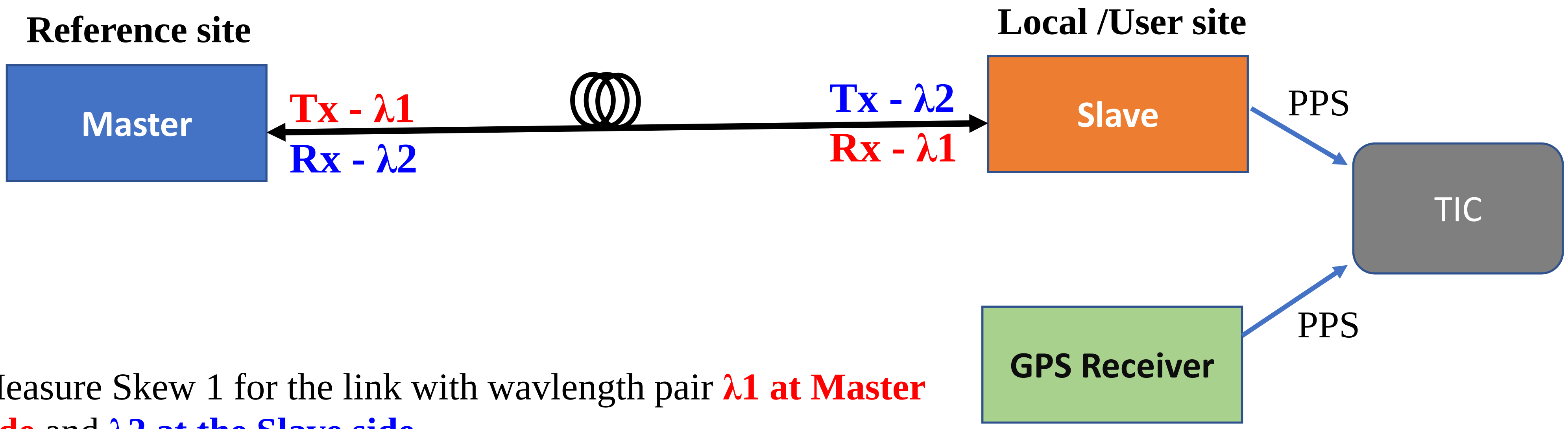
Wavelength swapping technique

Estimating the propagation asymmetry of a Bi-directional link



WR calibration – Fiber asymmetry

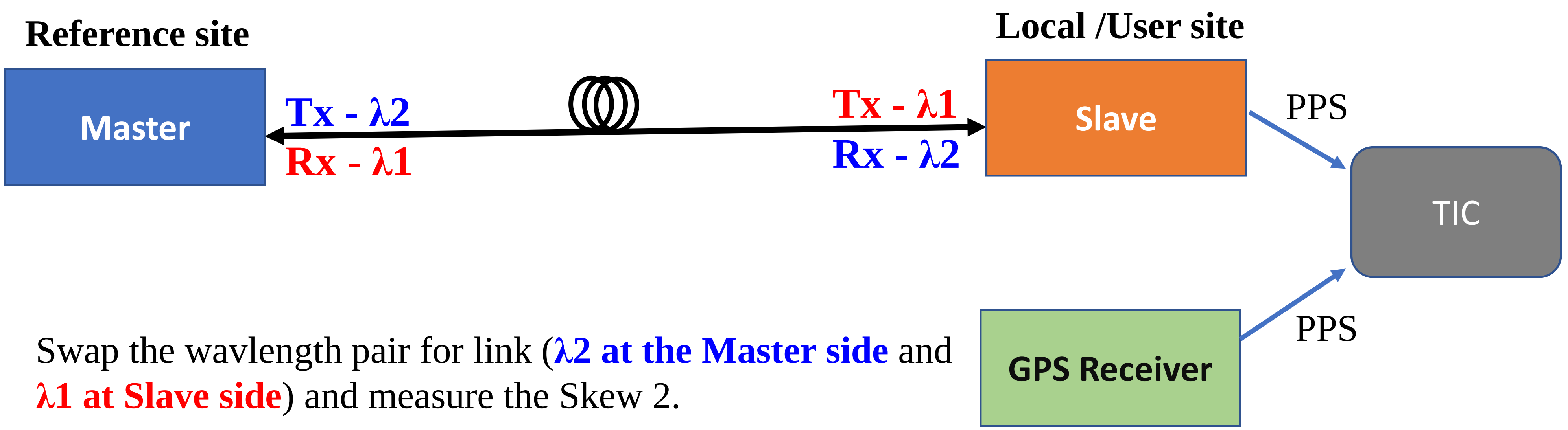
Bi-directional link – Wavelength swapping technique



Measure Skew 1 for the link with wavlength pair **λ1 at Master side** and **λ2 at the Slave side.**

WR calibration – Fiber asymmetry

Bi-directional link – Wavelength swapping technique

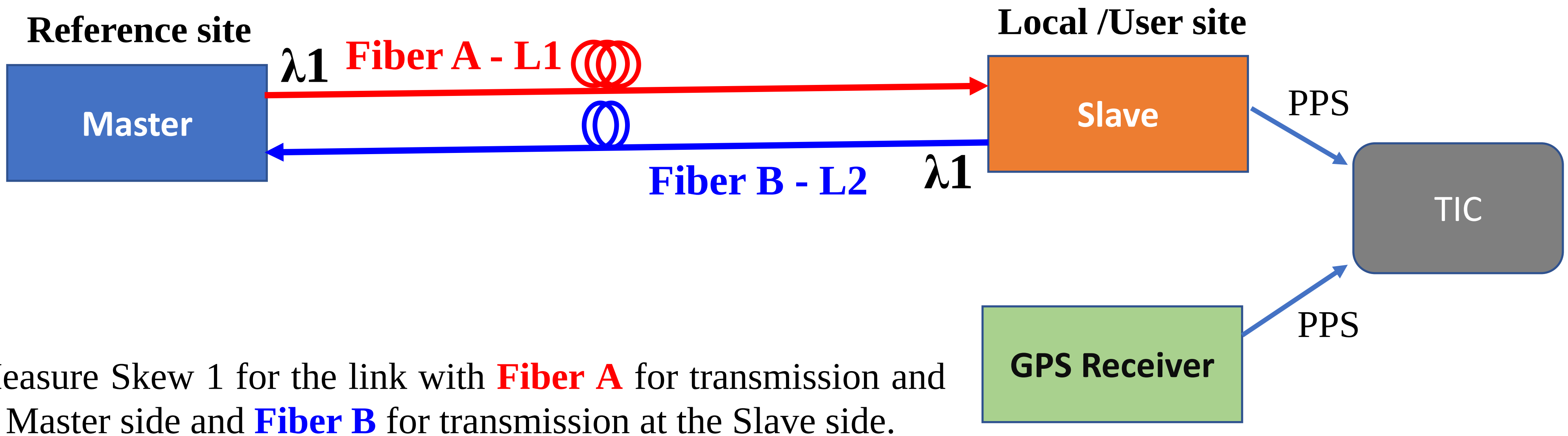


- Swap the wavlength pair for link (**λ2 at the Master side** and **λ1 at Slave side**) and measure the Skew 2.

- Skew for alpha calculation = $\frac{(Skew\ 1 - Skew\ 2)}{2}$

WR calibration – Fiber asymmetry

Uni-directional link – Fiber swapping technique

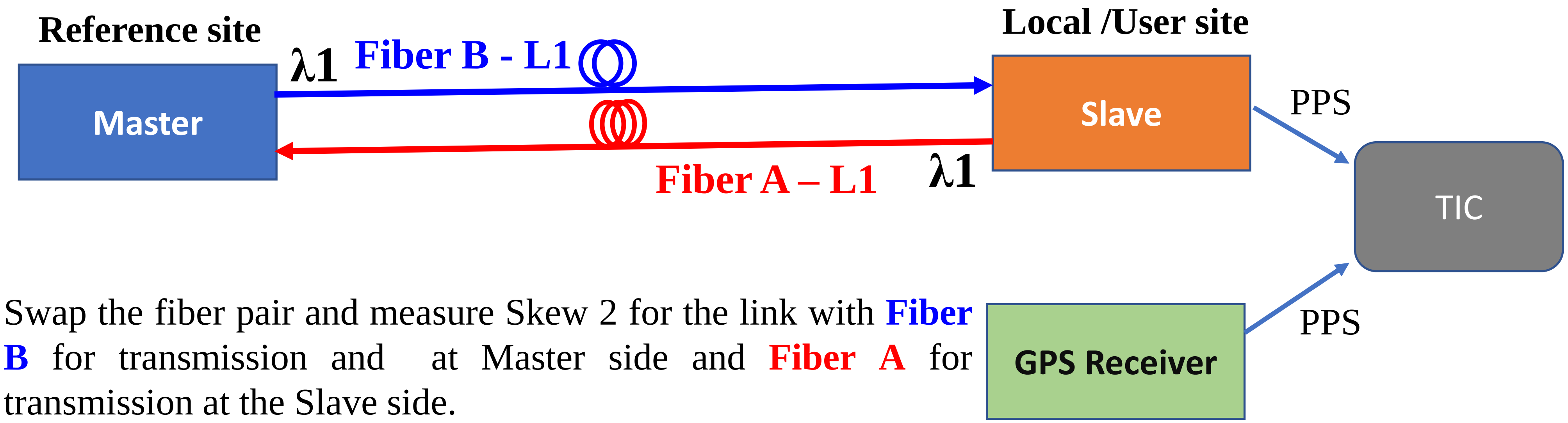


Measure Skew 1 for the link with **Fiber A** for transmission and at Master side and **Fiber B** for transmission at the Slave side.

Only for a Private network!!

WR calibration – Fiber asymmetry

Uni-directional link – Fiber swapping technique



- Swap the fiber pair and measure Skew 2 for the link with **Fiber B** for transmission and at Master side and **Fiber A** for transmission at the Slave side.

- Skew for alpha calculation = $\frac{(Skew\ 1 - Skew\ 2)}{2}$

Only for a Private network!!

WR calibration – Challenges

- Calibration is a challenging task:
  - Device calibration
  - Link calibration when deployed

- Requires manpower of two teams – one at reference and other at remote end.

- For an existing telecommunication network:
  - Optical Multiplexers and Optical Amplifiers can't be calibrated individually.
  - Only a global calibration can be done.

- Recalibration must be performed if any of the link components are changed.

- A technique for Autocalibration !?

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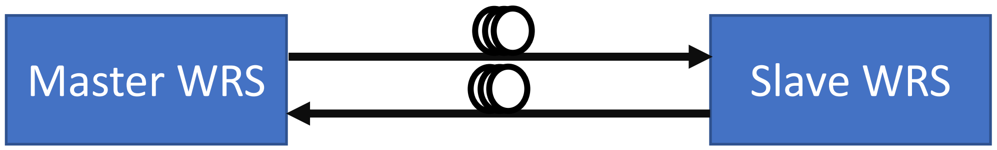
Building long haul WR links

Uni-directional links

1. Single span



Building long haul WR links

Uni-directional links

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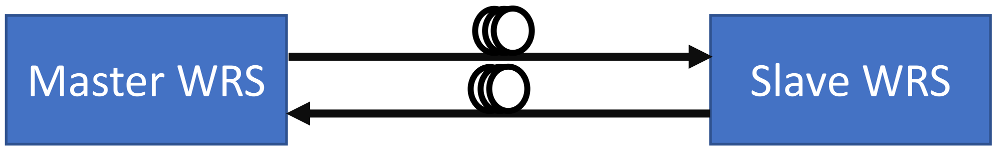
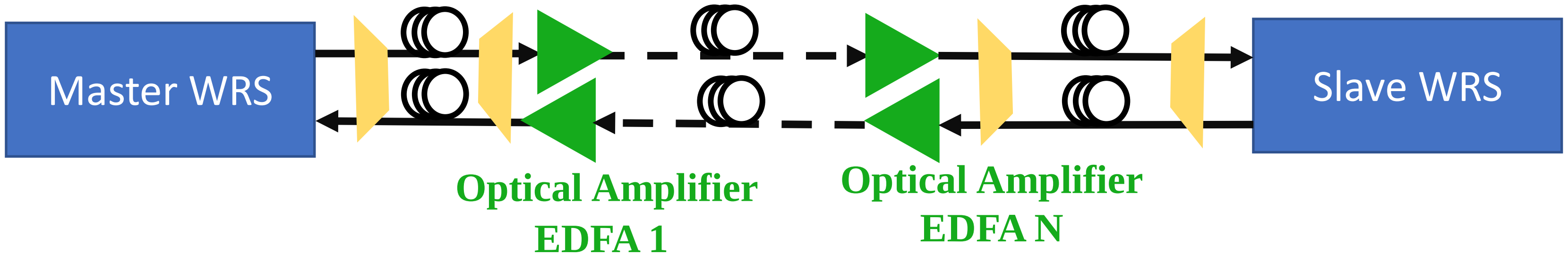


