Time transfer over a White Rabbit network

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8 June 2017

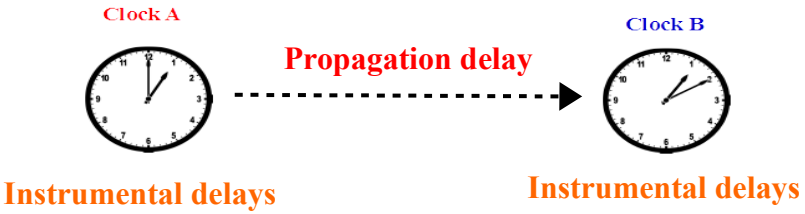
FIRST-TF General Assembly, l'Institut d'Optique d'Aquitaine, Talence.

Outline

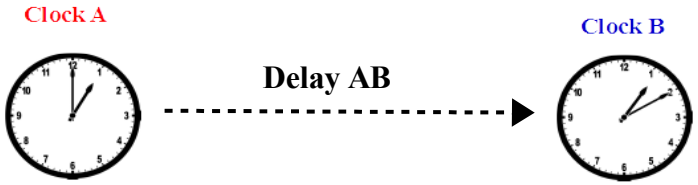
- A brief introduction to Time transfer
- Experimental work on improving White Rabbit (WR)
- Latest experimental results using a cascaded 500 km White Rabbit link
- Outlook

A brief review of time transfer methods

Time transfer = mastering delays
- Instrumental delays
- Propagation delays
- Other… (Sagnac effect)

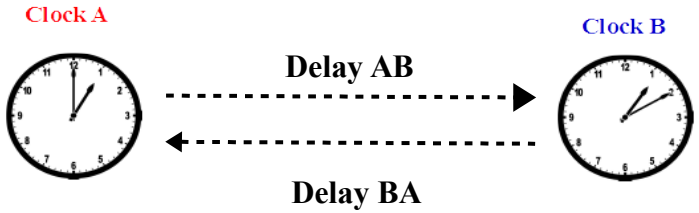


One way time transfer



- The path delay AB needs to be determined.
  - Hypothesis
    - A signal is sent from clock A
    - Input :
      - Celerity of the waves
      - Propagation modeling
      - Spatial coordinates
    - Measure a time interval at B side
- Applied in GPS time transfer method

Two way time transfer



- Both clocks must transmit signals.
- Measure the Round trip time (RTT).
  - One way delay is estimated as half of the round trip value.
  - Results depend on the hypothesis that the path delay is same in both directions.
- Applied Two-Way satellite T&F transfer, NTP, PTP...

Performance comparison of some Time transfer methods

Very high performance time transfer through optical fiber links

Accuracy ~ few 100 ps to a few ns

Range ~ hundreds of km, National/continental scale

High performance time transfer by Two way Satellite time transfer and GPS common view methods

Accuracy ~ a few ns

Range ~ more than 1000 km
GPS CV ~ Global scale

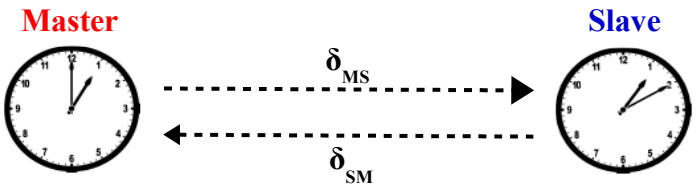
Time over Internet by
Network time protocol (NTP)
Precision Time Protocol (PTP)
White Rabbit PTP (WR-PTP)

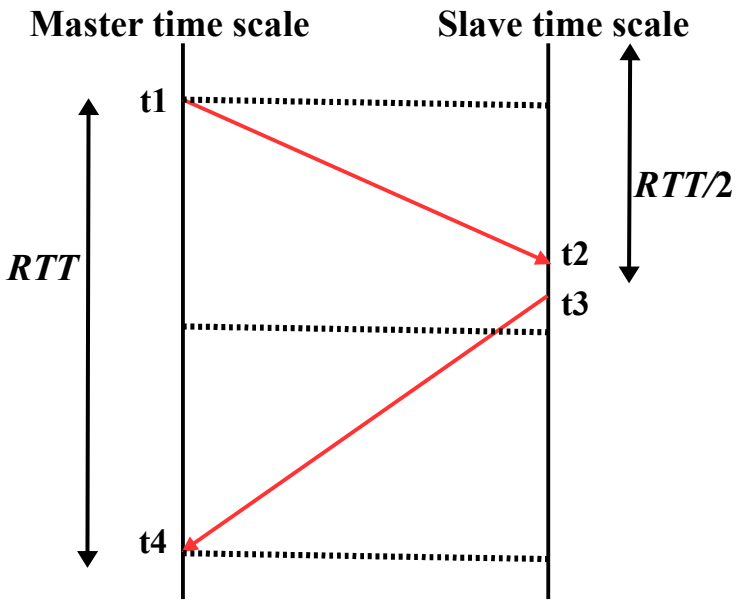
Accuracy NTP ~ ms
PTP ~ µs
WR-PTP ~ ns range

Range NTP-WAN
PTP-LAN
WR-PTP – typical 10 km, extended up to 1000 km

Introduction to White Rabbit (WR) technology

(WR-) PTP : Precision Time Protocol (IEEE 1588)





- Frame-based synchronization protocol.
- Synchronizes slave clock with the master clock.
- Link delay evaluated by measuring and exchanging frames with tx/rx timestamps.

