Automated Parallel Precise Time Calibration of White Rabbit Switches for T-Refimeve

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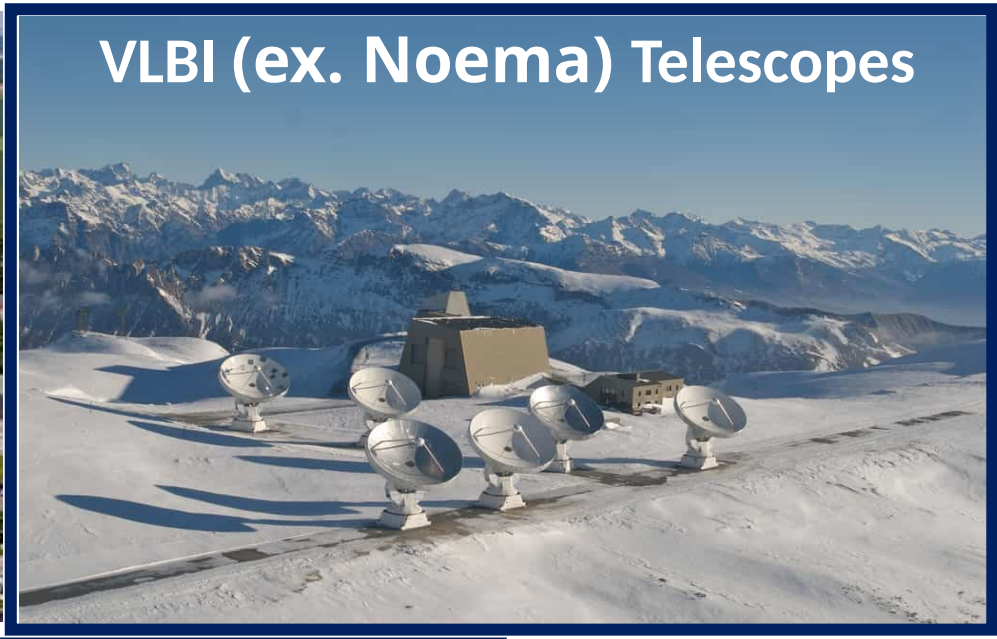
OVERVIEW

- Motivation & Context:
  - White Rabbit (WR) in the context of T-REFIMEVE
  - White Rabbit: key elements and working principle
  - Time accuracy challenges in a live network
- Instrumental delays calibration of WR switches
- Results
- Outlook

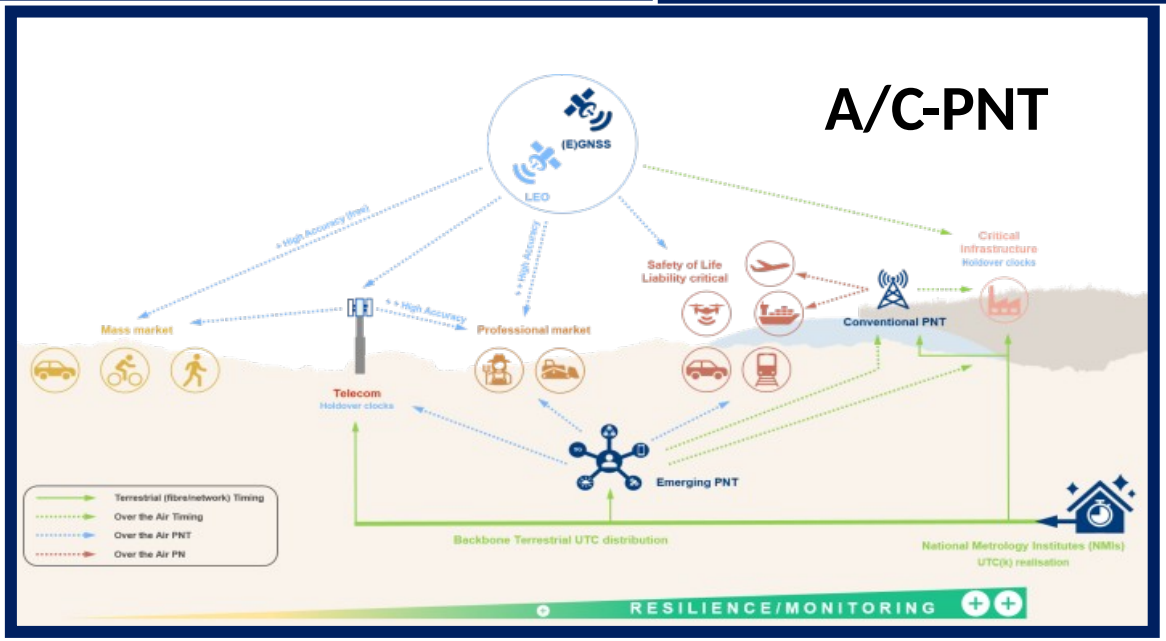
MOTIVATION for RF and Time Dissemination

- **Advanced Scientific Research :**
  High energy physics, Astronomy, quantum telecomm-unications, etc.



- **For society :**
  Complementary / Alternative Position, Navigation and Timing systems

- **Resiliency of infrastructures**



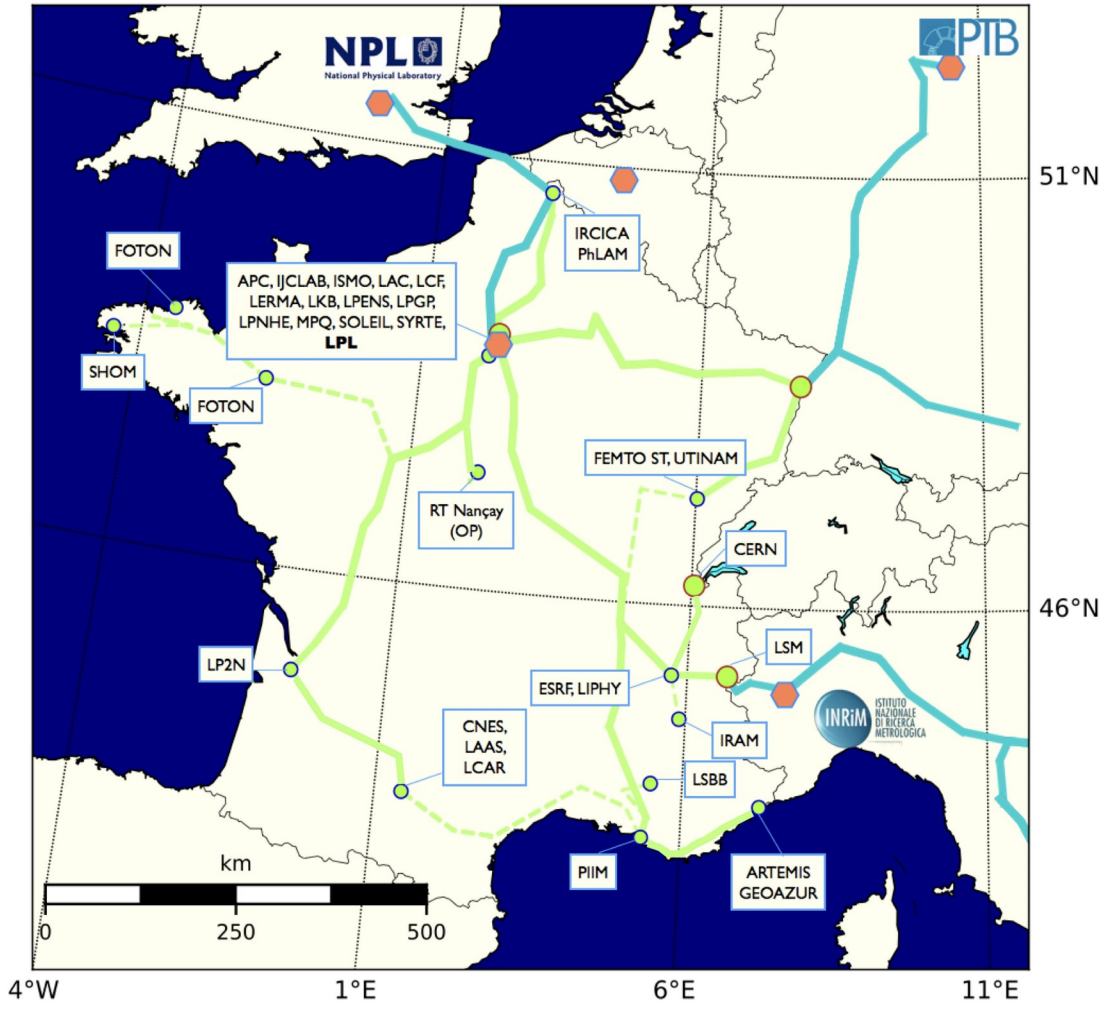
Reference: A/C-PNT: https://joint-research-centre.ec.europa.eu/projects-and-activities/complementary-position-navigation-and-timing_en

REFIMEVE is a French national research infrastructure

- Reference signals originate at LTE, Paris Observatory
- based on the fiber backbone of National Research and Education network RENATER CONNECTEUR DE SAVOIRS
- disseminates time and frequency signals over long distances

It connects +30 laboratories

The network also extends internationally through four cross-border links. Connects CERN

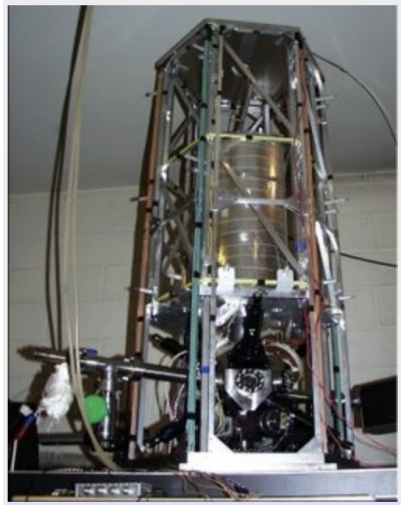


White Rabbit component of T-REFIMEVE

- **Adds Time and RF dissemination -** National-scale WR timing network over 5,000 km optical fiber network.
- Target to achieve time transfer uncertainty of better than 10 ns across more than 80 interconnected nodes over RENATER.