2. Link with EDFAs



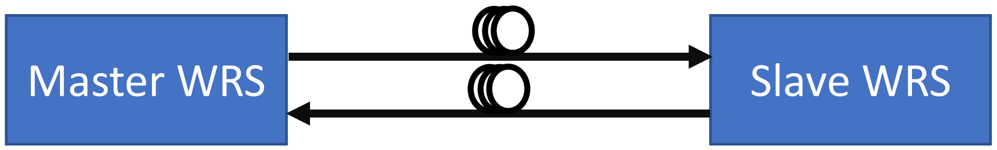
Optical Mutliplexer and Demultiplexer pair

Building long haul WR links

Uni-directional links

Optical Mutliplexer and Demultiplexer pair

1. Single span



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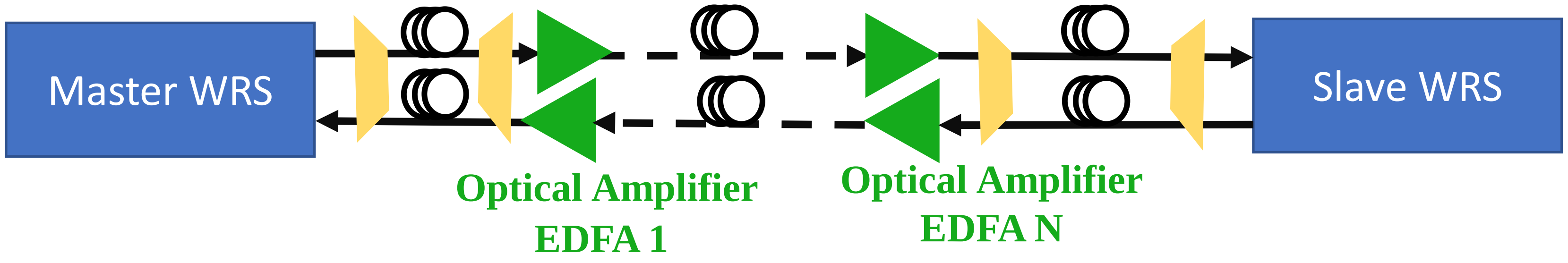
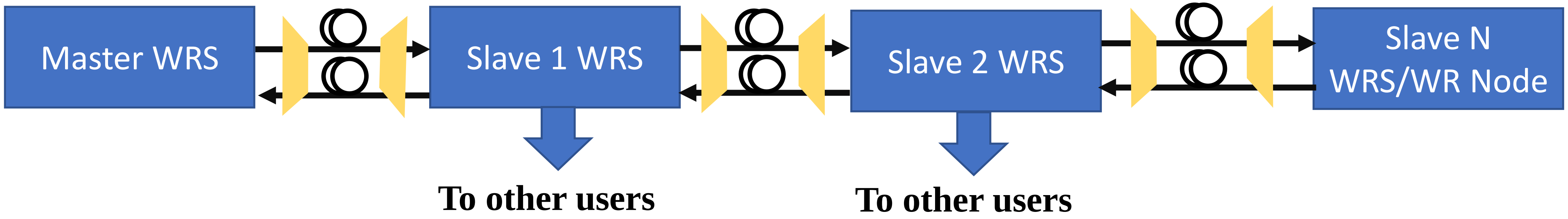
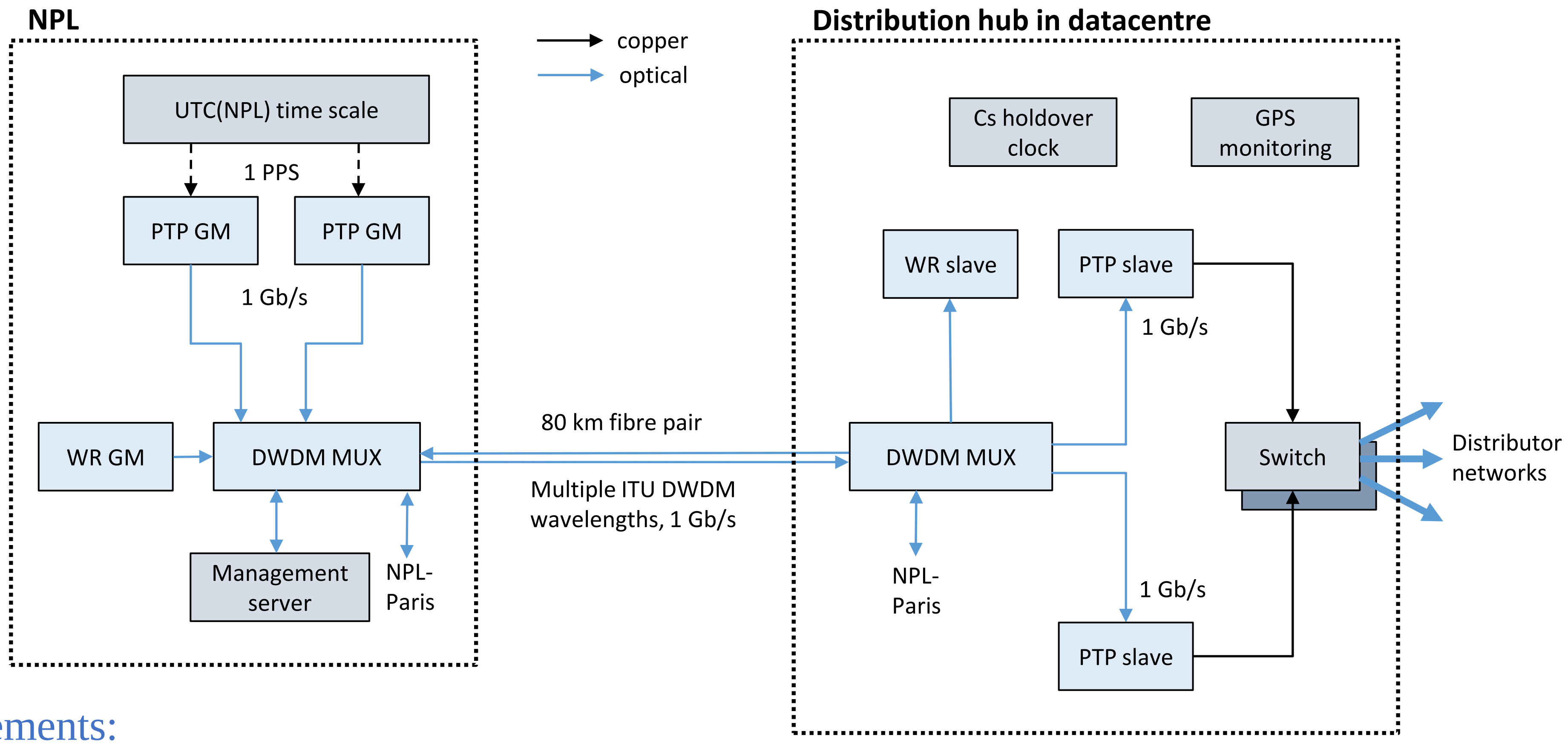


3. Cascaded links (may require EDFAs dependig upon link losses)



NPL*Time* deployment with WR

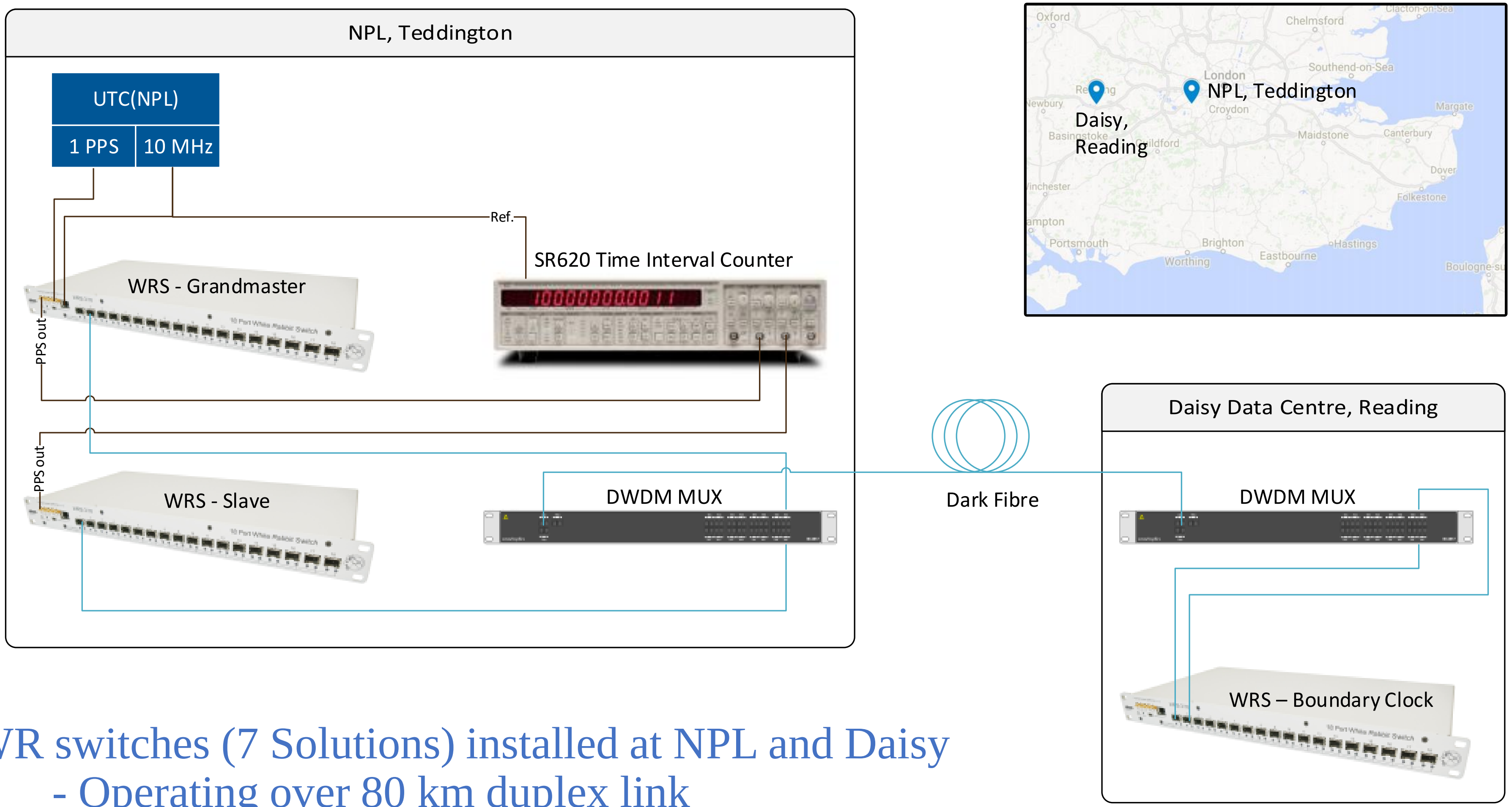


Enhancements:

- Passive optical DWDM multiplexers in place of switches
- Allows installation of White Rabbit (WR) on another channel