Round trip time (RTT) = (t2−t1) + (t4−t3)

Link latency δ_{MS} ***= RTT/2***

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

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

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

Add-ons of WR-PTP : SyncE, DDMTD and asymmetry compensation

Synchronous Ethernet (SyncE)

- Layer-1 syntonization
- A common frequency reference for the entire network
- All nodes of the network are locked to the frequency of the System timing master

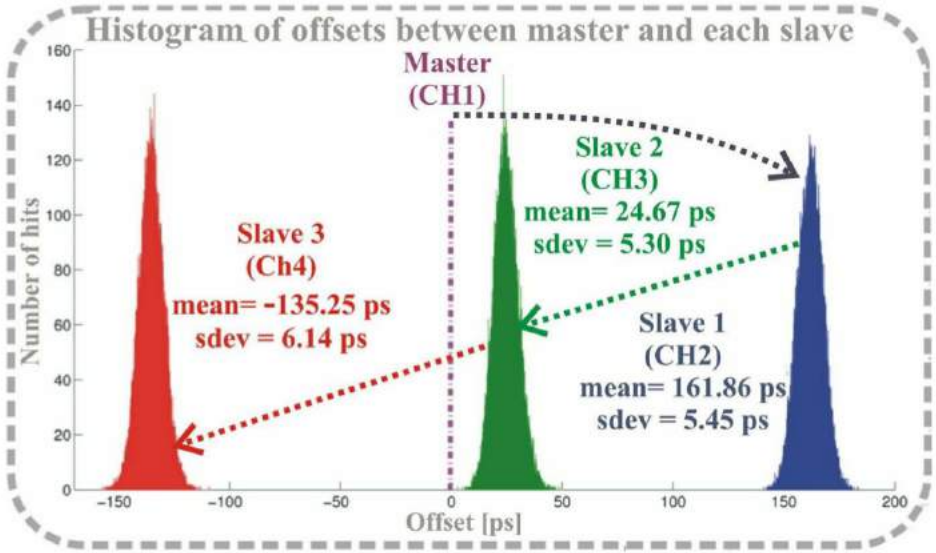
Digital Dual Mixer Time Difference (DDMTD)

- Precise phase measurement
- A phase compensated clock signal for the slave

Asymmetry compensation

- PTP accounts for node asymmetries.
- Sources of propagation asymmetry in a White Rabbit link:
  - **Chromatic dispersion** (in a bidirectional single fiber (Bi-color) link, the wavelength in one way is different from the wavelength in the opposite direction)
  - **Unequal fiber lengths** (in a unidirectional dual fiber (Bi-fiber) link, the fiber length in one way is usually different from the fiber length in the other way).
  - 'Static' correction of propagation asymmetry possible with WR.

White Rabbit technology: Early results @ CERN (2013)

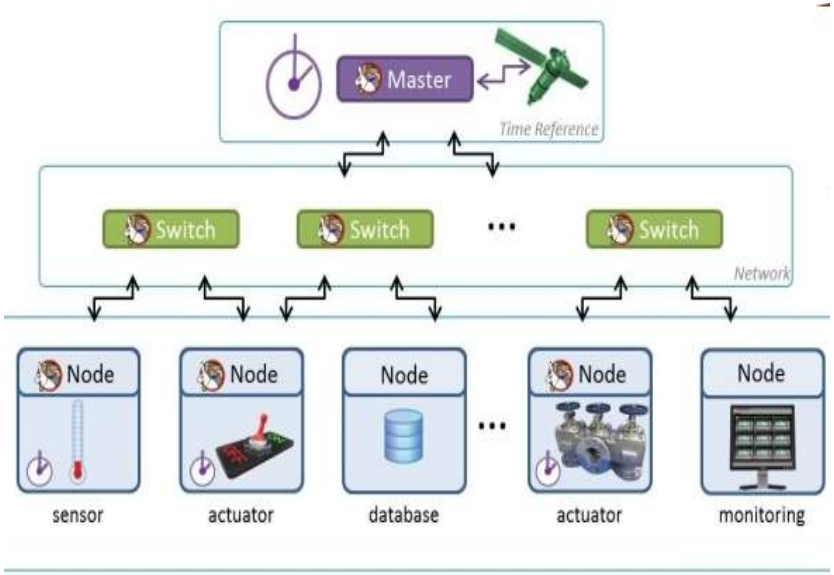


Histograms of PPS output offsets of three cascaded WR switches with respect to the PPS pulse output in the master switch.

White Rabbit technology: some nice features

- Gigabit Ethernet data transfer
- Single/Dual fiber medium, works also on air !
- Network hierarchy : scalable to 1000s of nodes
- Developed by CERN for typ. 10 km
  - Extension to longer distances up to 100-1000 km on telecom backbones (VTT, VSL*)
- **Fully open hardware and software**
  - Initiated by CERN in 2008. After 10 years:
  - Mutli-laboratory
  - Multi-company collaboration
  - >60 engineers involved
  - Standardization @ IEEE1588 : 2018?