White Rabbit (WR) : Key elements to establish WR

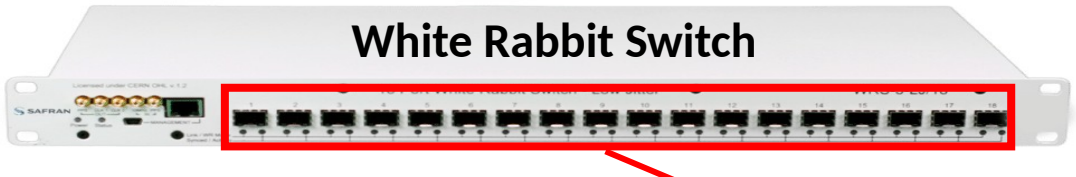
- Most Frequent Questions:
  - How 10 MHz and 1PPS signals are Transferred

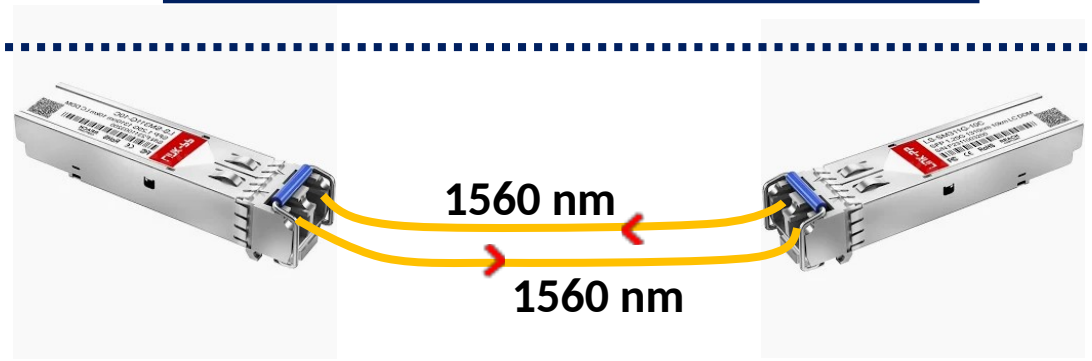


Atomic clock: Source of Reference Signals (Time and Frequency) at LTE

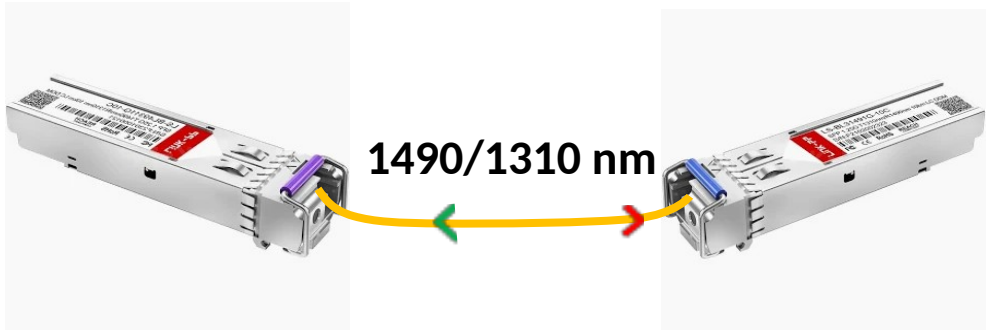
❖ **WR links are standard 1 Gb/s data link**

This is standardised IEEE 1588 protocol



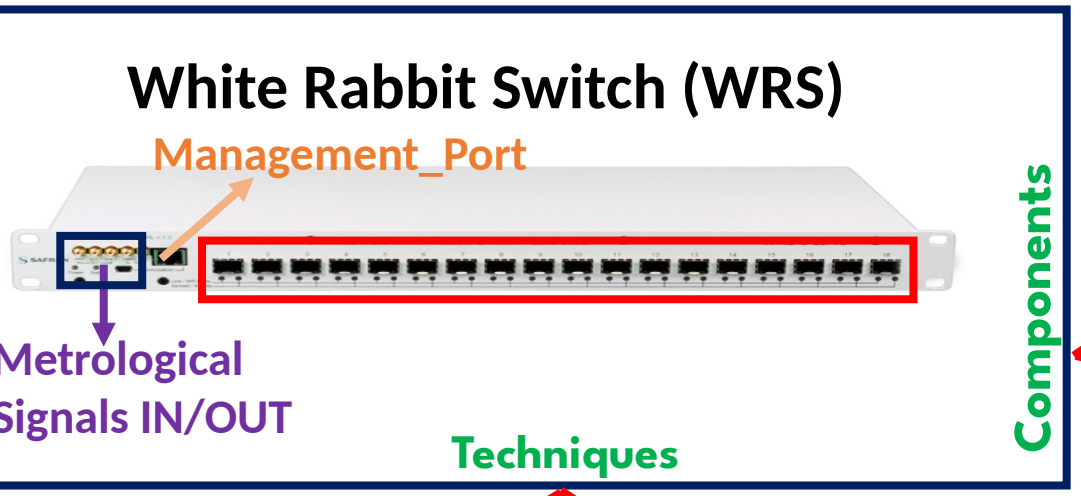


Unidirectional SFPs, same wavelengths on two fibres



Bidirectional SFPs, two different wavelengths on same fibre

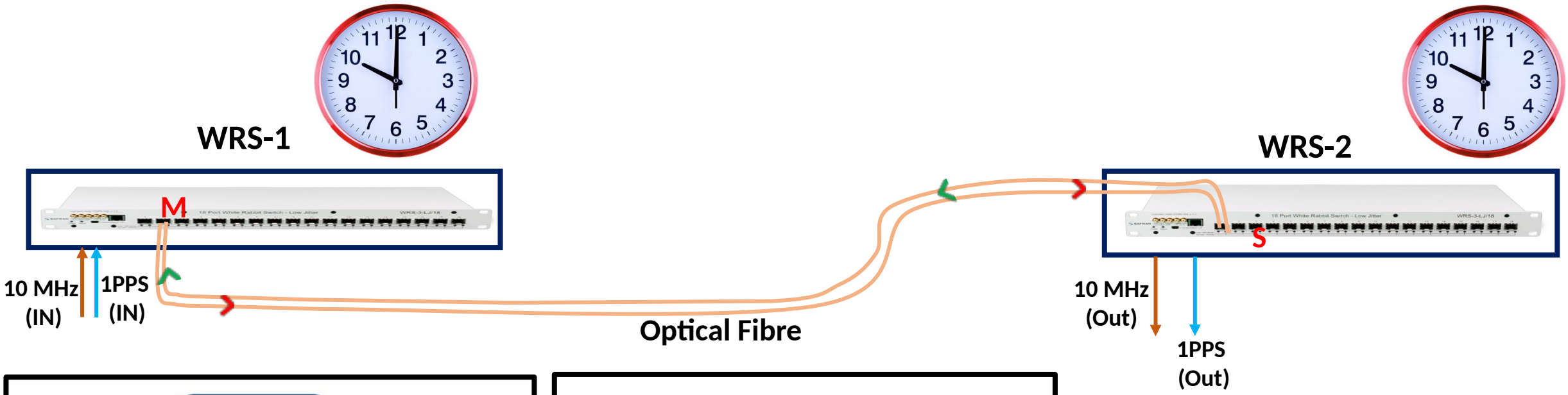
White Rabbit : Key Components and Techniques to Transfer Time and Frequency Signals

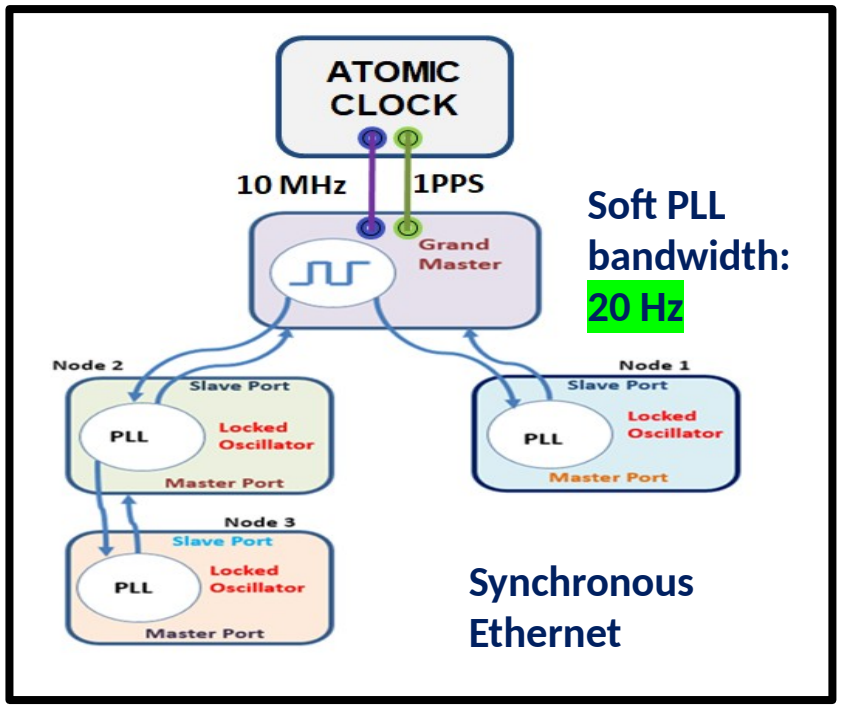


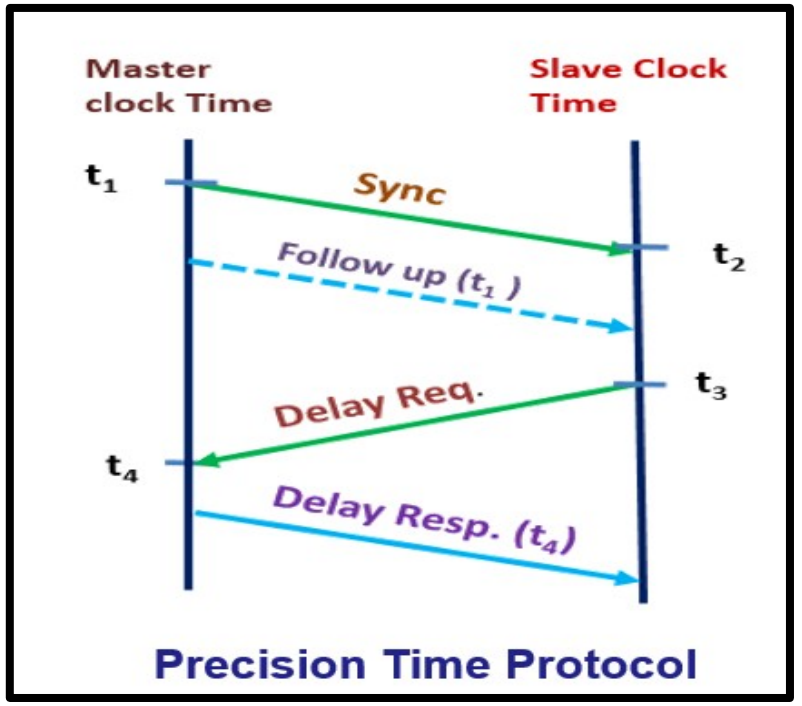
- VCXO- Voltage Controlled Crystal Oscillator
- FPGA- Field Programmable Gate Arrays
- PLL –Phase Locked Loop
- Clock-Data Recovery Circuit
- PPS Generation Circuit