P Whibberley, NTS, NPL

White Rabbit on NPL-Daisy link



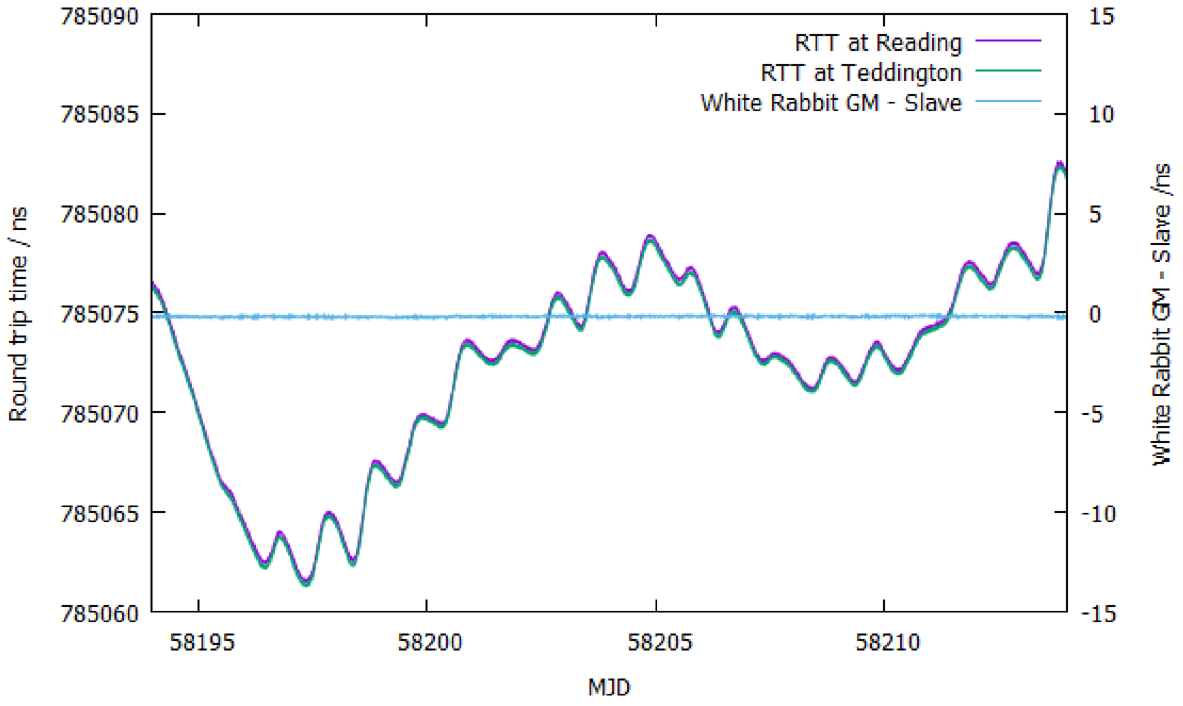
WR switches (7 Solutions) installed at NPL and Daisy
- Operating over 80 km duplex link

Daisy switch returns WR signal to NPL on a different channel

P Whibberley, NTS, NPL

Results

Round trip times (RTT)
measured over
20 days, 5 ns /d



Results

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Round trip times (RTT)
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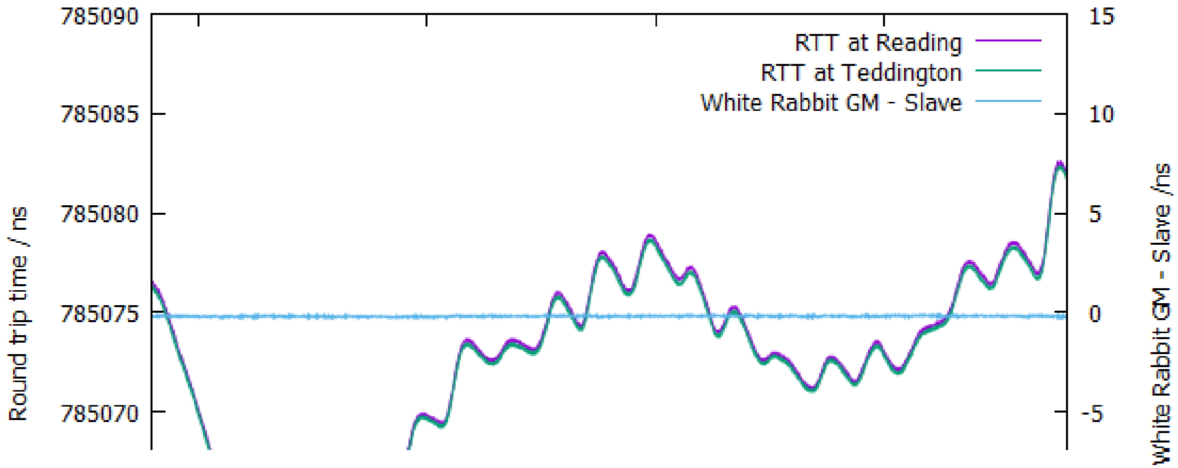
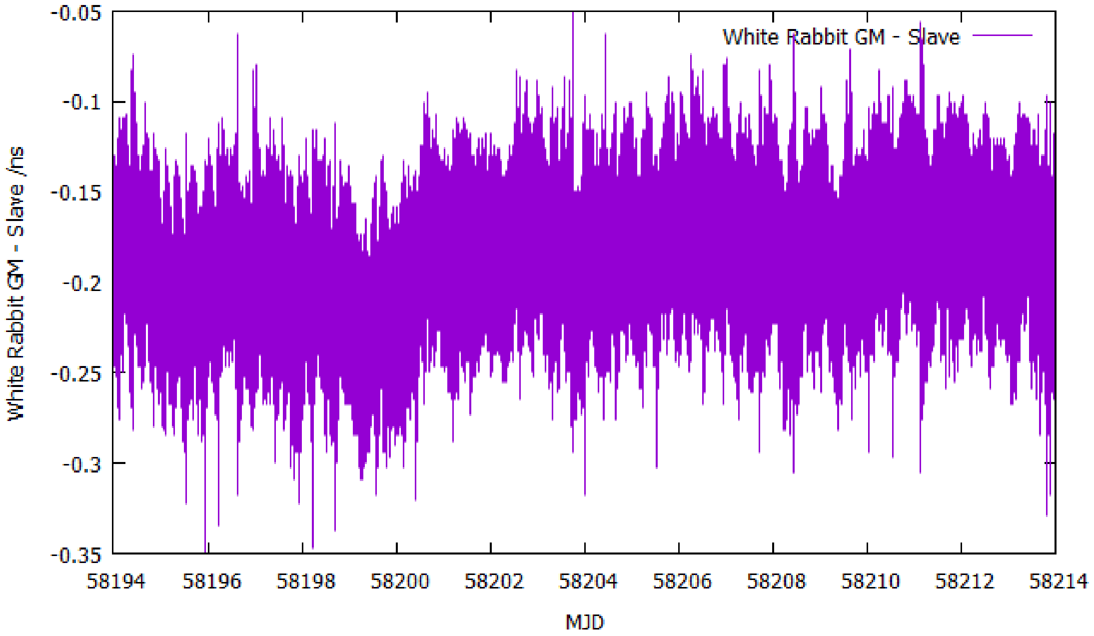


Offset between GM input and
slave output 1 PPS signals,
50 ps /d



Stability of WR over 160 km link

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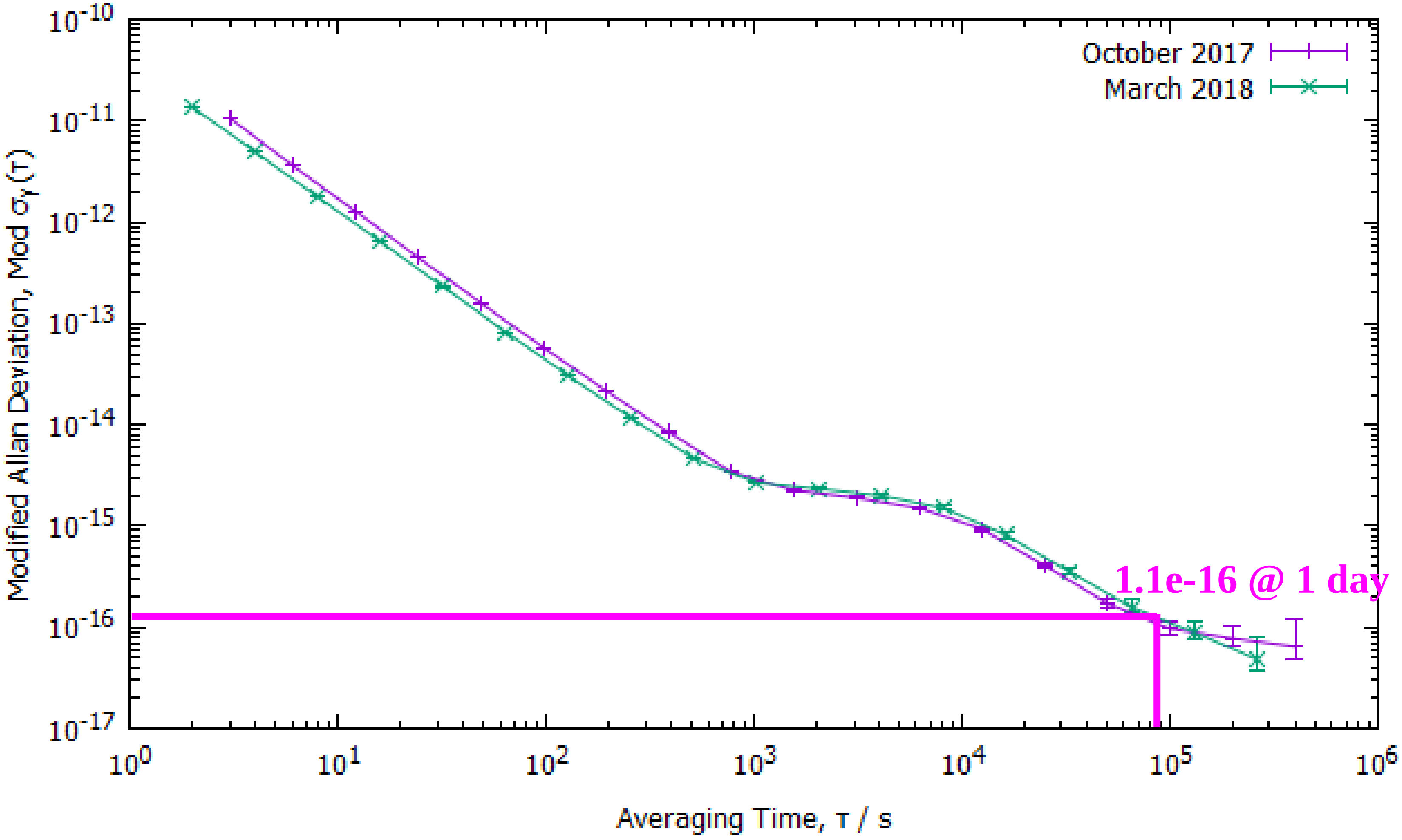
Modified Allan deviation (MDEV)



A four span cascaded 500 km WR link

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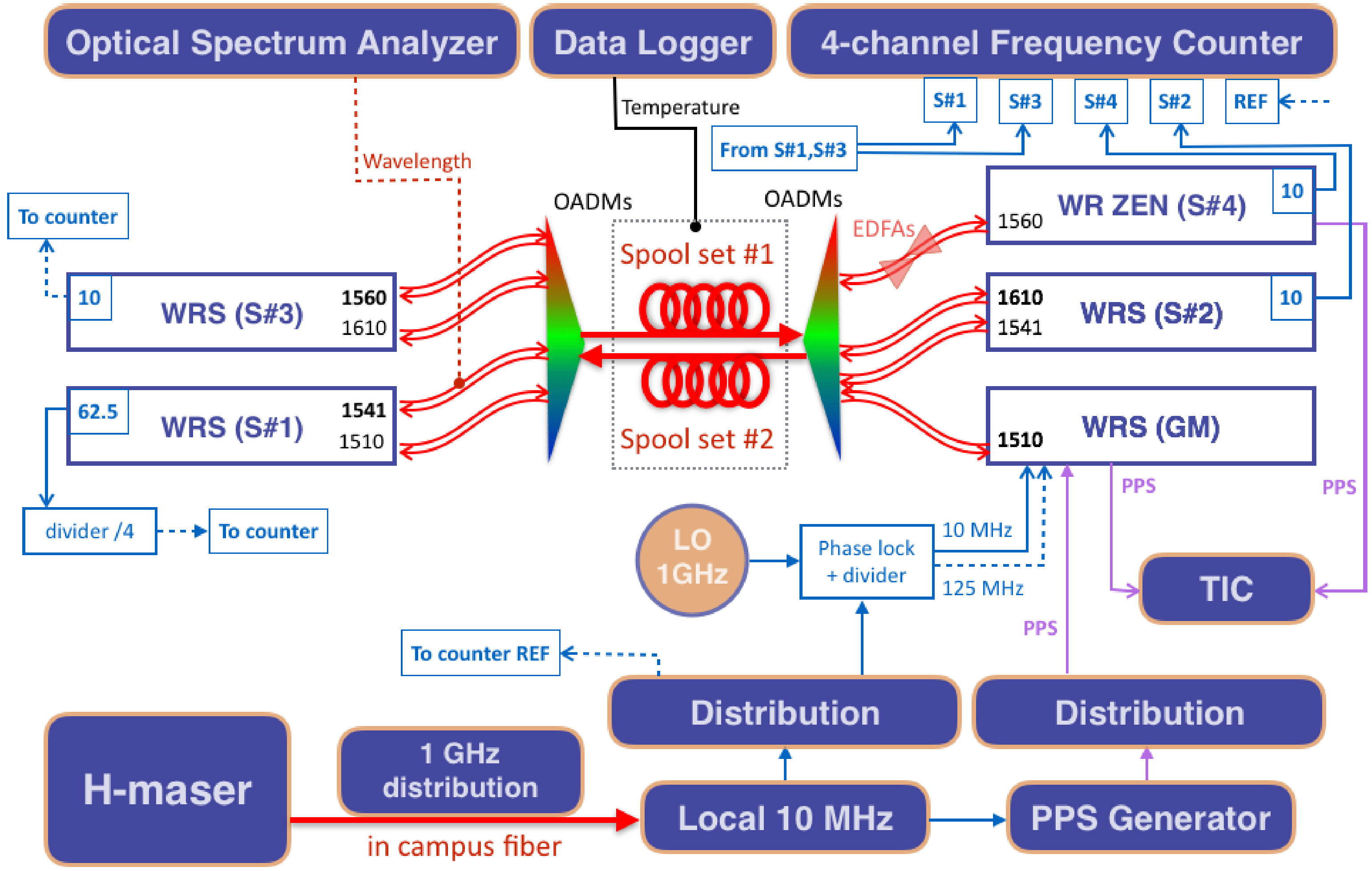