Extremely fast developments

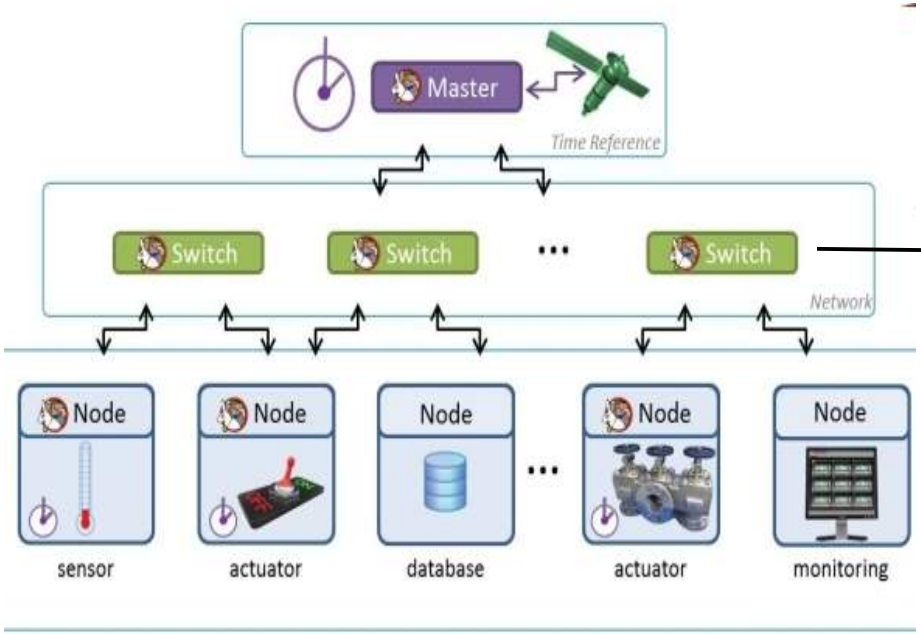


Schematic of a White Rabbit Network

* E.F. Dierikx et al, "White Rabbit Precision Time Protocol on Long Distance Fiber Links", DOI: 10.1109/TUFFC.2016.2518122 (2016).