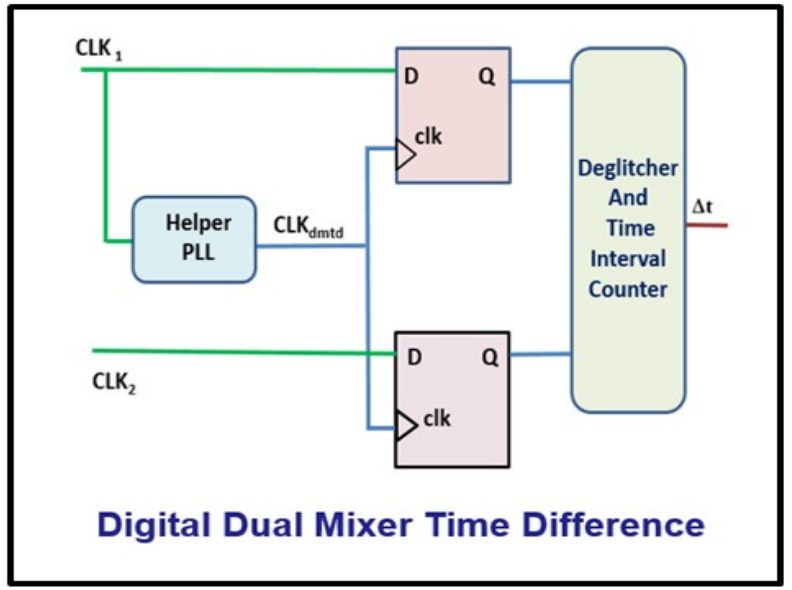
- **Synchronous Ethernet (Sync-E)**
  - Used for Syntonization
- **Precision Time Protocol (PTP)**
- **Digital Dual Mixer Time Difference (DDMTD)**
  - Used for Synchronization at sub-nanoseconds level stability

Time (1PPS) and Frequency (10MHz) Signals Transfer using White Rabbit

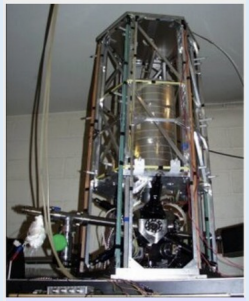








White Rabbit Network



Atomic clocks -> UTC(OP) reference signals: Time (1PPS) and Frequency (10 MHz)

10 MHz(IN)

1PPS (IN)

White Rabbit Switch (WRS)/ Grandmaster

M

10 MHz (out)

1PPS (Out)

Optical Fibre

WRS-3

S

10 MHz (Out)

1PPS (Out)

Optical Fibre

WRS-1

M

M

S

1PPS (Out)

10 MHz (Out)

Optical Fibre

WRS-2

S

10 MHz (Out)

1PPS (Out)

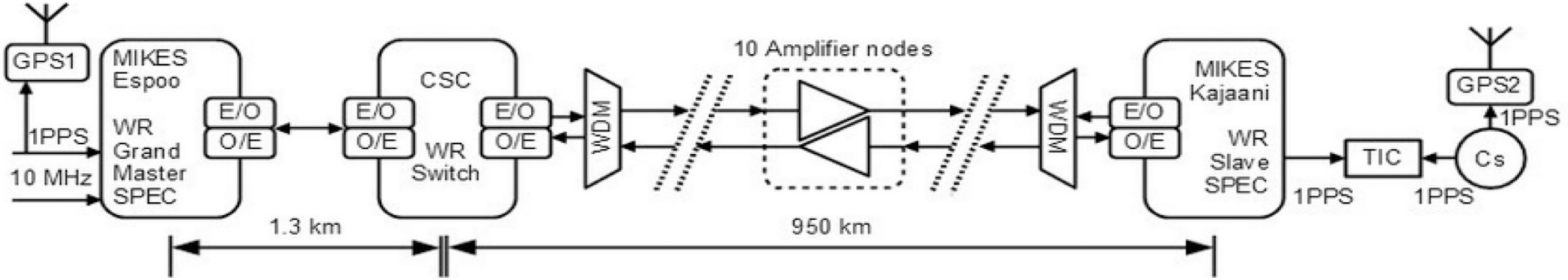
SFP Used:

Unidirectional 1560 nm

Fibre lengths :

From 10 m to Few Hundreds of Km

Long –range White Rabbit Network



Reference: E.F. Dierikx, et al. IEEE T-UFFC 63, 945–952 (2016).

- WR deployment leverages the unidirectional optical amplifiers of the RENATER backbone. WR packets are transmitted as alien wavelengths.
  - ✓ Cost reduction
  - ✓ Faster deployments
  - ✓ Meets most of user's need with specific objective : < 10 ns accuracy
- Standard xWDM technology and long haul telecommunication backbone

Challenges: Accurate Time Transfer in a live network

- WR Link Delays = Instrumental delays (hardware and firmware delays at both ends : master and slave WR switches) + Propagation delays (signal travel time through fibre, amplifiers, etc)

Time Calibrations involves :

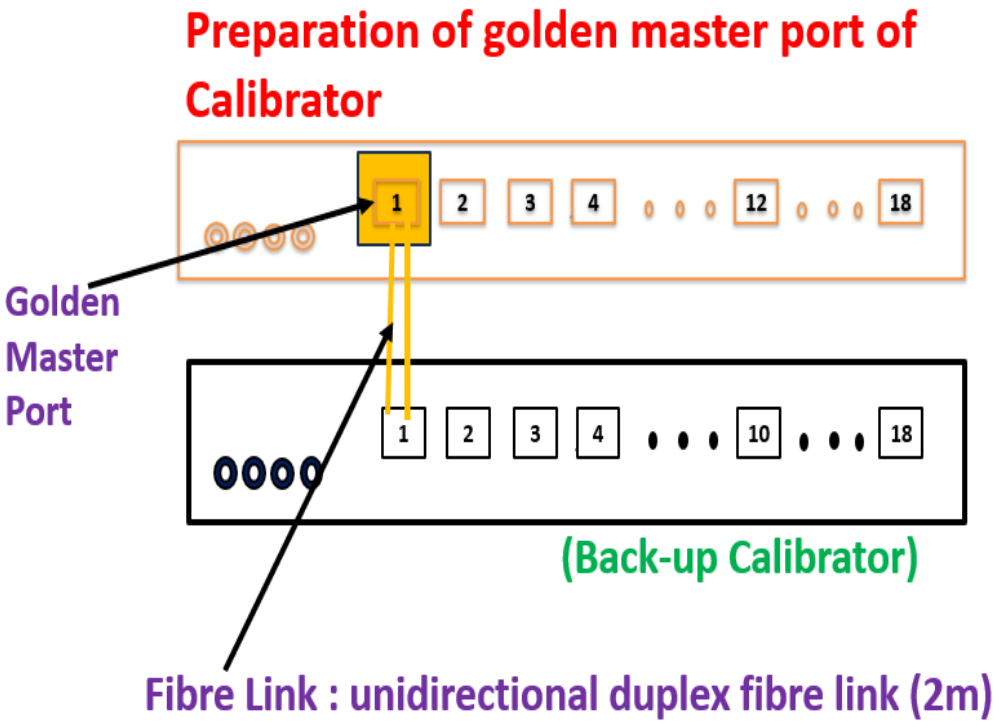
Calibration of the instrumental delays (before the deployment of the WRS in the network)	+	Calibration of the propagation delays (on a live network)

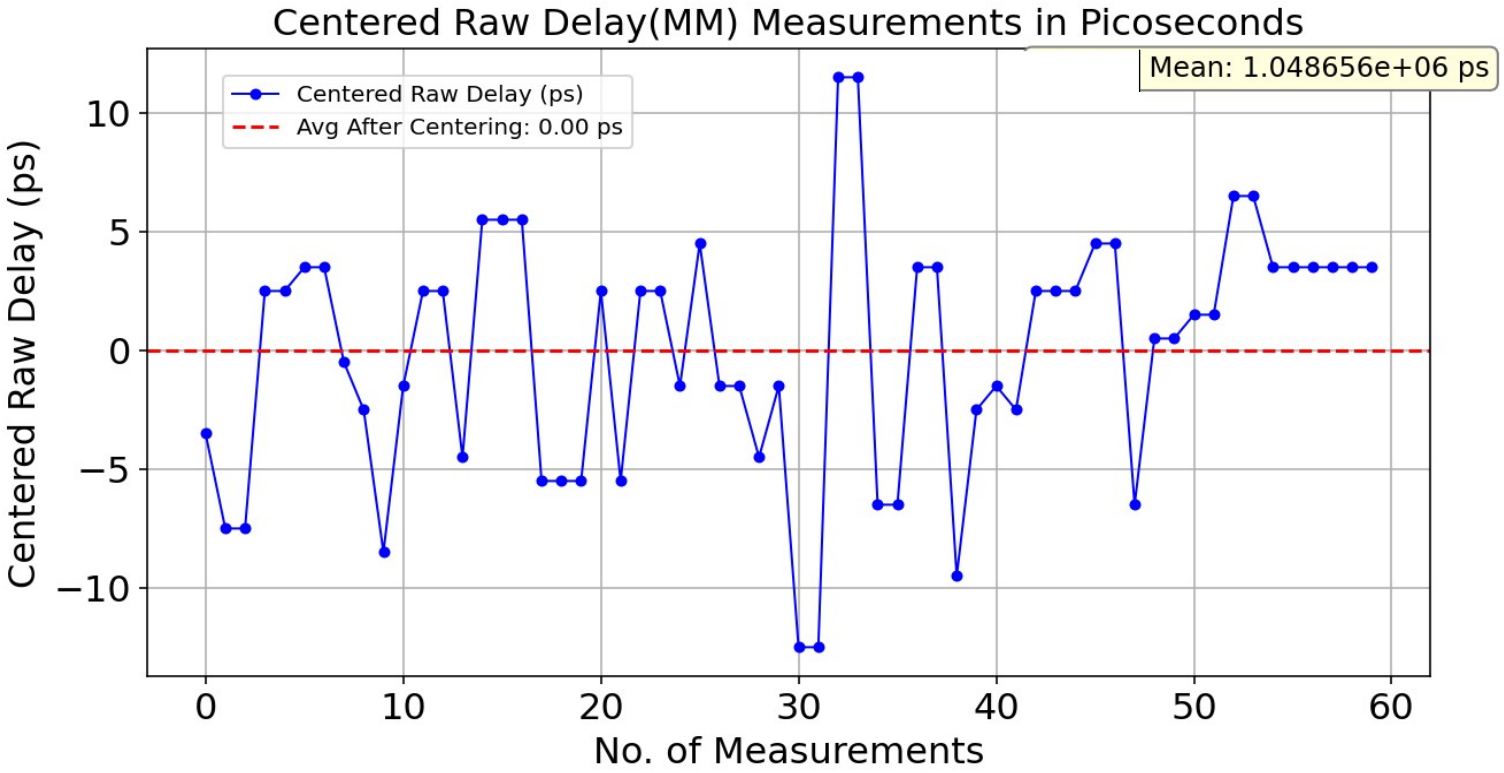
Key Challenges are :