N Kaur et al, IEEE UFFC 2022, 10.1109/TUFFC.2021.3134163

Comparison with GPS performance

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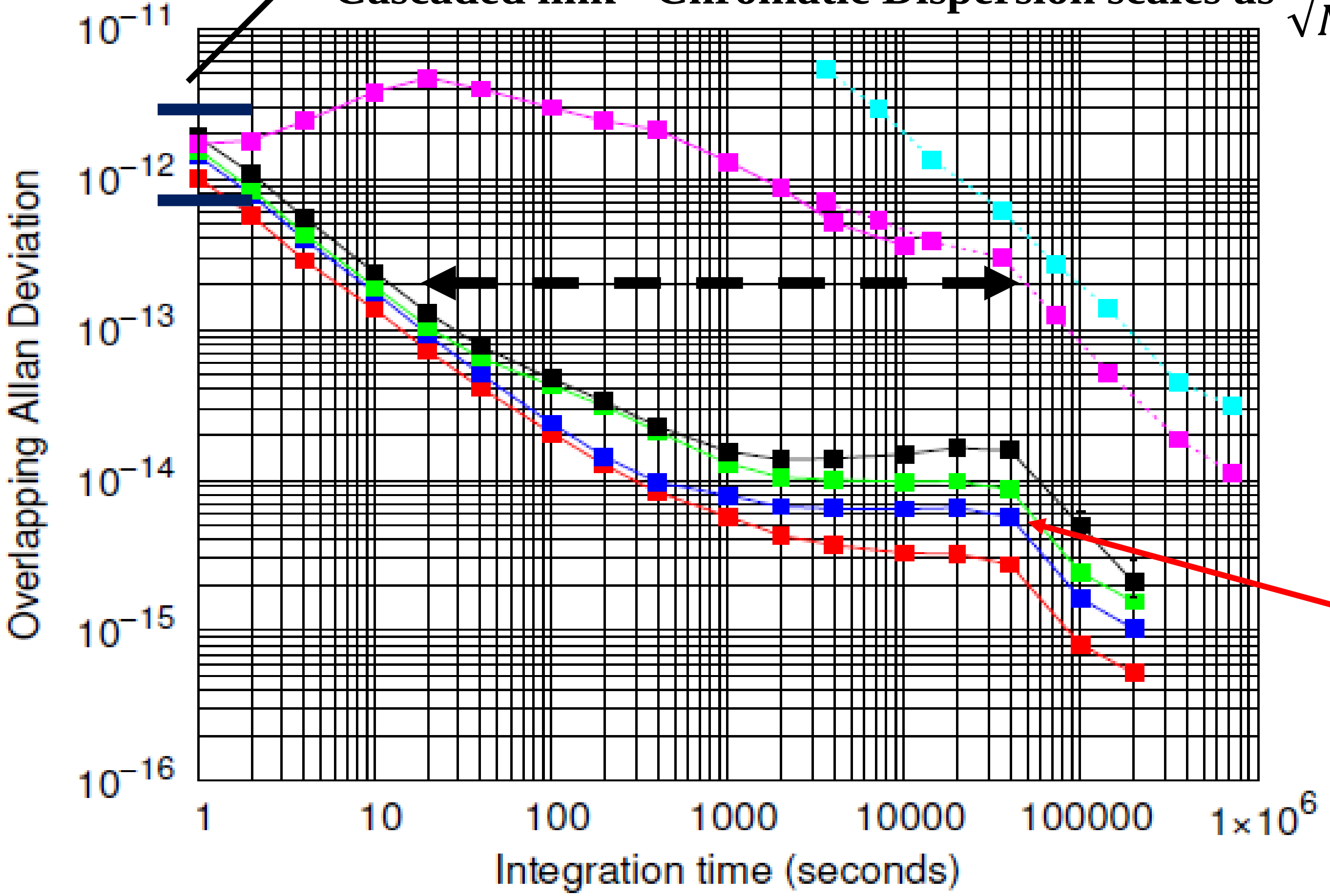
Single span link - Chromatic Dispersion scales as L

Cascaded link - Chromatic Dispersion scales as $\frac{L}{\sqrt{N}}$



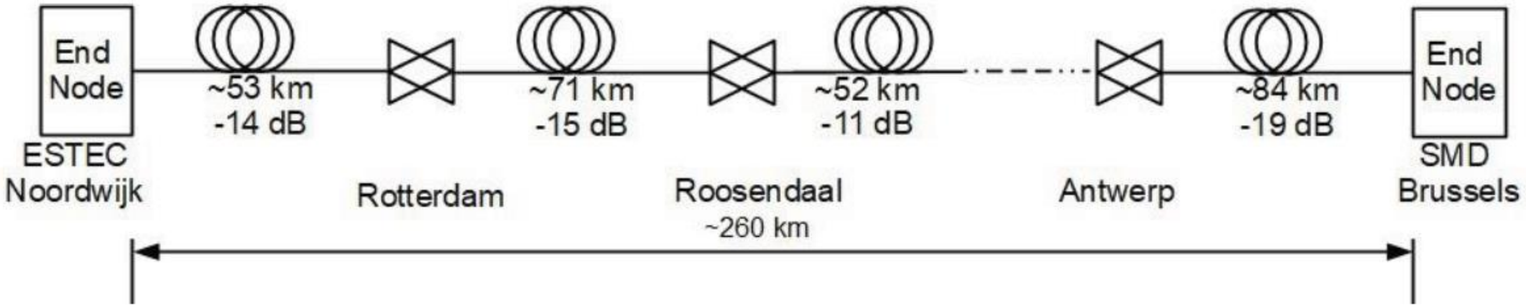
Slave 1 – 125 km
Slave 2 – 250 km
Slave 3 – 375 km
Slave 4 – 500 km
GPS Oscilloquartz
GPS Quartzlock

4e-15 @ 1 day

Fiber thermal noise (reduced by a factor of 5 for buried fiber)

N Kaur et al, IEEE UFFC 2022, 10.1109/TUFFC.2021.3134163

ESA ESTEC to SMD WR link

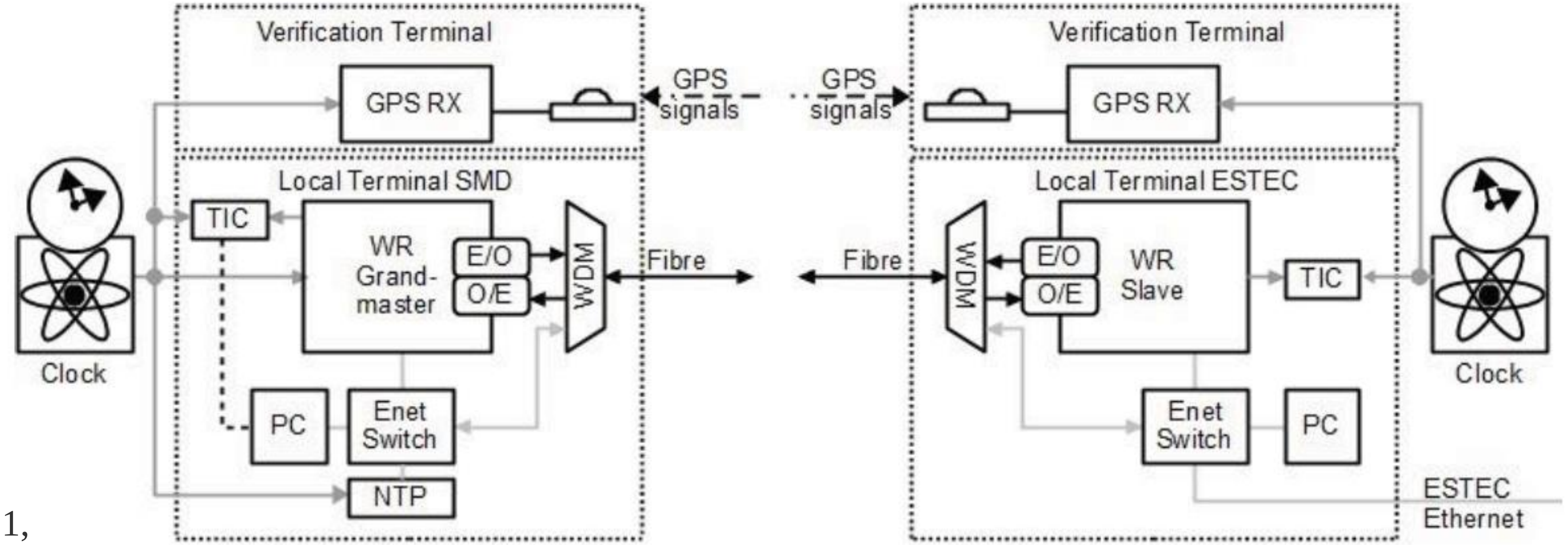


Single fiber link (Dark fiber)