White Rabbit equipments

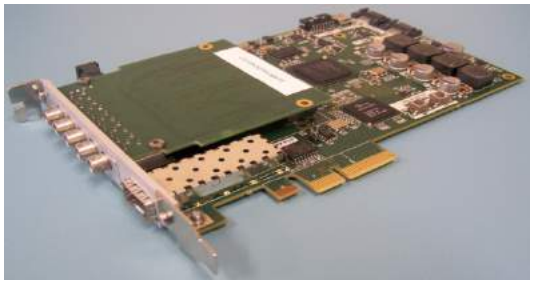
Collaboration with SevenSol



Emission/detection :
Small form factor pluggable (SFP) optical transceivers

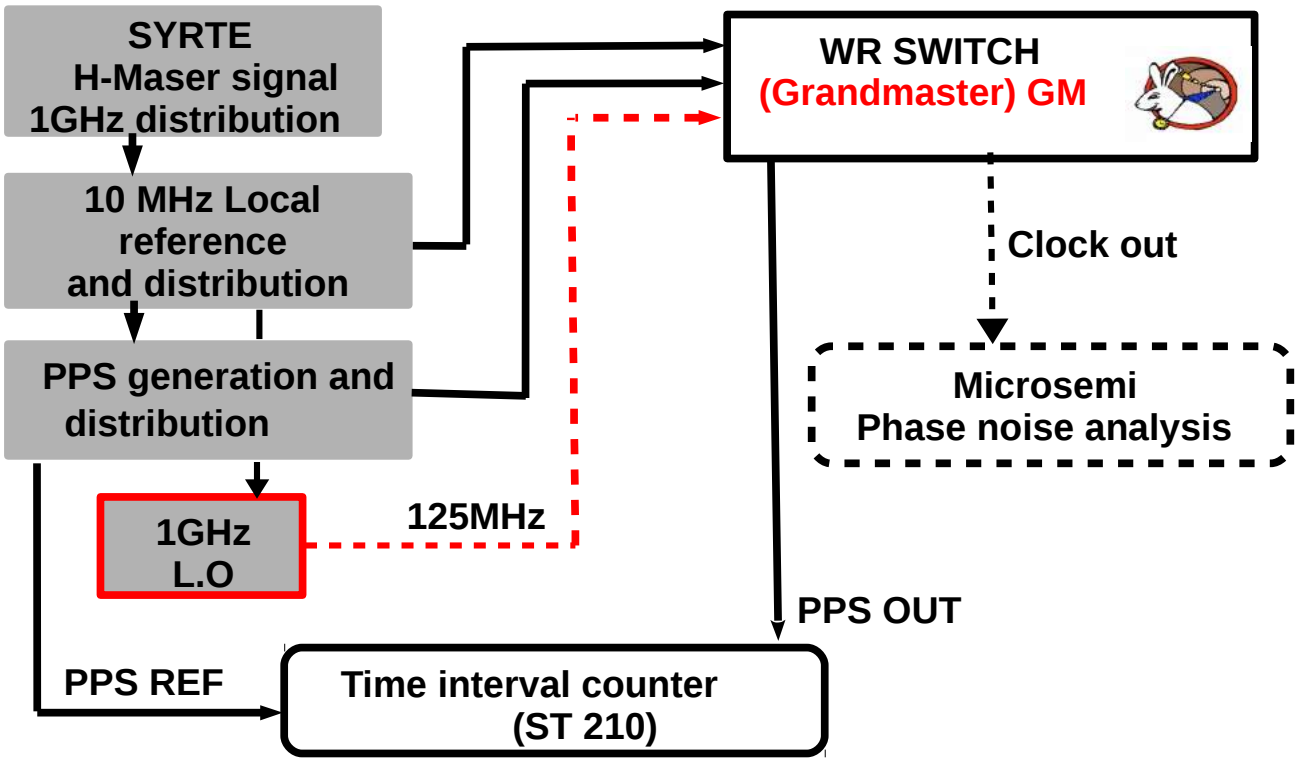
Switch

SPEC