1. Instrumental delays : Calibration of +80 switches with several port
2. Propagation delays : Estimation and mitigation of the propagation time asymmetry in forward – backward path introduced by active and passive components in the live network

Steps for preparing WRS switch Golden Calibrator

Performed with v7 and v8





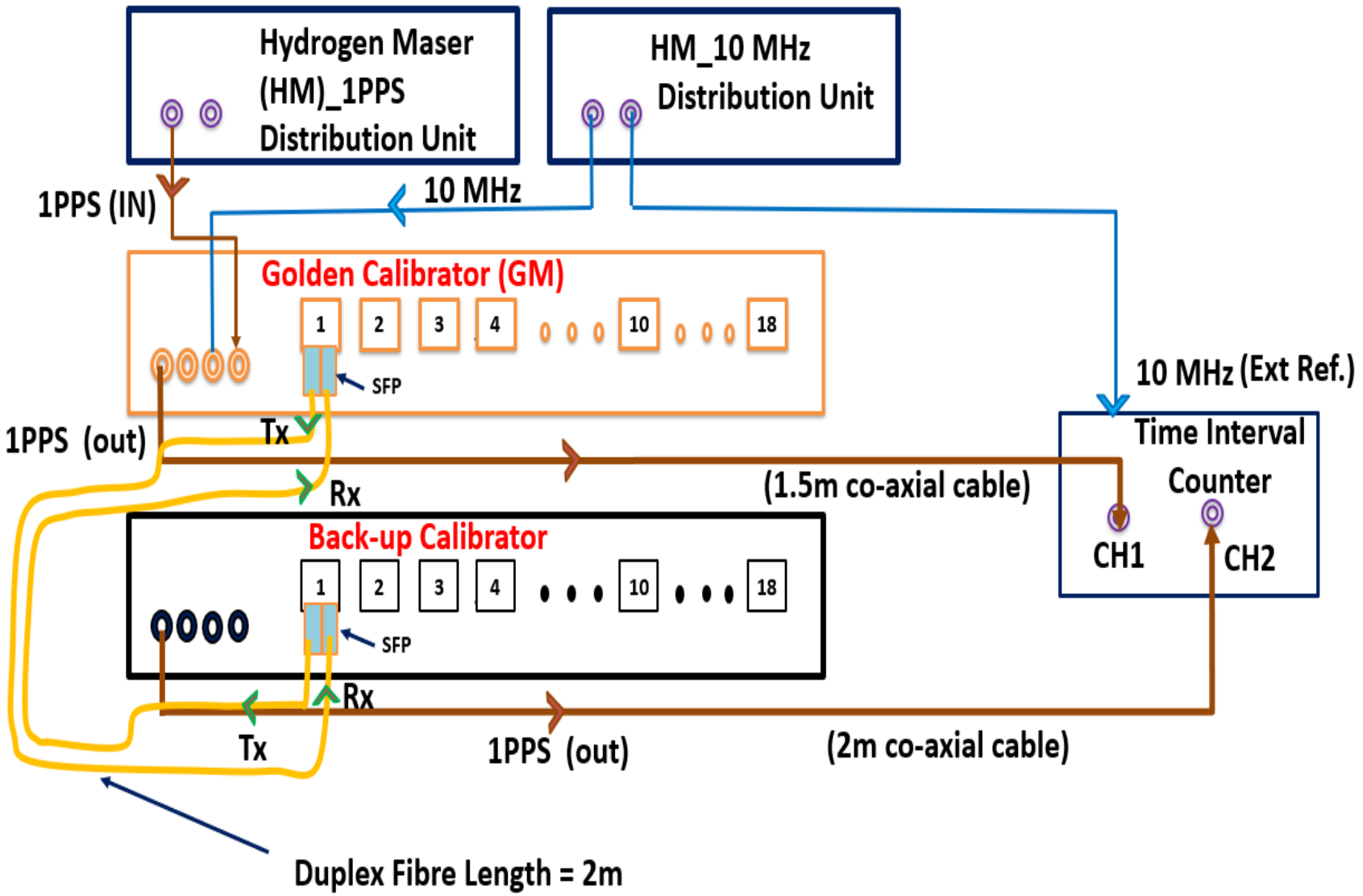
SFP Port	Egress (Tx) delays (ps)	Ingress (Rx) delays (ps)
1	257131	257131

$$Delay_{MM} = \text{Instrumental delay} + \text{Propagation delay}$$

1. $Delay_{MM}$ = 1048.656 ns
2. Round trip delay of the 2m fibre = 20.134 ns

*Reference : "White Rabbit calibration procedure version 1.1 https://white-rabbit.web.cern.ch/documents/WR_Calibration-v1.1-20151109.pdf).

First port instrumental delays Calibrations of WRS back-up Calibrator



Three steps to calibrate instrumental delays :

1. Calculation of asymmetric delay coefficient
2. Total round trip delays Delay MM (master to master) measurement to estimate coarse instrumental delays
3. Time offset measurement between master and slave WRS using TIC and adjust the coarse delays by measured time offset to get the fine calibrated values of Egress (Tx) and Ingress (Rx).

Raw Measurements for port 1 calibration of Back-up Calibrator

The asymmetric delays measured using fibre swapping method : -18 ps

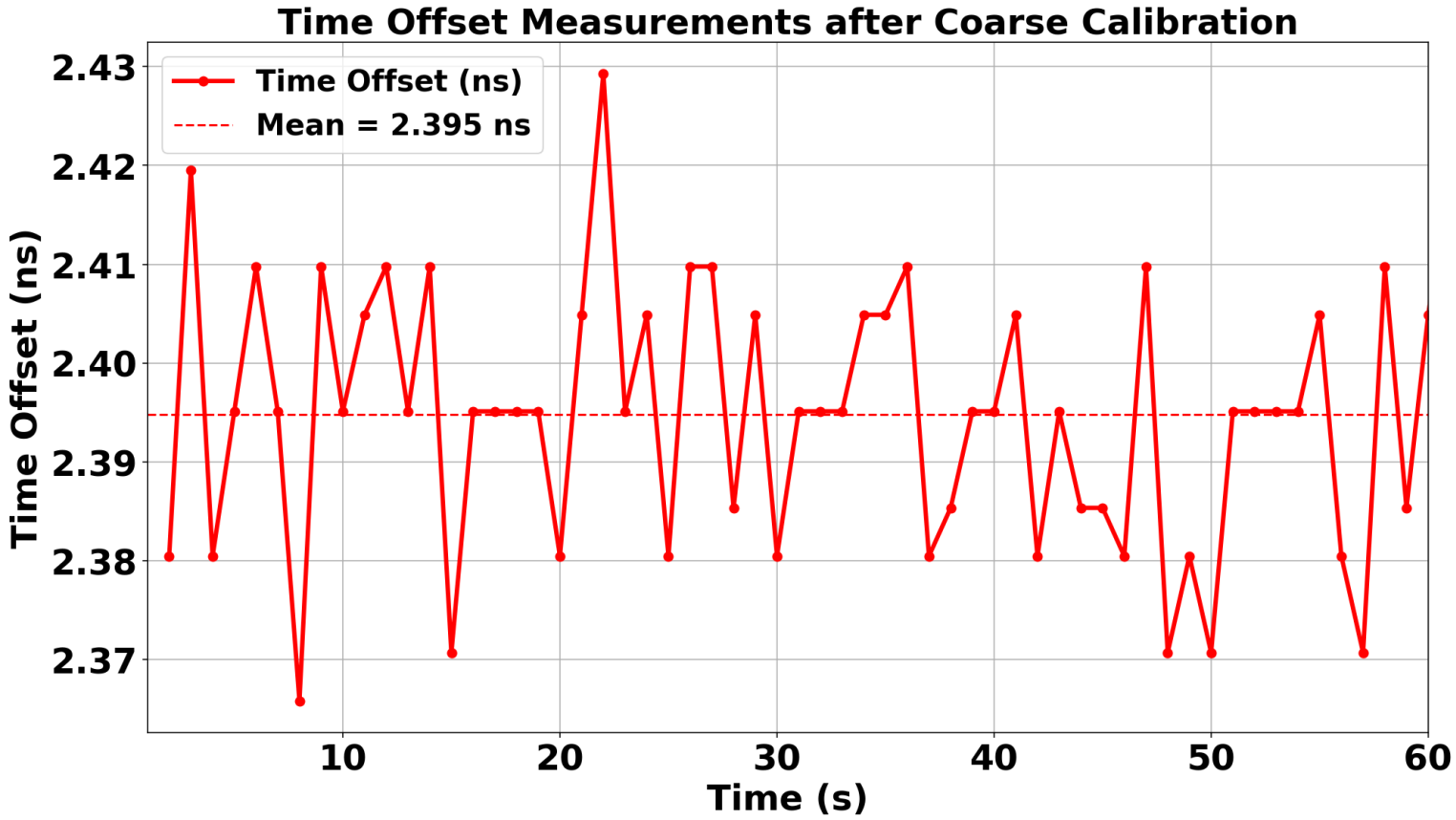
Asymmetric delays coefficient for the same (2m) fibre:

- 0.0017864

Fine Calibration of instrumental delays:

ΔTXS = (257130 - 99) ps
= 257031 ps

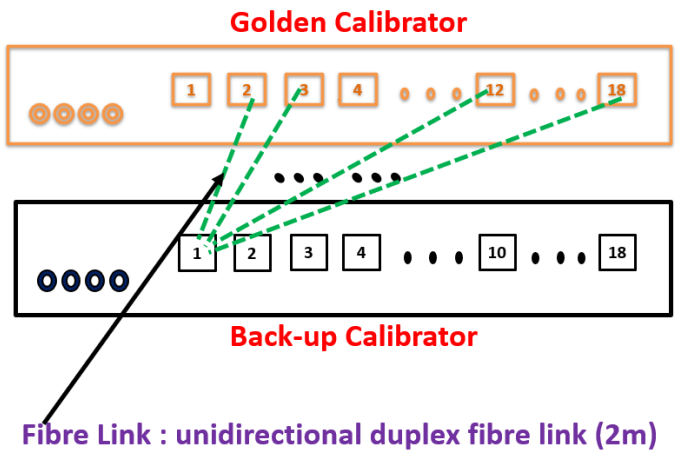
ΔRXS = (257130 +99) ps
= 257229 ps

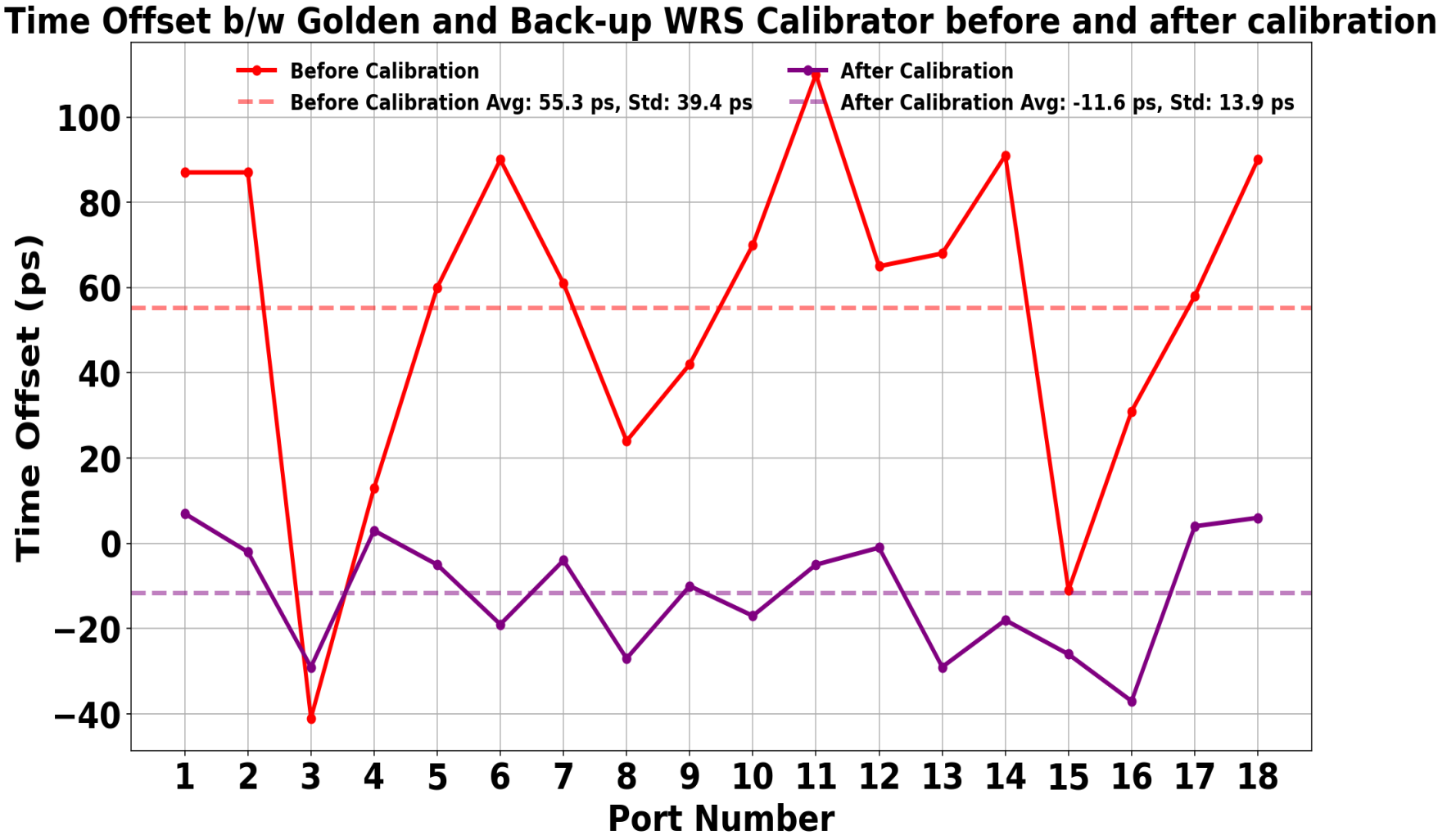


Actual Time offset = (2.395 -2.296)ns
= 99 ps

Fixed delay due to cable length difference

Results: Instrumental delays Calibrations of WRS Golden Calibrator





In this case study: The fibre link connection was made between first port (slave) of back-up WRS calibrator and first port (master) of Golden WRS calibrator and then keeping the same slave port, master ports were changed from port 1 to port 18.

Instrumental delays calibration of WR switches

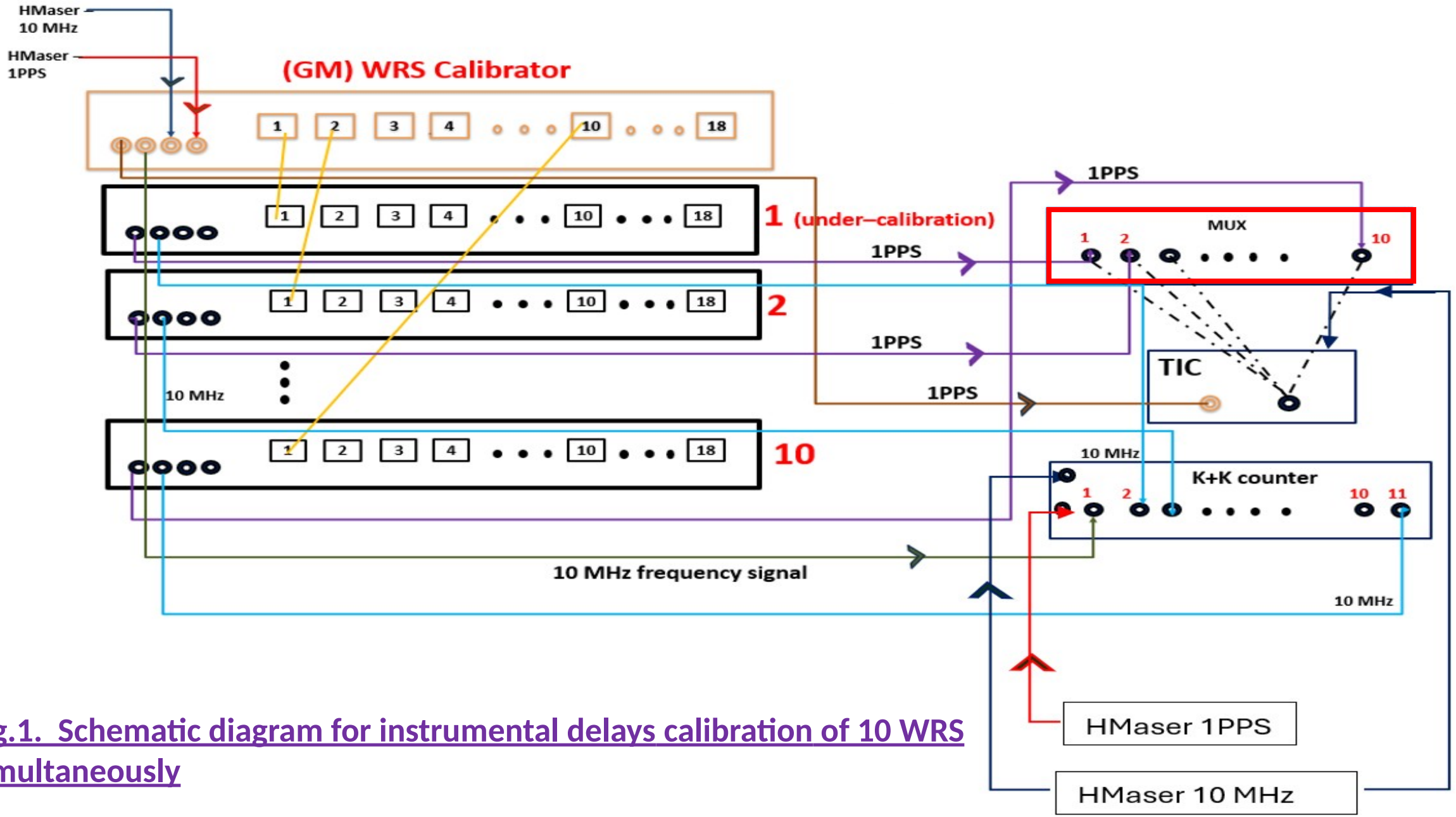
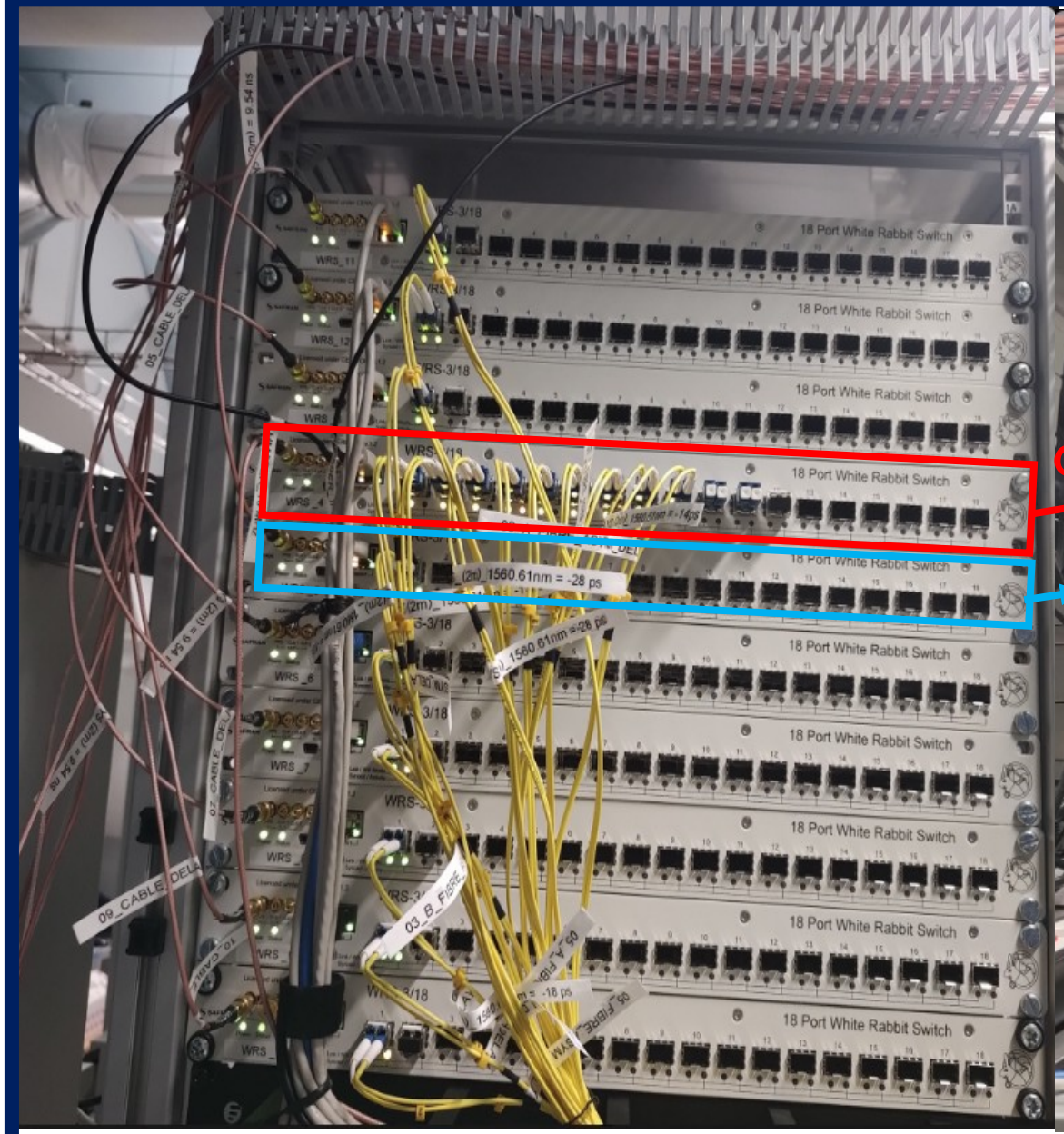