Custom built Bi-di Amplifiers

Estimated uncertainty < 0.2 ns

DWDM channels - 1552.52 nm from master to slave 1550.92 nm from slave to master



P Waller et al, PTTI proceedings 2021, https://doi.org/10.33012/2021.17784

ESA ESTEC to SMD WR link

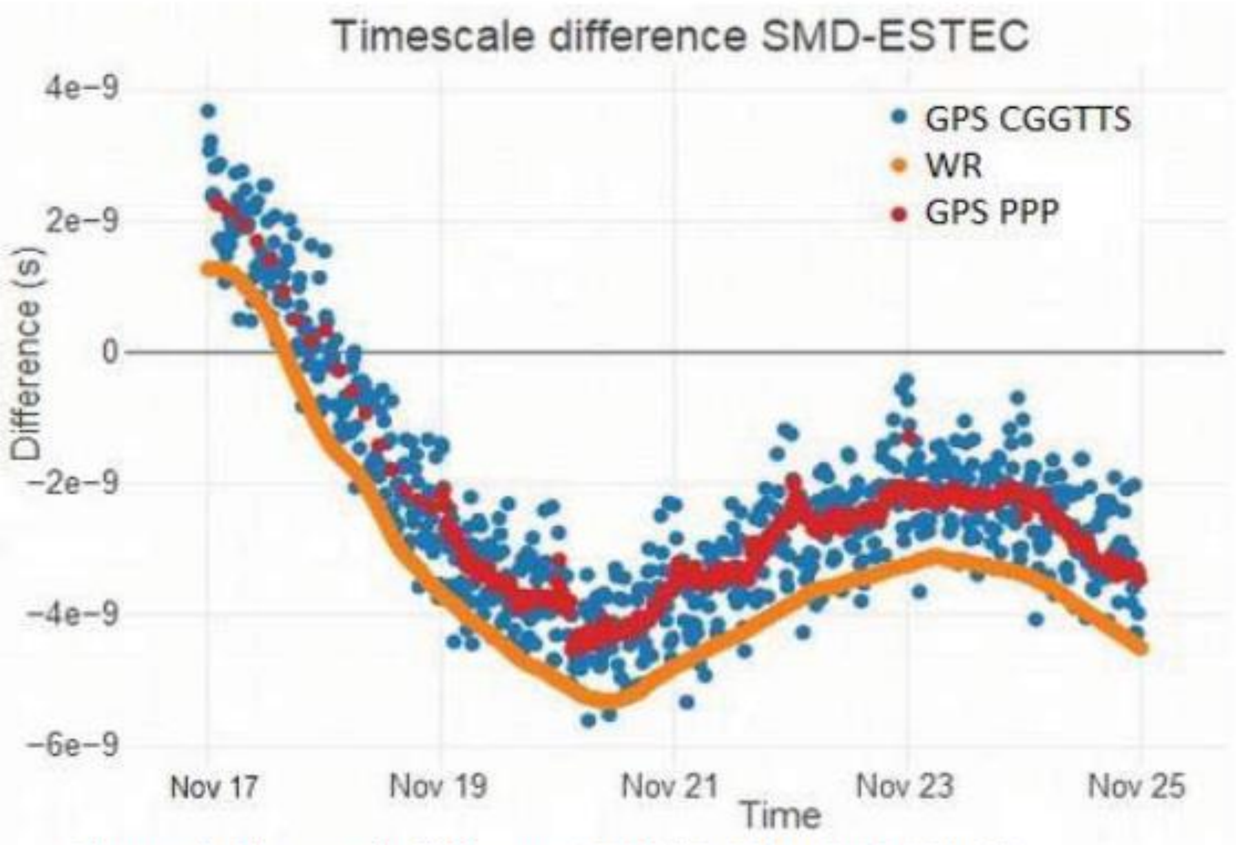


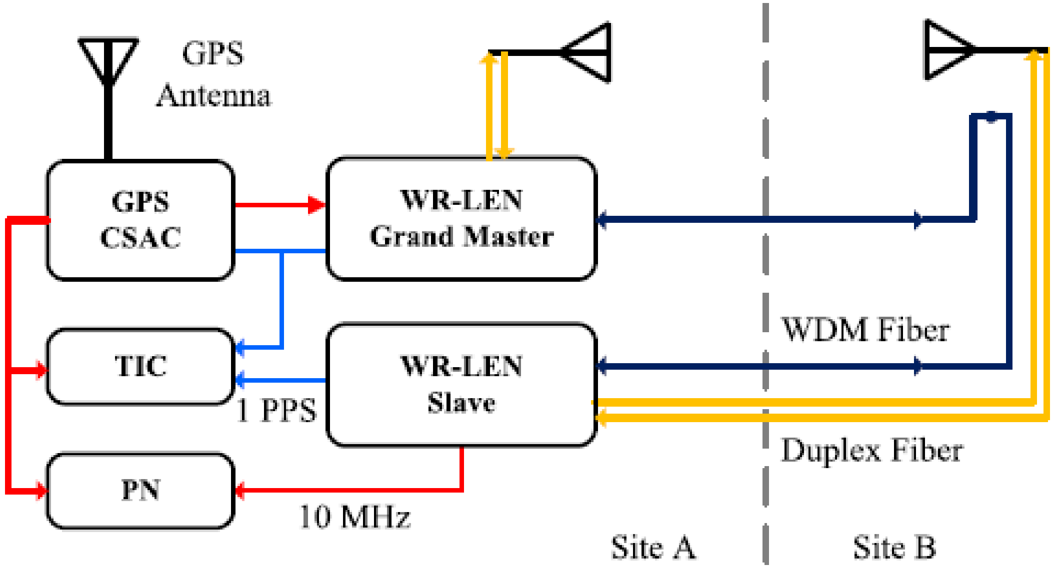
Figure 3. Timescale difference UTC(SMD) - UTC(ESTC)

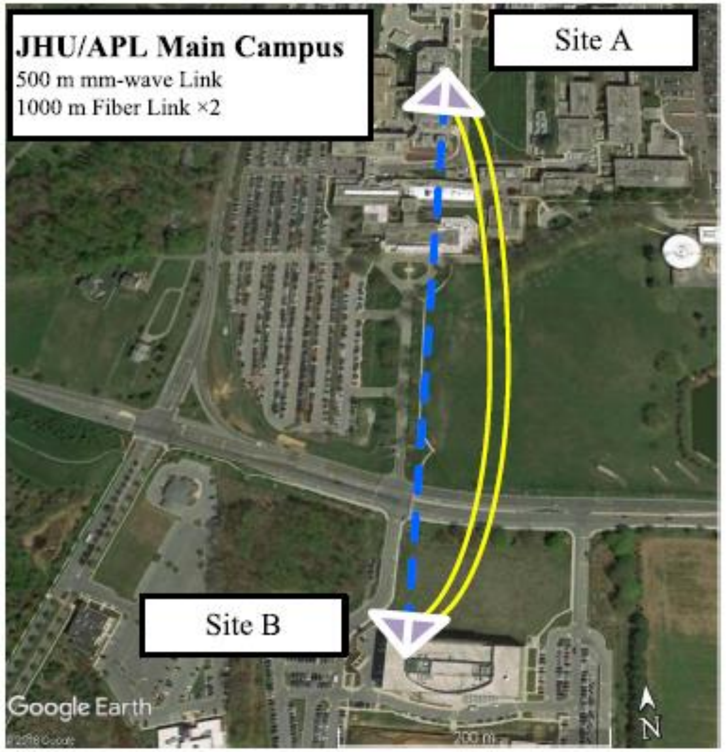
Difference between the two links is about 1.0 ns (well within the uncertainty of the GPS-link)

https://www.vsl.nl/en/about-vsl/news/two-utc-locations-are-connected-fibre-optic-connection

White Rabbit over mm wave

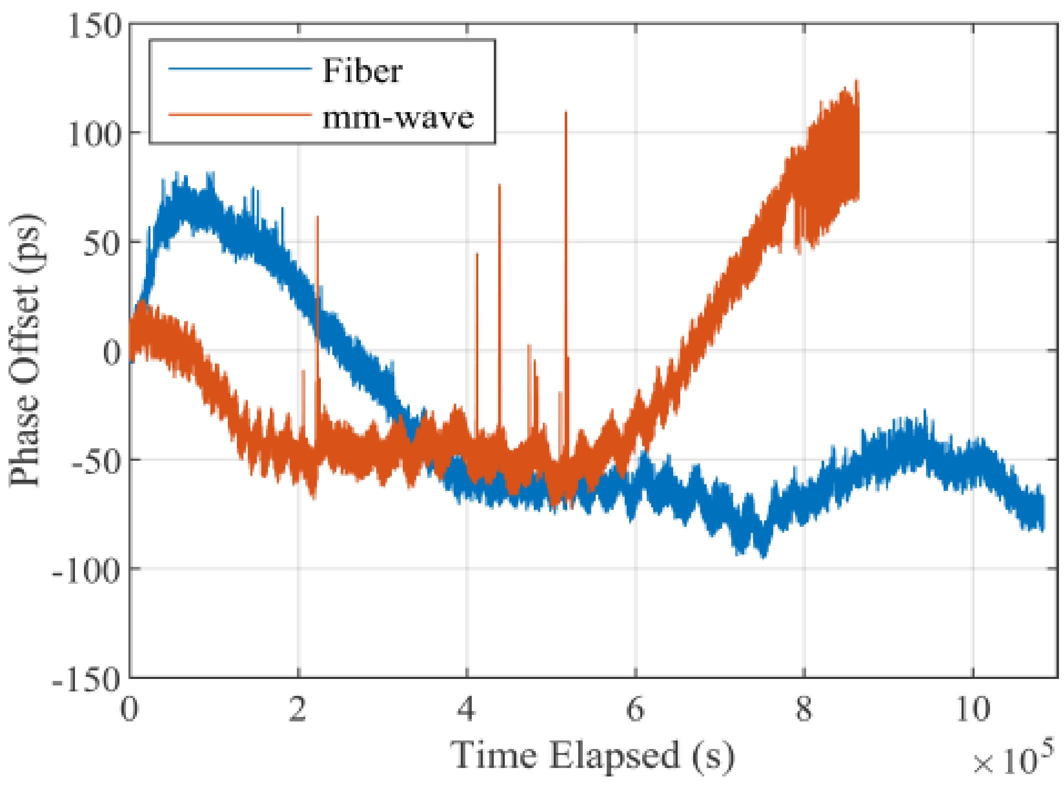
- WR over millimeter-wave (mm wave) 71-76 GHz carriers over 500 m.
- E-band transceivers to transmit timing signals to remote location.