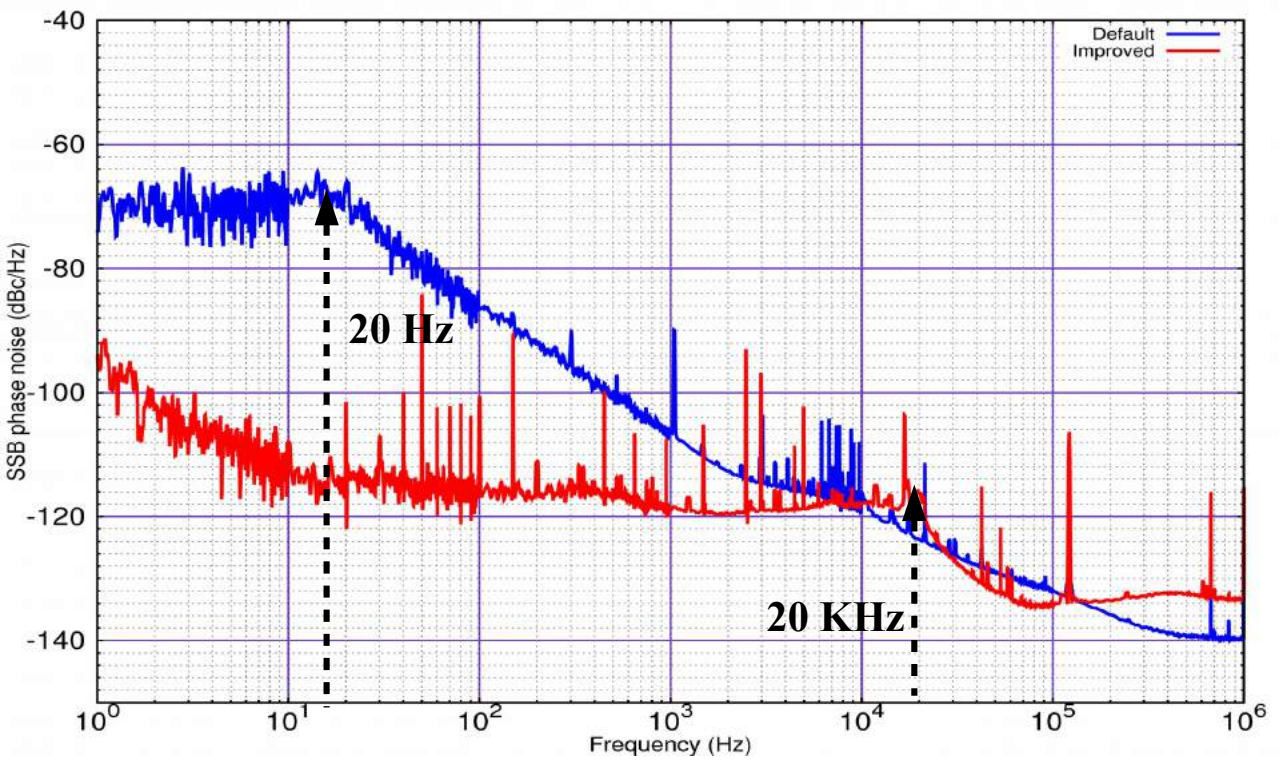
WR-ZEN

White Rabbit Switch
Stage 1: The Grandmaster



Default and Improved WR Switch performance

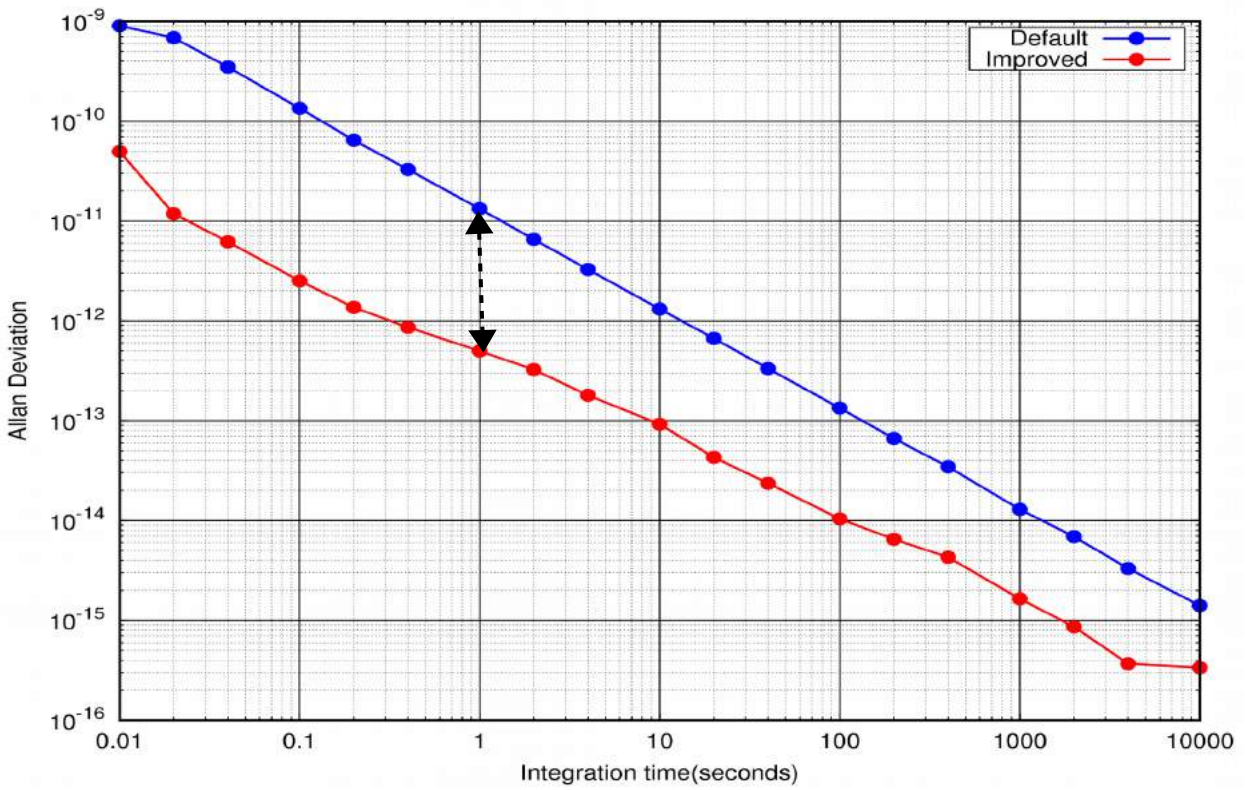
Phase noise Power Spectral density



Allan Deviation (NEQ BW – 500Hz)