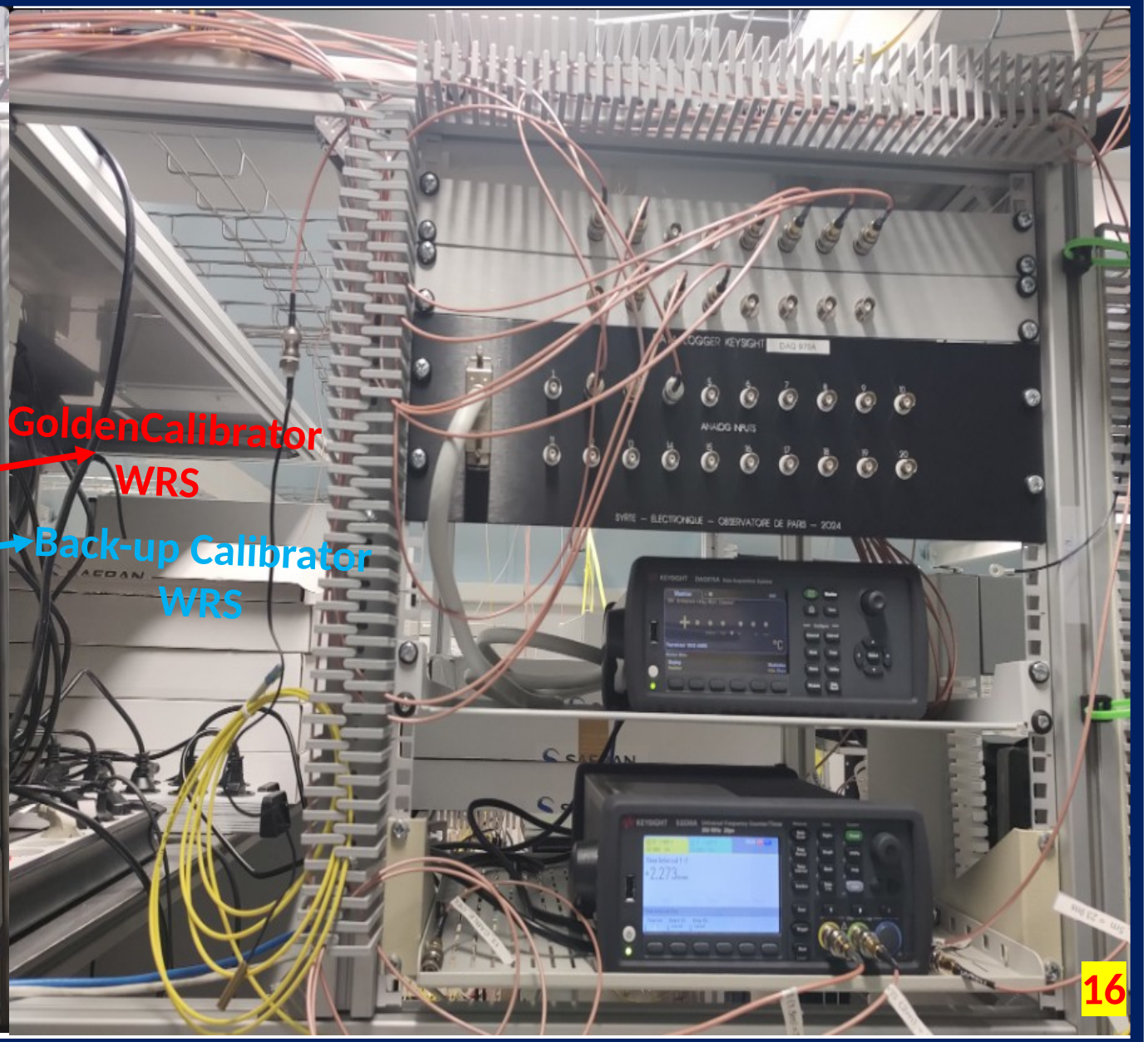
Fig.1. Schematic diagram for instrumental delays calibration of 10 WRS simultaneously