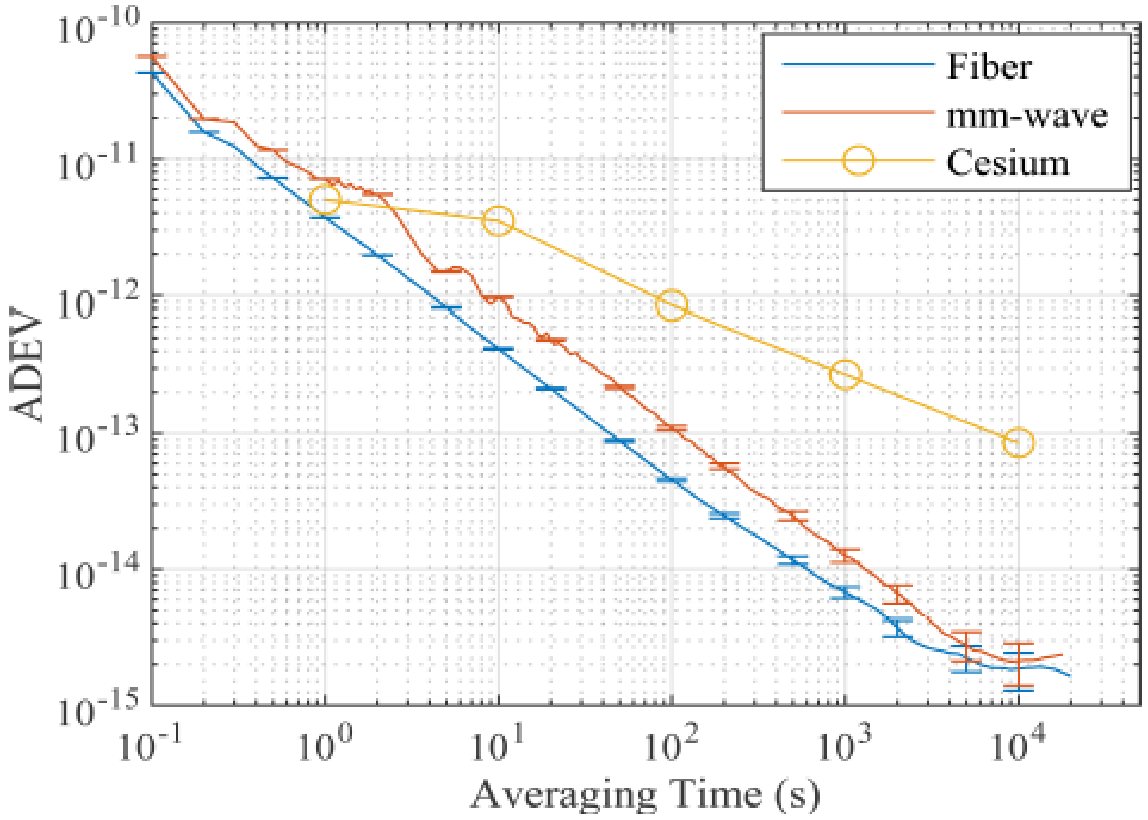




J. E. Gilligan et al, 2020, doi: 10.1109/TUFFC.2020.2989667.

White Rabbit over mm wave





Longest WR link ~ 1350 km

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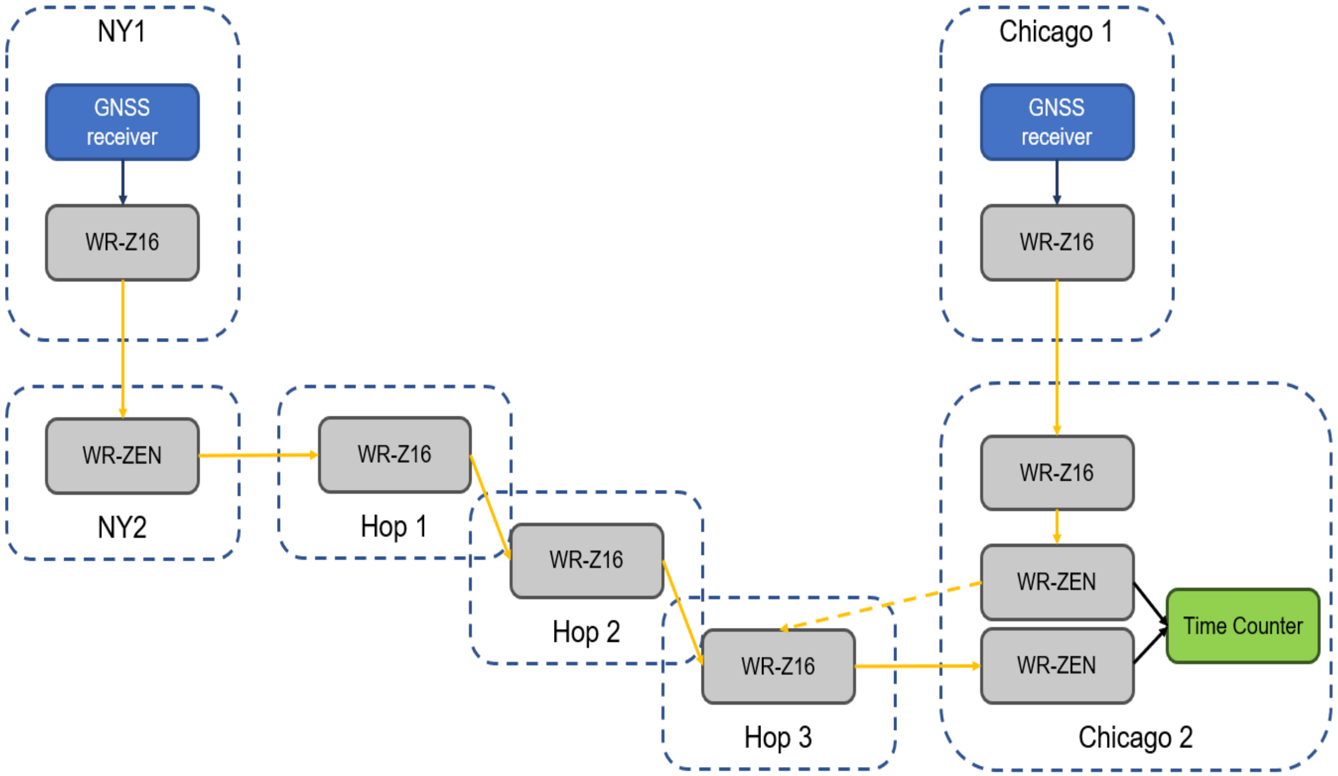
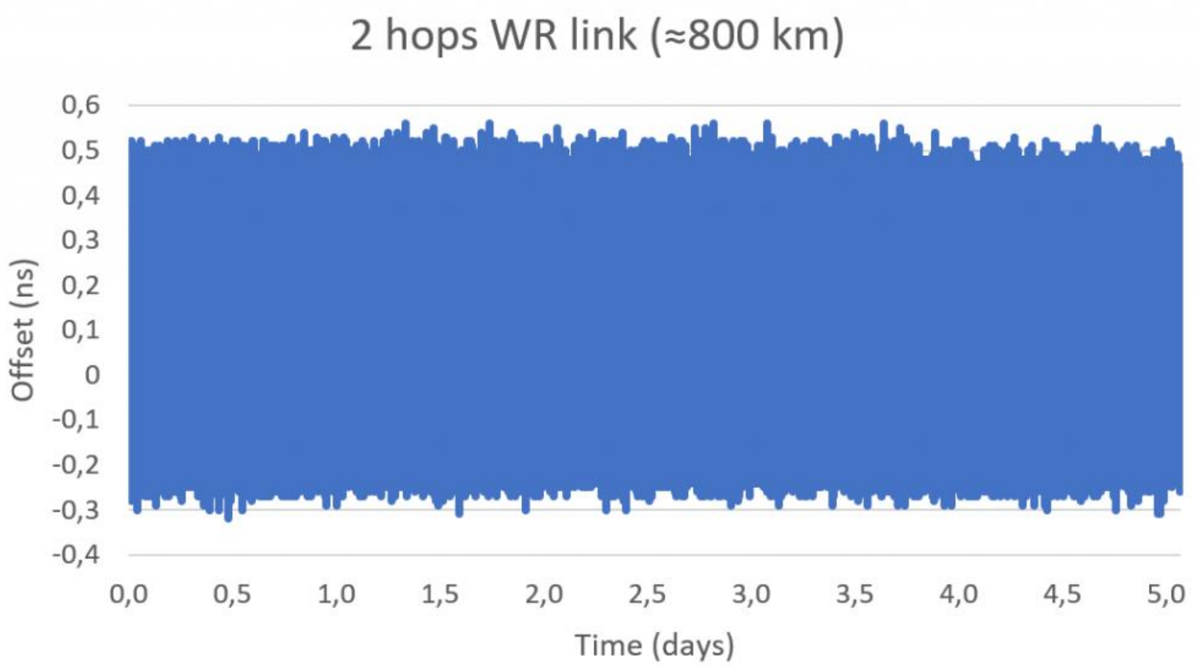
Seven Solutions sets new record for long-distance White Rabbit high-accuracy time-over-fiber link

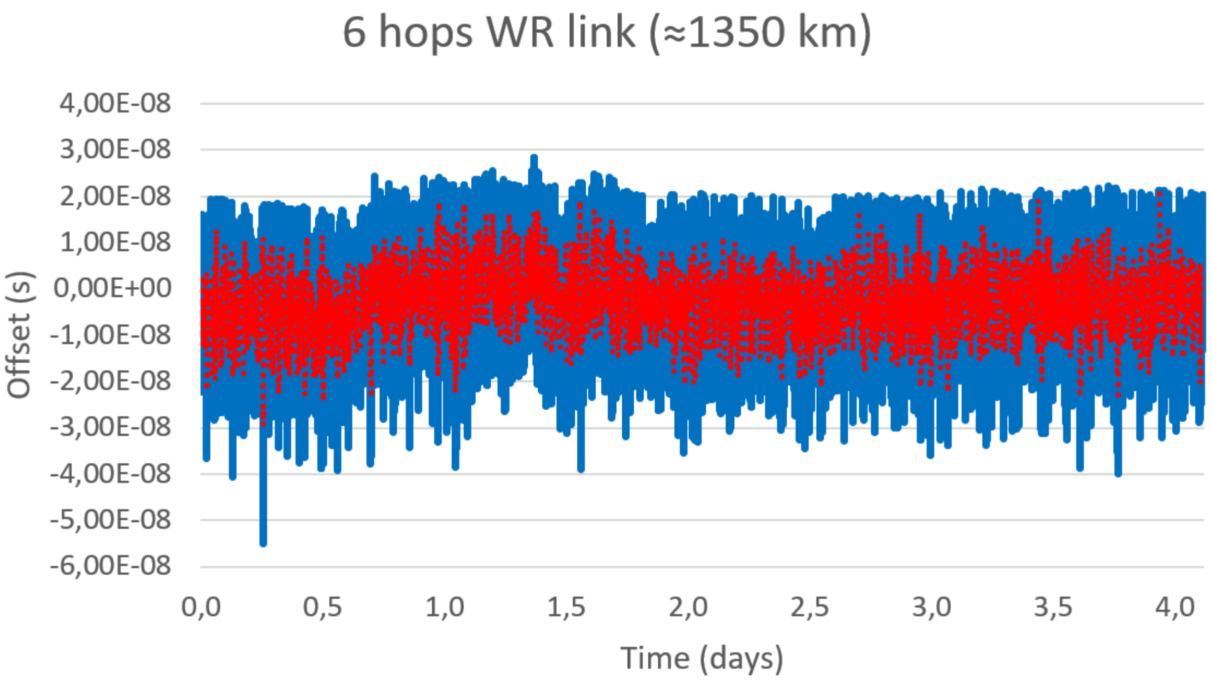
- WR link ~ 1,350 km (840 miles) to connect Chicago and New Jersey trading locations.
- Six long-distance WR hops using WR-Z16 and WR-ZEN TP devices.
- Connected by a combination of DWDM and SyncE-compliant transponders.
- Public telecommunication fiber network.



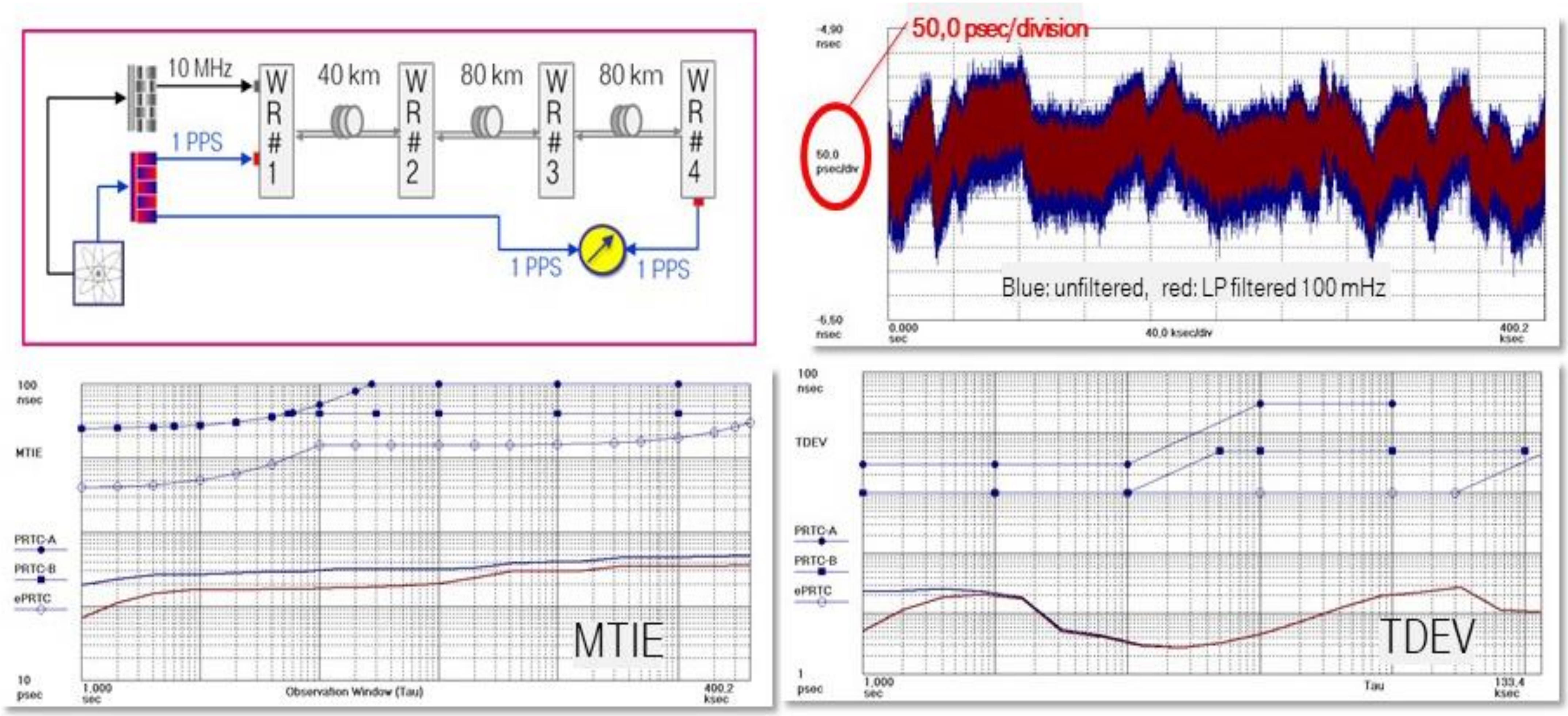
*https://www.gpsworld.com/white-rabbit-makes-leap-for-time-over-fiber/