No fiber

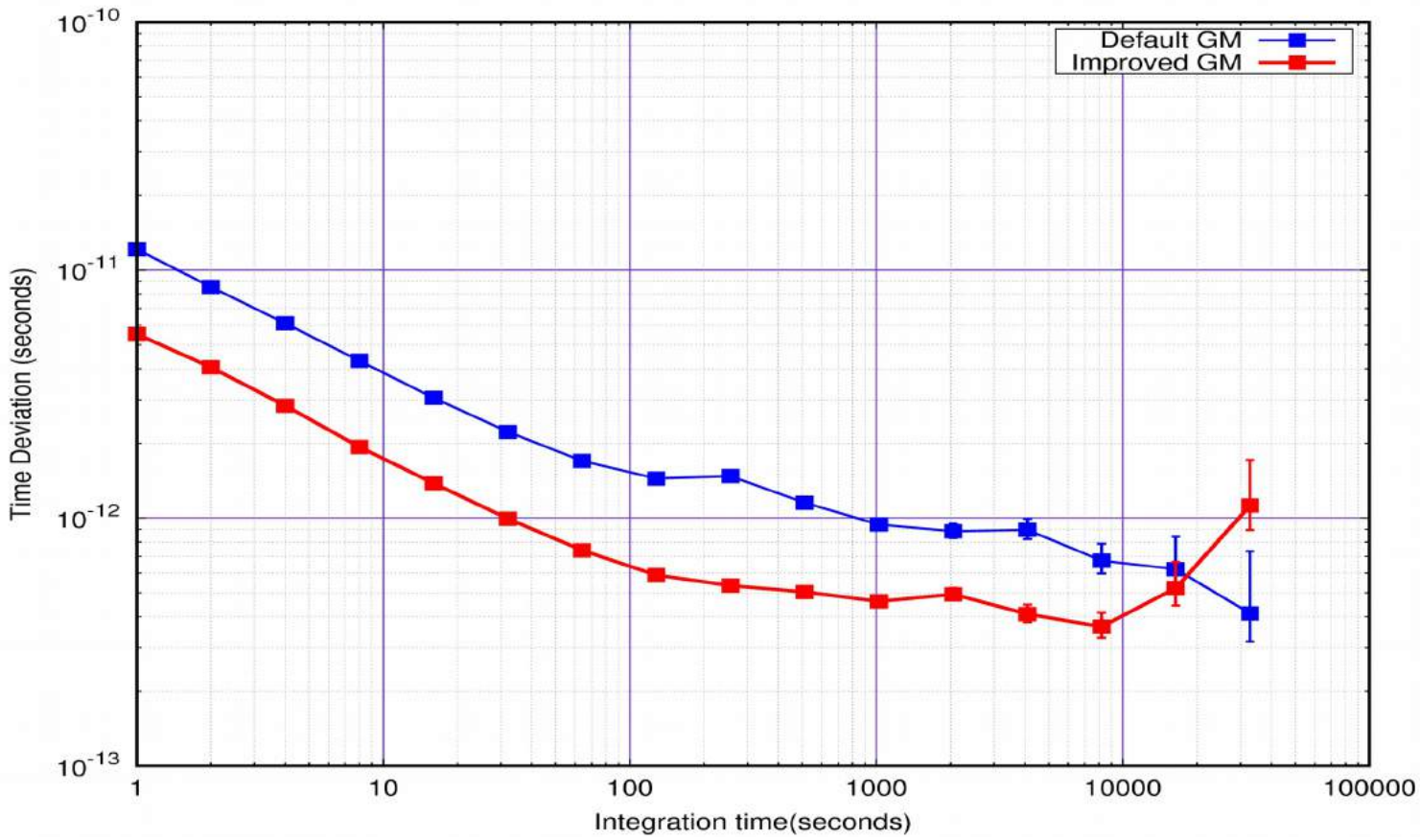
1.3×10^{-11}@1s ⟶ 4.9×10^{-13}@1s



* ADEV is measured by Microsemi Phase noise test set 5120A.