Image of Experimetal Setup for Instrumetal delays calibration of WRS



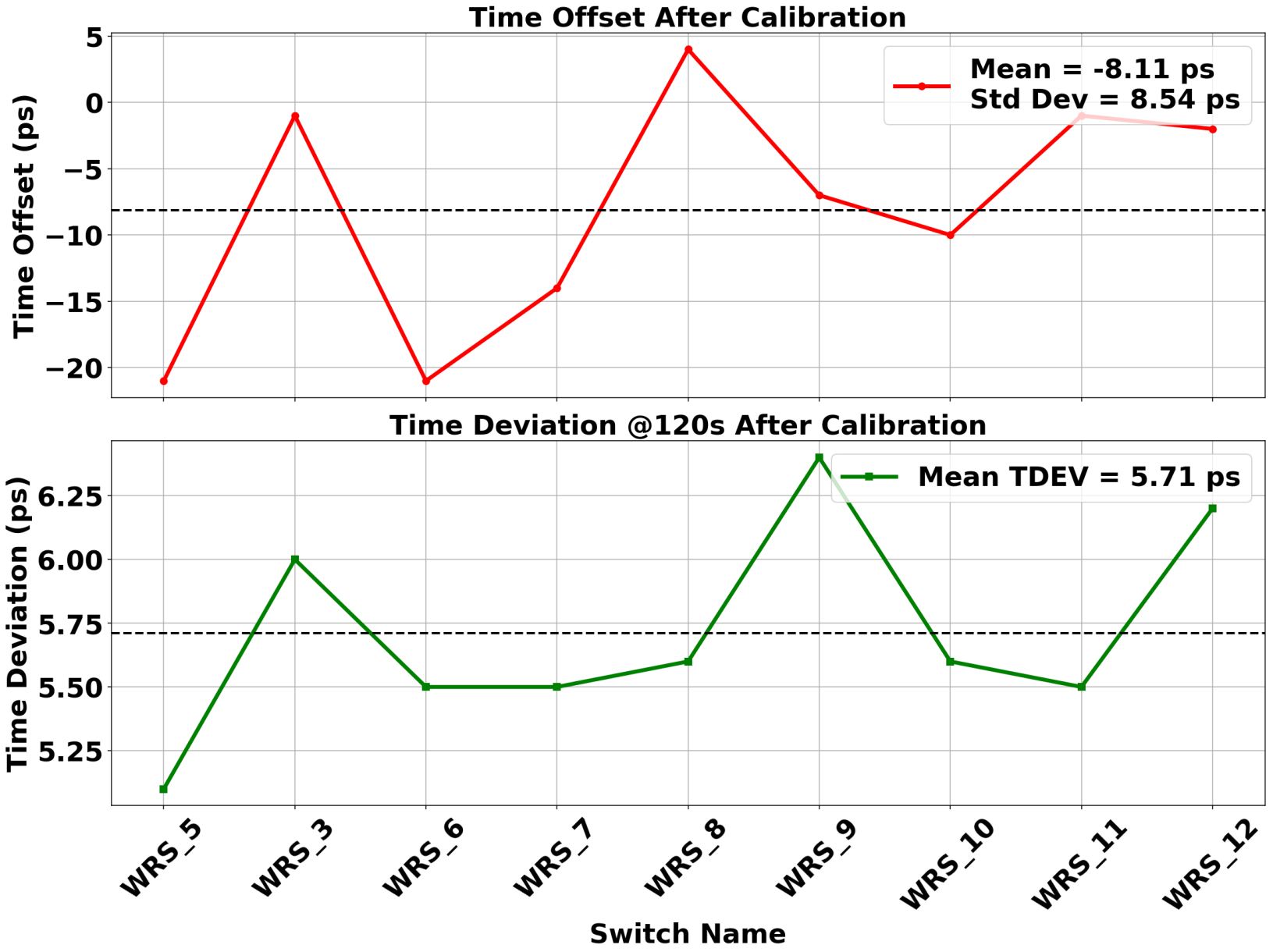
GoldenCalibrator
WRS

Back-up Calibrator
WRS

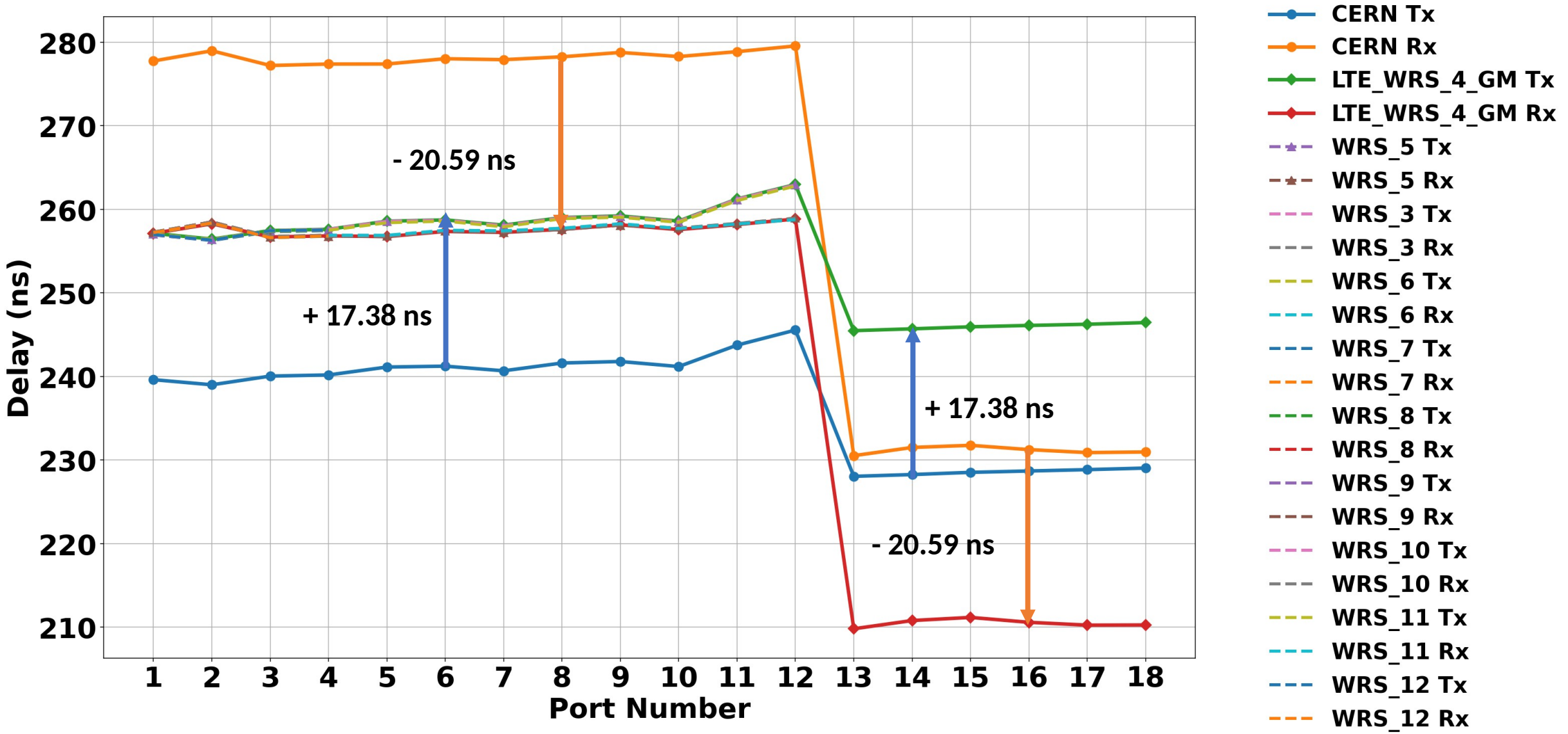


Results Contd.

Time offset and Time Stability for the WR switches calibrated at LTE



Contd. Results: Comparison of Tx and Rx delays of LTE calibrated and CERN calibrated switches



Outcomes

- We build a calibration benchmark for REFIMEVE.
  - SFP used:
    - 1560 nm, 160 km, 1 Gb/s
    - Uni-directional (2 fibers)

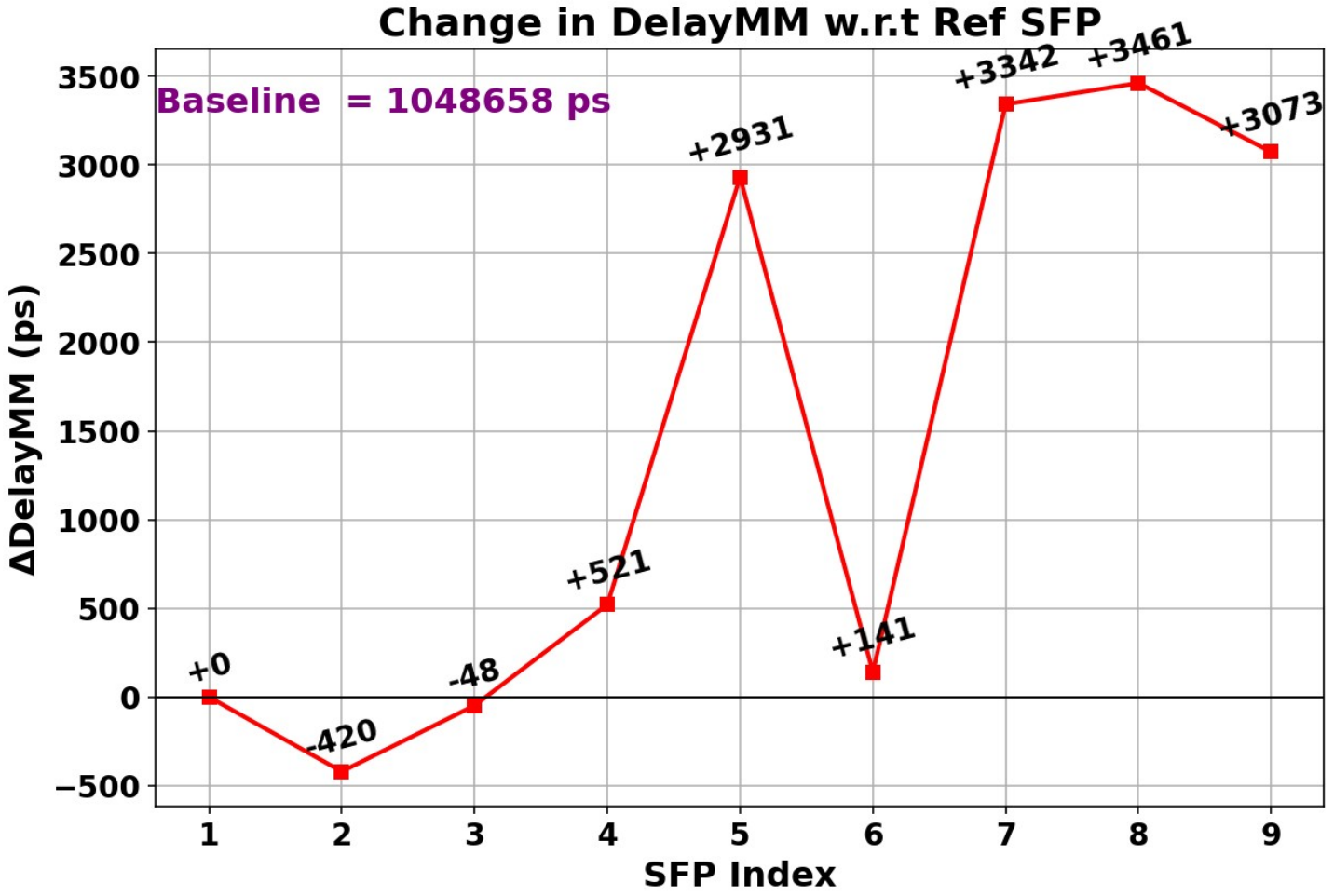
- Our reference can be represented as offsets from the CERN reference delays (Egress and Ingress):

  Egress (Tx) = +17.38 ± 0.07ns (preliminary statistical uncertainty)

  Ingress (Rx) = -20.59 ± 0.08 ns

SFP Calibration

- SFP calibration: delay corrections relative to our reference SFP
- Total delay variations on changing the SFPs: up to 4 ns
- Asymmetry variations: 10s ps
- 16 SFPs (distinct part numbers) used in refimeve network have been calibrated.



Index	SFP Type
1	1560.61_wavetel
2	1560.61_FS
3	1547.72_FS
4	1550_FS
5	1550_FiberStore
6	1510_FS
7	1490/1310_AXCEN
8	1490/1310_FS_10km
9	1490/1310_FS_20km

Additional Tests

Other tests were performed (v7):

- Connection/disconnection: < 10 ps (tested with LPDC ports)
- Shut - down, power cycle: < 10 ps (tested with LPDC ports)
- Reboot of GM (tested with v7 and v8) : Misalign PPS_OUT with PPS_IN by few nanoseconds

Outlook

- Instrumental Delays Calibration : 50 WRS (including WRZEN) completed
- Deployment of WRS in Refimeve network for Paris Region : Completed
- Currently preparing for WRS deployments within REFIMEVE network across France.

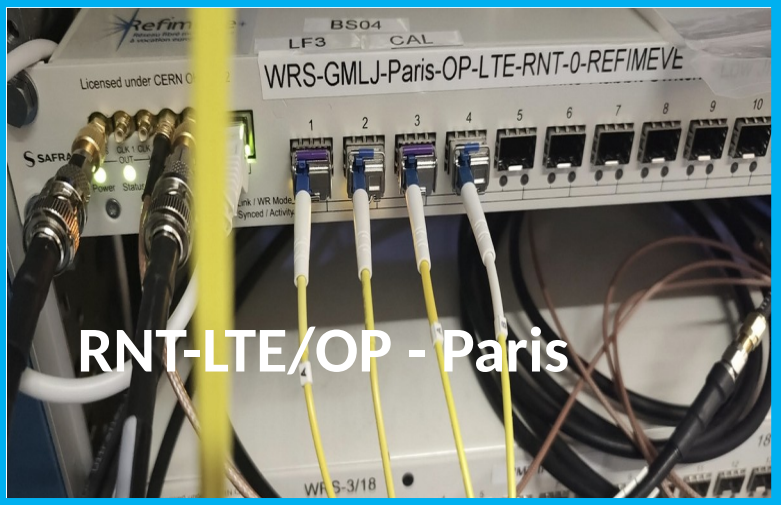
- Concerns and Future works:
  - To estimate propagation delay and mitigate active components delay that induces time-varying asymmetries.
  - Daisy chain : up to 9 WRS in cascade at worse case.
    - Issue* ? If yes, mitigation strategy ?