Longest WR link - performance





Deustch Telecom WR Lab results



*https://www.researchgate.net/publication/336013265_Highly_Accurate_Time_Dissemination_and_Network_Synchronization_at_ISPCS_2019

WR for Swedish network - Netnod

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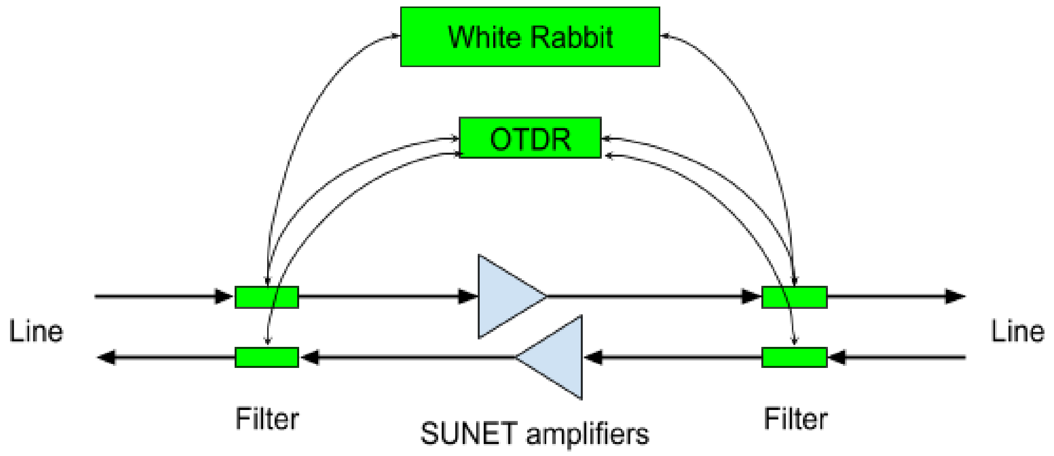
- Bi-directional fibre link between Stockholm and Sundsvall with a distance of about 440 km.
- Tested in cooperation with the Swedish National Research and Educational Network, SUNET.
- Adapted to work in parallel with the SUNET equipment by running WR wavelengths on the side of SUNET's DWDM network.
- Custom built amplifiers were used.



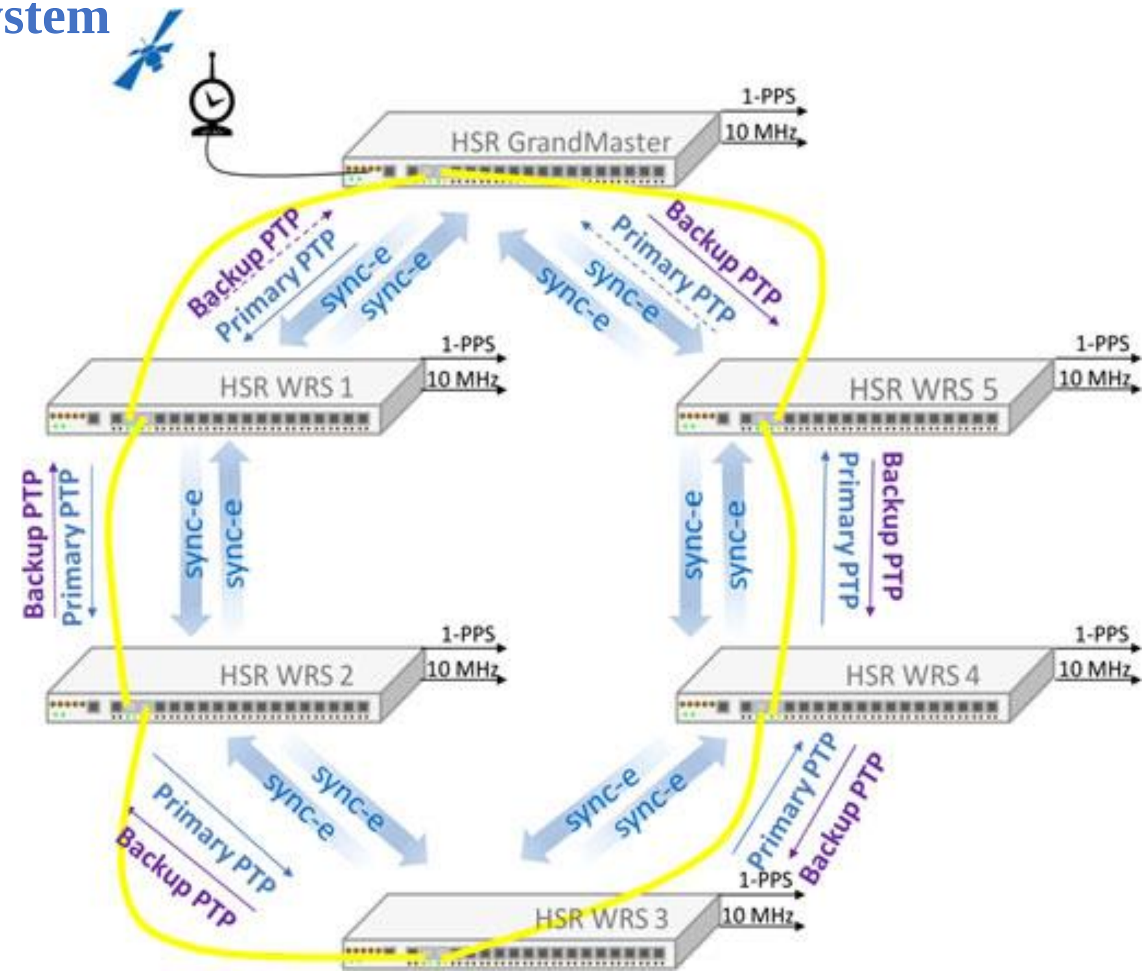
https://www.netnod.se/time-and-frequency/netnods-white-rabbit-implementation-achieves-sub-nanosecond-accuracy-in-live-swedish-network

White Rabbit HSR

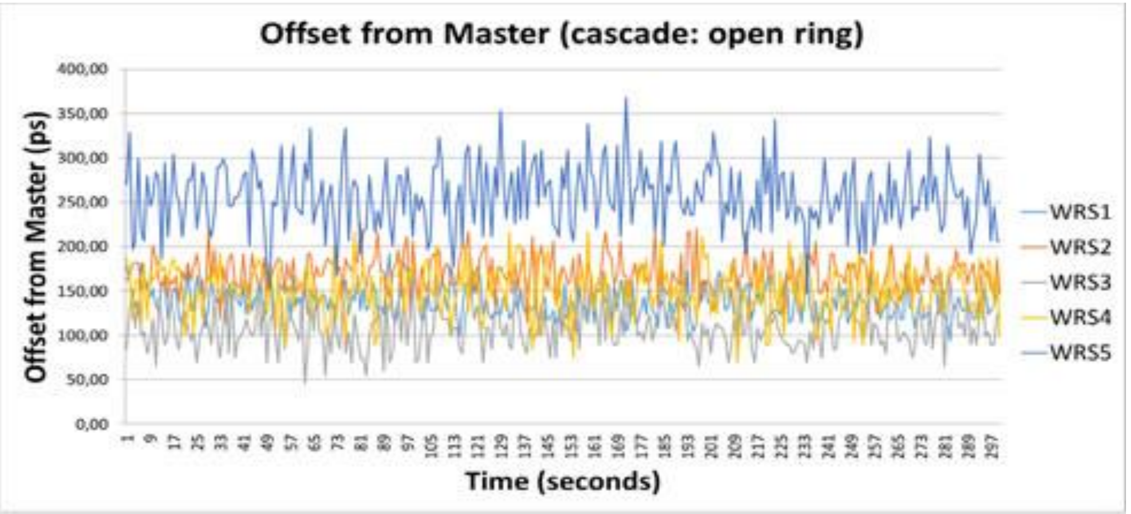
National Physical Laboratory | Quantum Metrology Institute

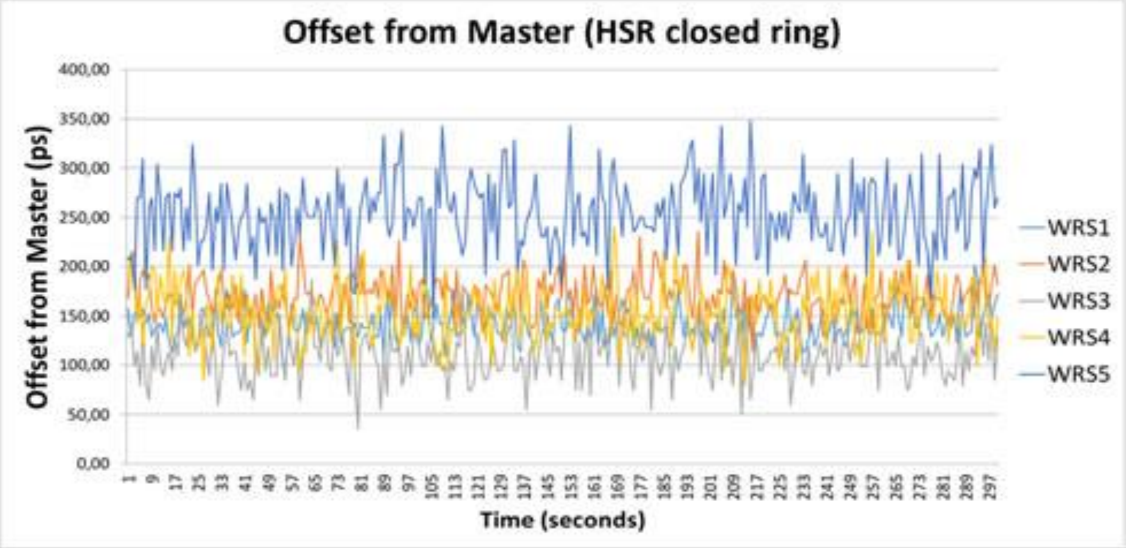
High-availability Seamless Redundant Timing system

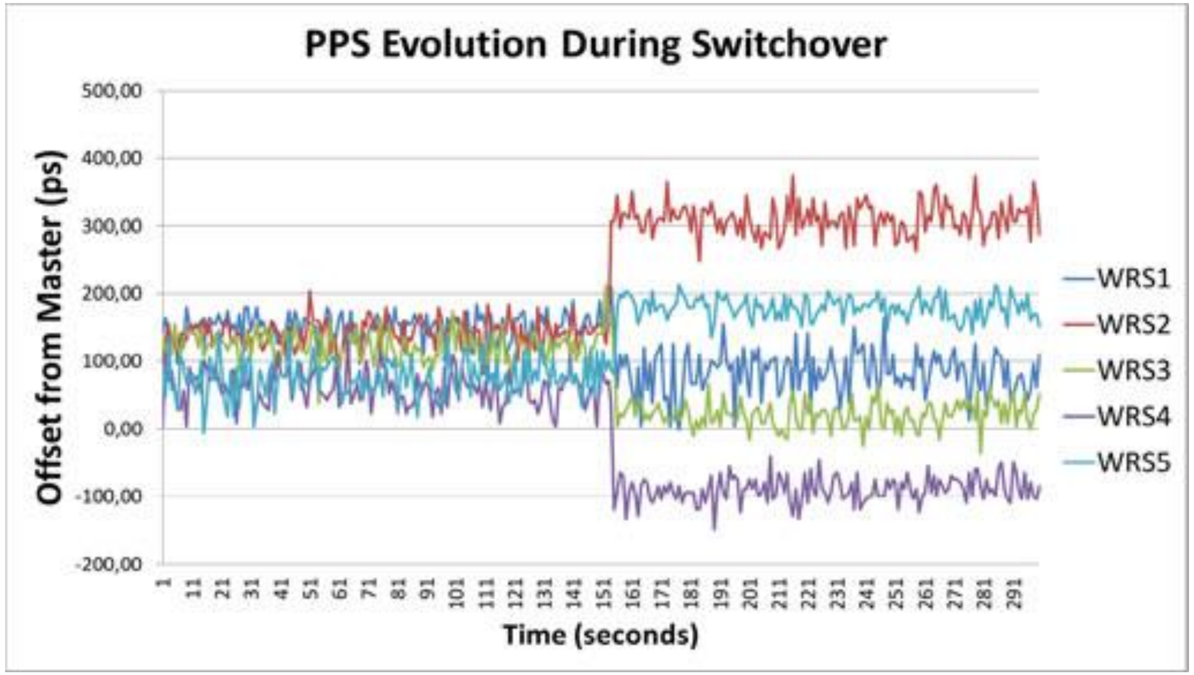
- White Rabbit HSR was developed for Smart grids.
- Reliable ultra-accurate timing system.
- Ring topology – same notion of time either clockwise or anticlockwise.
- A Slave can lock to two reference sources at the same time.