Time deviation

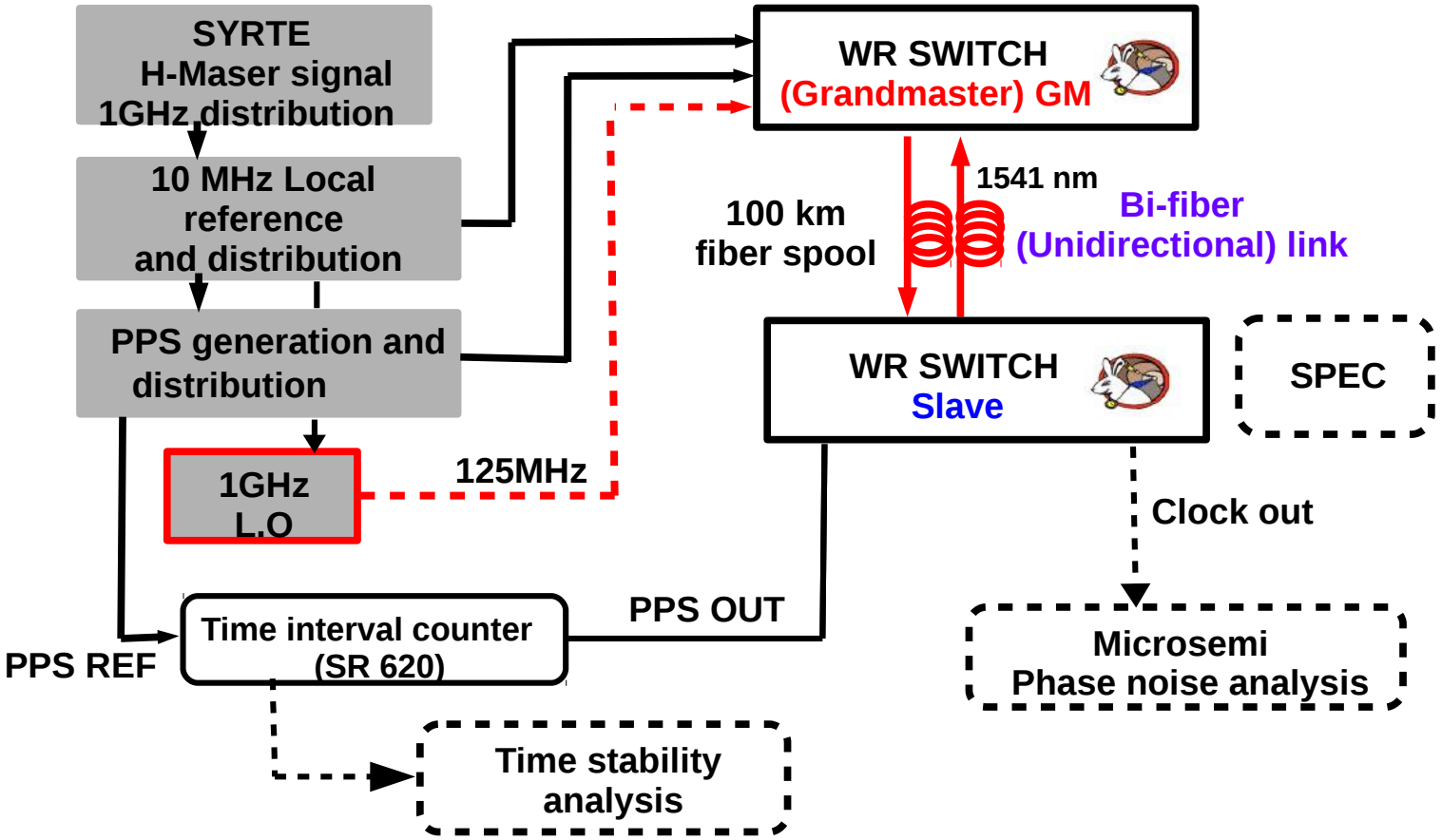
1.2×10^{-11} s@1s ⟶ 5.5×10^{-12}s@1s



* BW of measurement=1 Hz

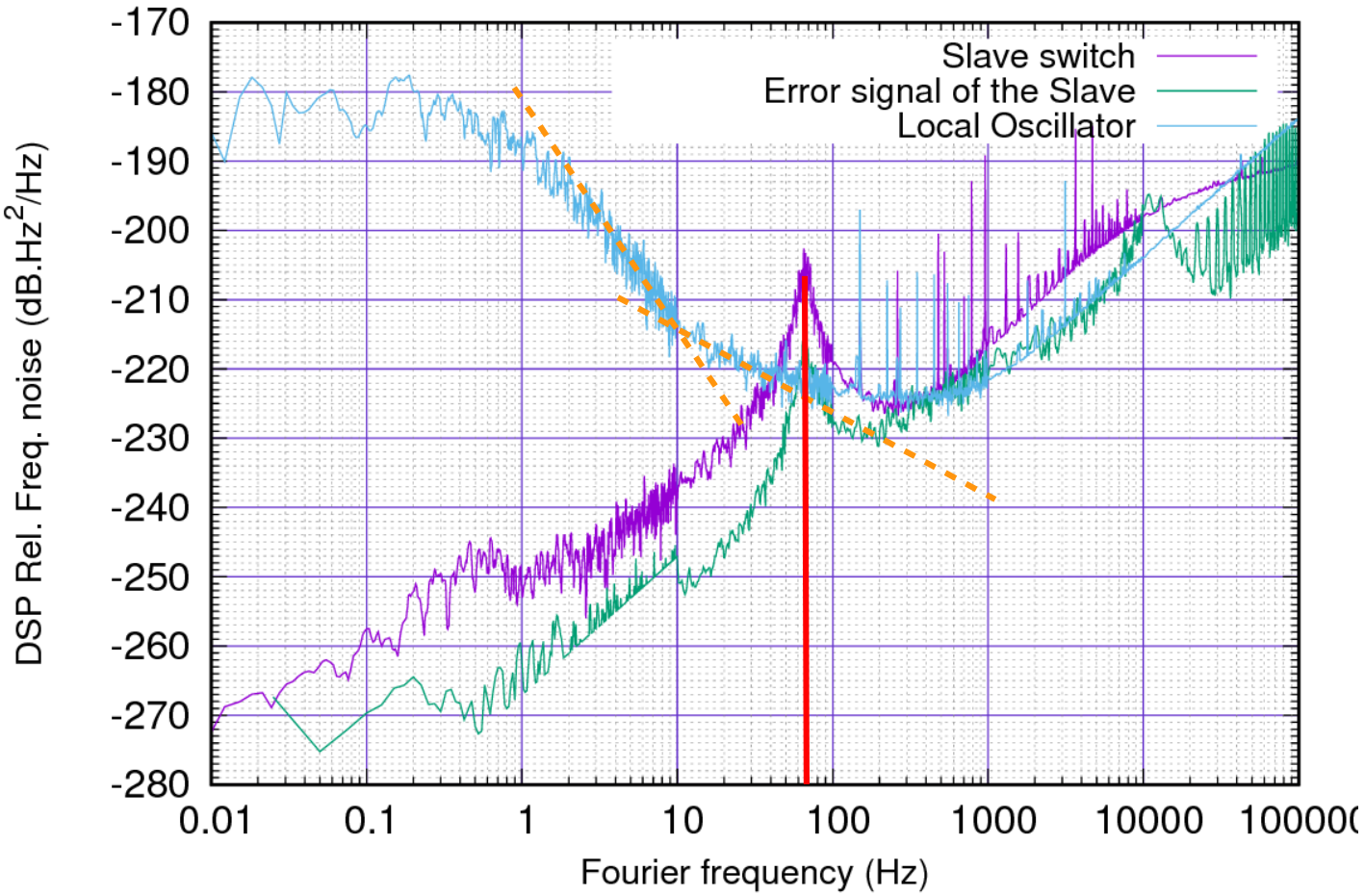
A 100 km White Rabbit link

Stage 2: Slave White Rabbit Switch