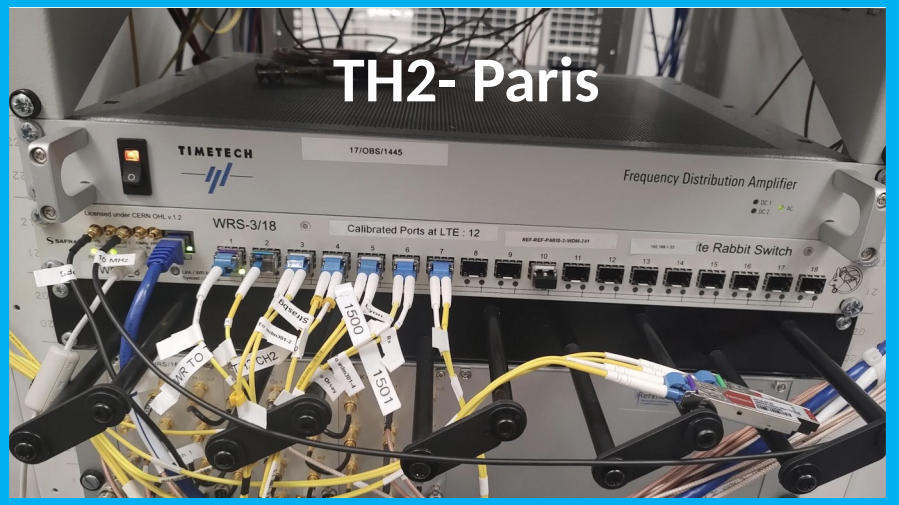
*References:

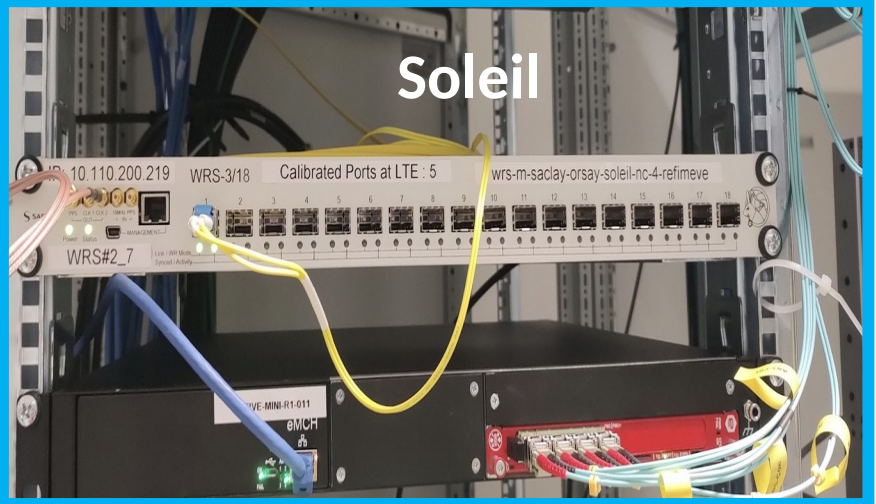
1. J. L. Gutiérrez-Rivas, et al; « Enhancing White Rabbit Synchronization Stability and Scalability Using P2P Transparent and Hybrid Clocks », *IEEE Transactions on Industrial Informatics*, 2021.
2. Kaur, Namneet, et al. "Time and frequency transfer over a 500 km cascaded White Rabbit network." *2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*. IEEE, 2017.

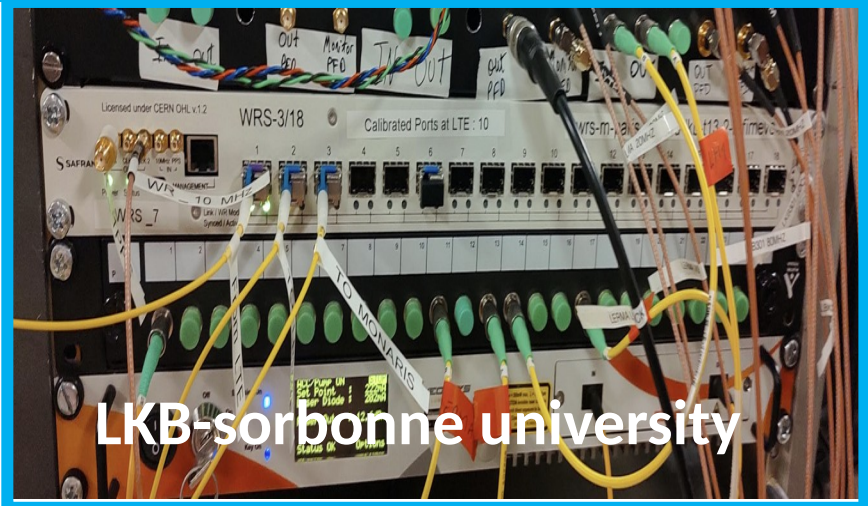
- Exploit scientifically the network

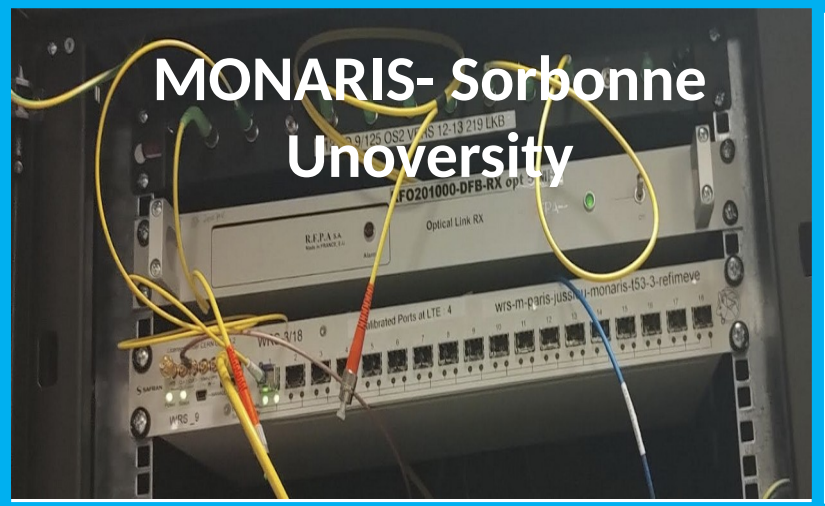
Images and List of WRS Deployed in Paris Region

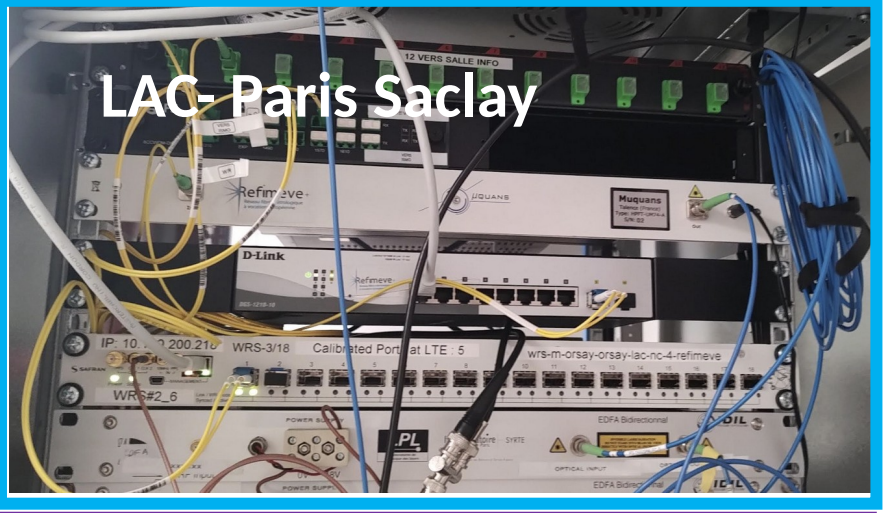










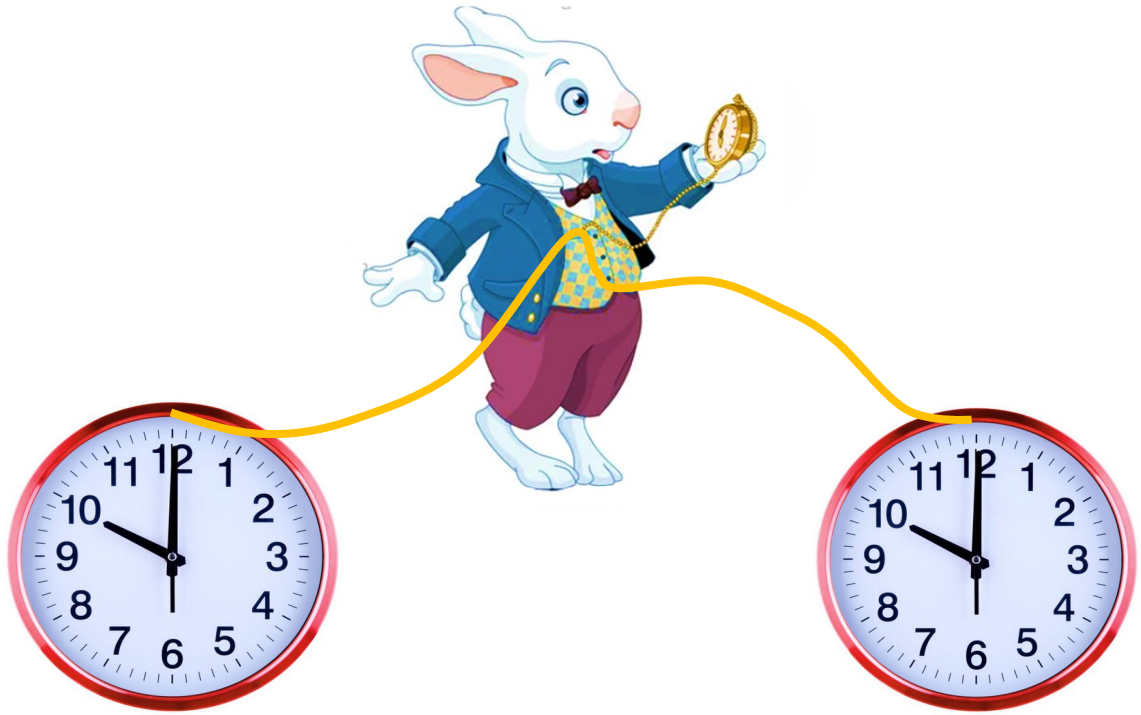


Deployed Calibrated WRS List :

- Observatoire de Paris
- Paris-Saclay, University
- Sorbonne University, Jussieu
- Nancay

Upcoming/Next Deployments:

- Lille
- Reims, Nancy, Strasbourg



Thank You