White Rabbit HSR Results







Summary

- WR is able to achieve:
  - MDEV of **1-16 @ 1 day (buried fiber)**
  - Time accuracy < **200 ps**
  - **Cascaded link for best short term stability**

- WR is being improved continuosly to adapt to industrial requirements (**3Rs Robust, Reliable, Redundant**):
  - WR HSR
  - Redundant links
  - Best Master Clock Algorithm (BMCA) for switchover

- IEEE standardization and an Active WR community.

- Validated by NMIs around the world.

- The list of WR users has been ever since **increasing** - https://ohwr.org/projects/white-rabbit/wiki/WRUsers

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Advanced Quantum Metrology Laboratory AQML

Vision for test & evaluation facility

- Create traceable T&F signals and provide an independent testing capability

T&F signals → **Industry**
Products & services
Quantum technologies

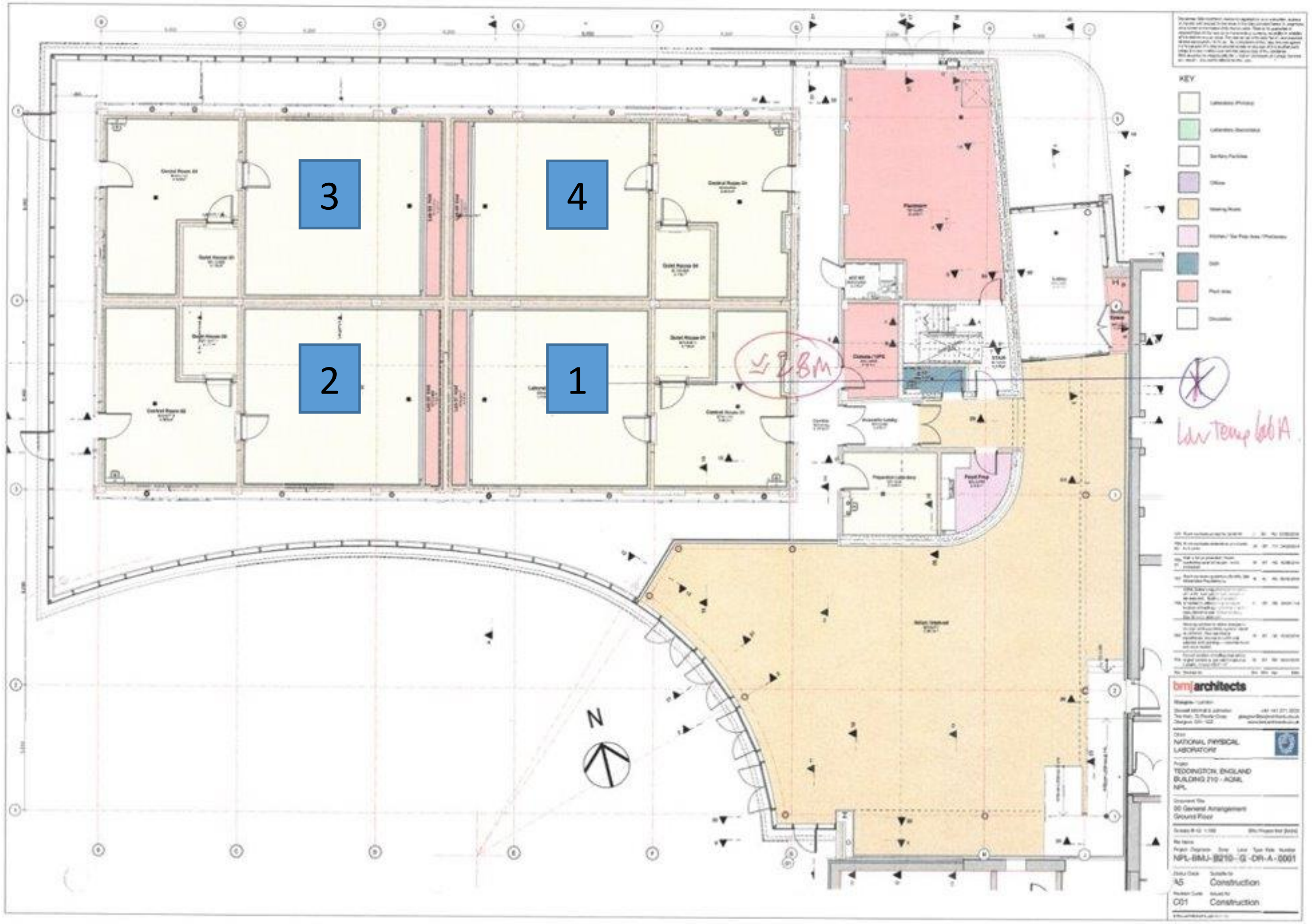
T&F signals → **NMIs**
T&F metrology
International time scales

T&F signals → **Universities**
Research
Fundamental physics

Layout within AQML

- Most (but not all) of clock evaluation facility will be based in AQML

Lab	
1	**Frequency combs & Hub of UK fibre network**
2	Innovation & testing space + Cavities for space & aerospace
3	**Continuously running optical clocks**
4	Innovation & testing space + Microcombs & low phase noise μ-waves



Clock evaluation facility overview

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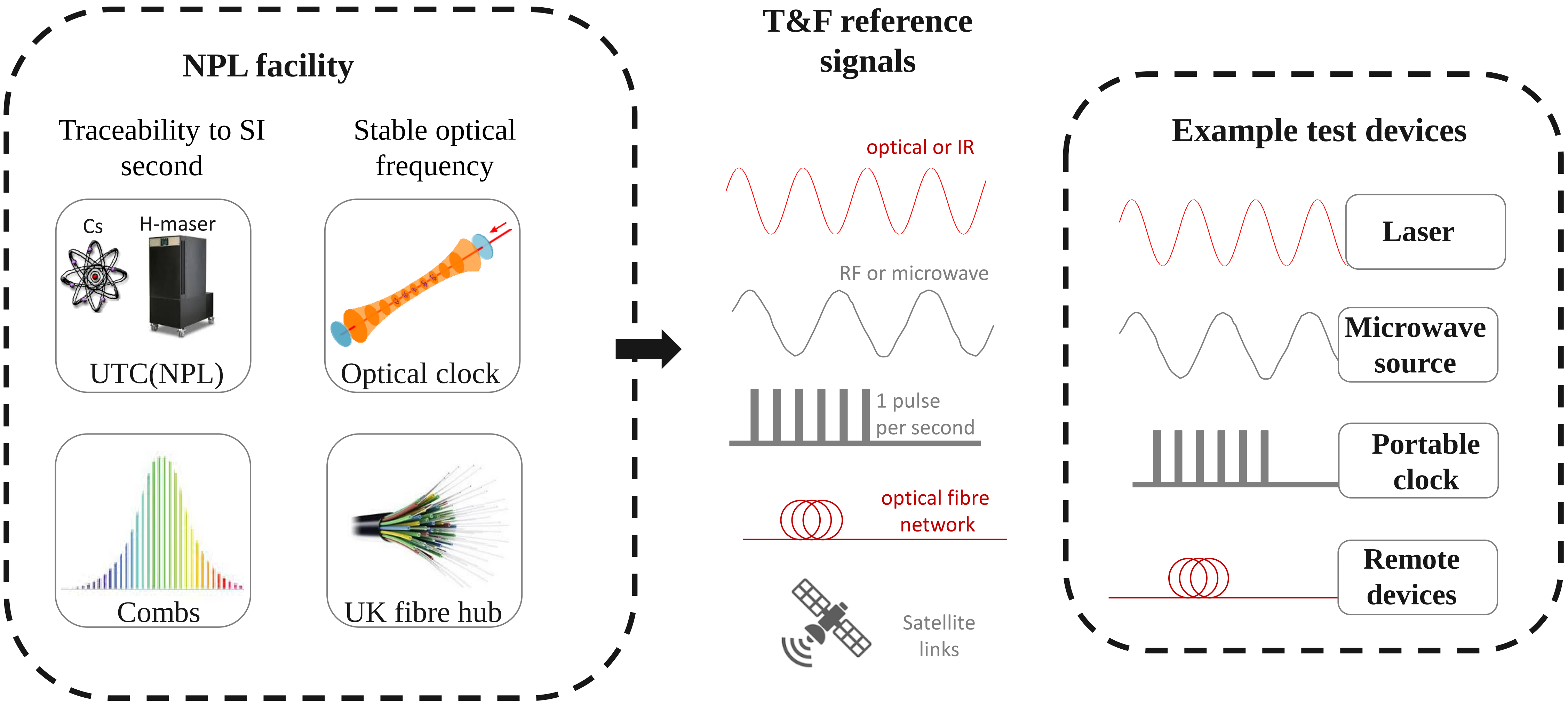

Links with external partners

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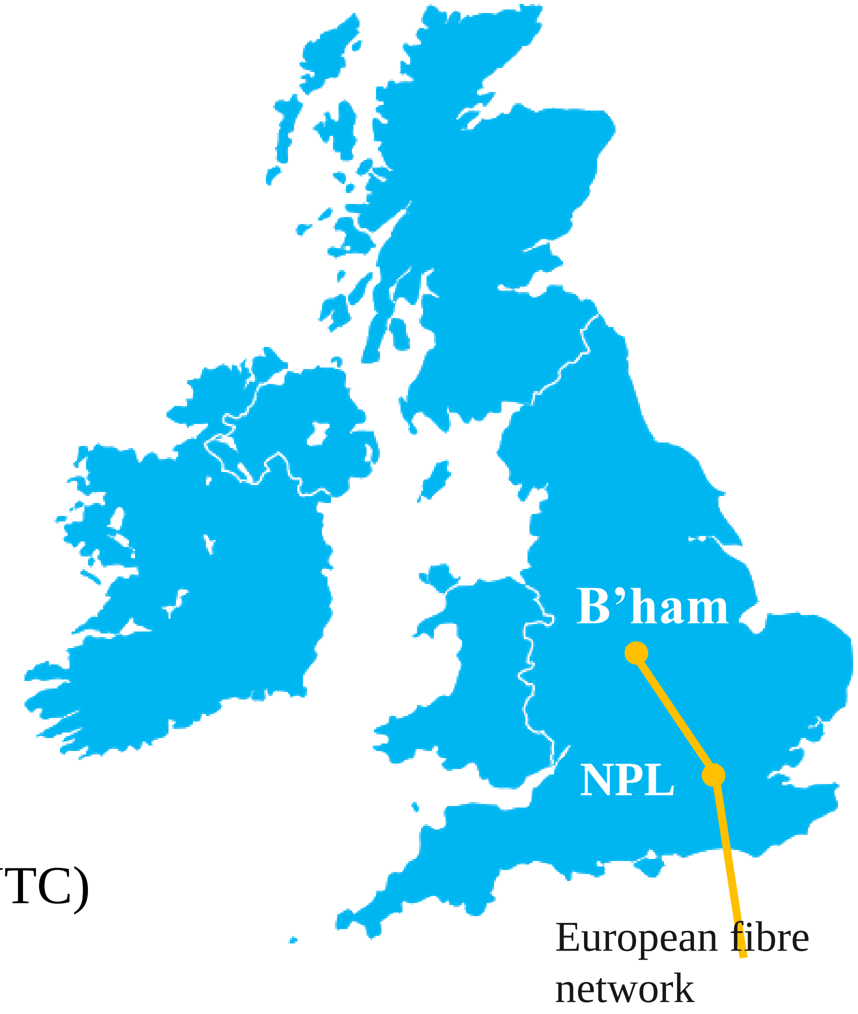
- Academic partners
  - Characterisation of portable clocks developed in NQTP
    - Birmingham, Strathclyde, Sussex, NPL
  - For future spectroscopy and fundamental physics
    - Birmingham, Sussex, Imperial, Durham, Oxford …

- Optical fibre link to Birmingham
  - Dark fibre, transferring both time and frequency signals
  - Applications:
    - Timing signal for Birmingham radar testbed
    - Frequency signal for fundamental physics research
    - Could become a node of National Timing Centre (NTC)



Thank you for your attention!