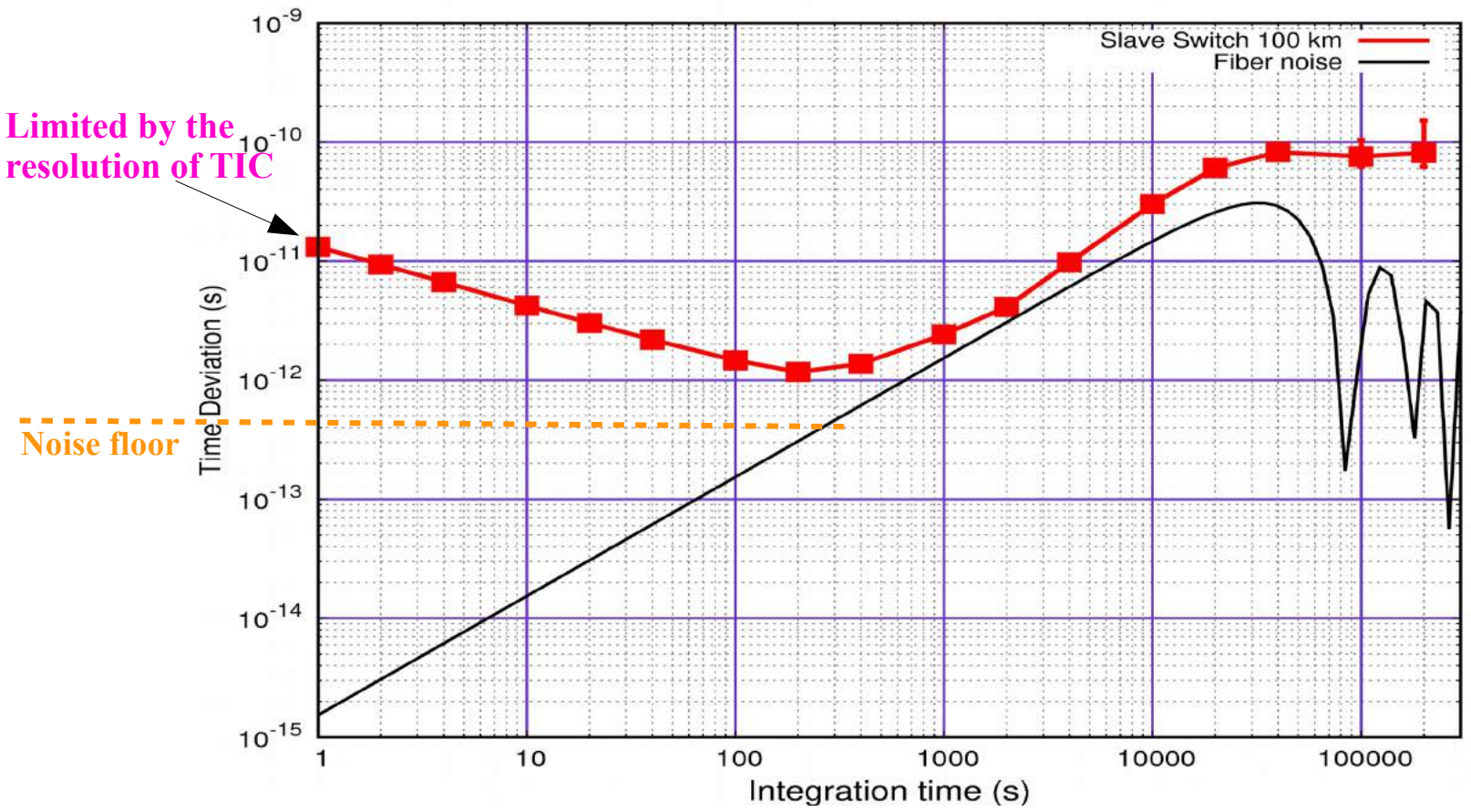


The local oscillator performance

Slave Bandwidth increased from 20 to 60 Hz

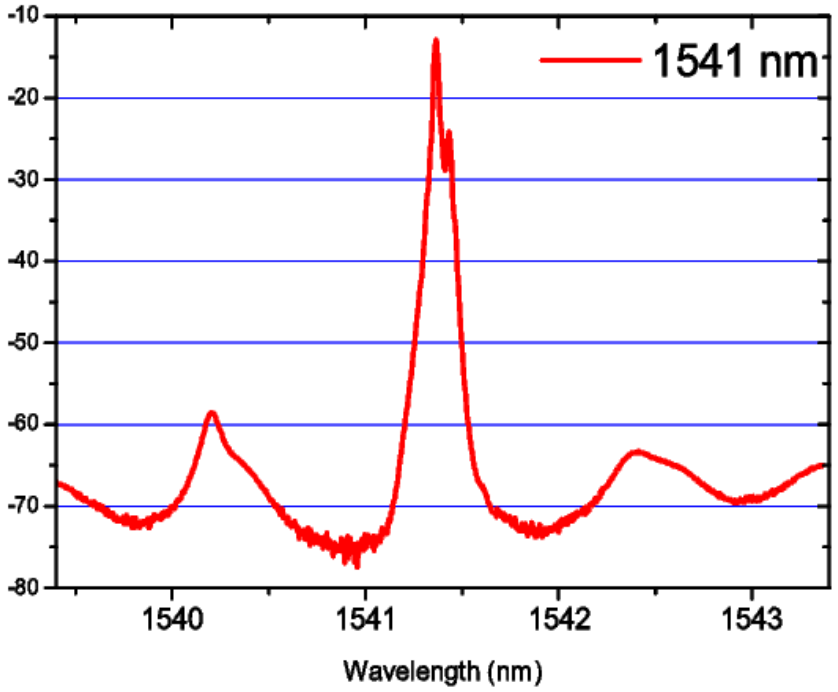


Time transfer performance for a 100 km WR link and its limitations

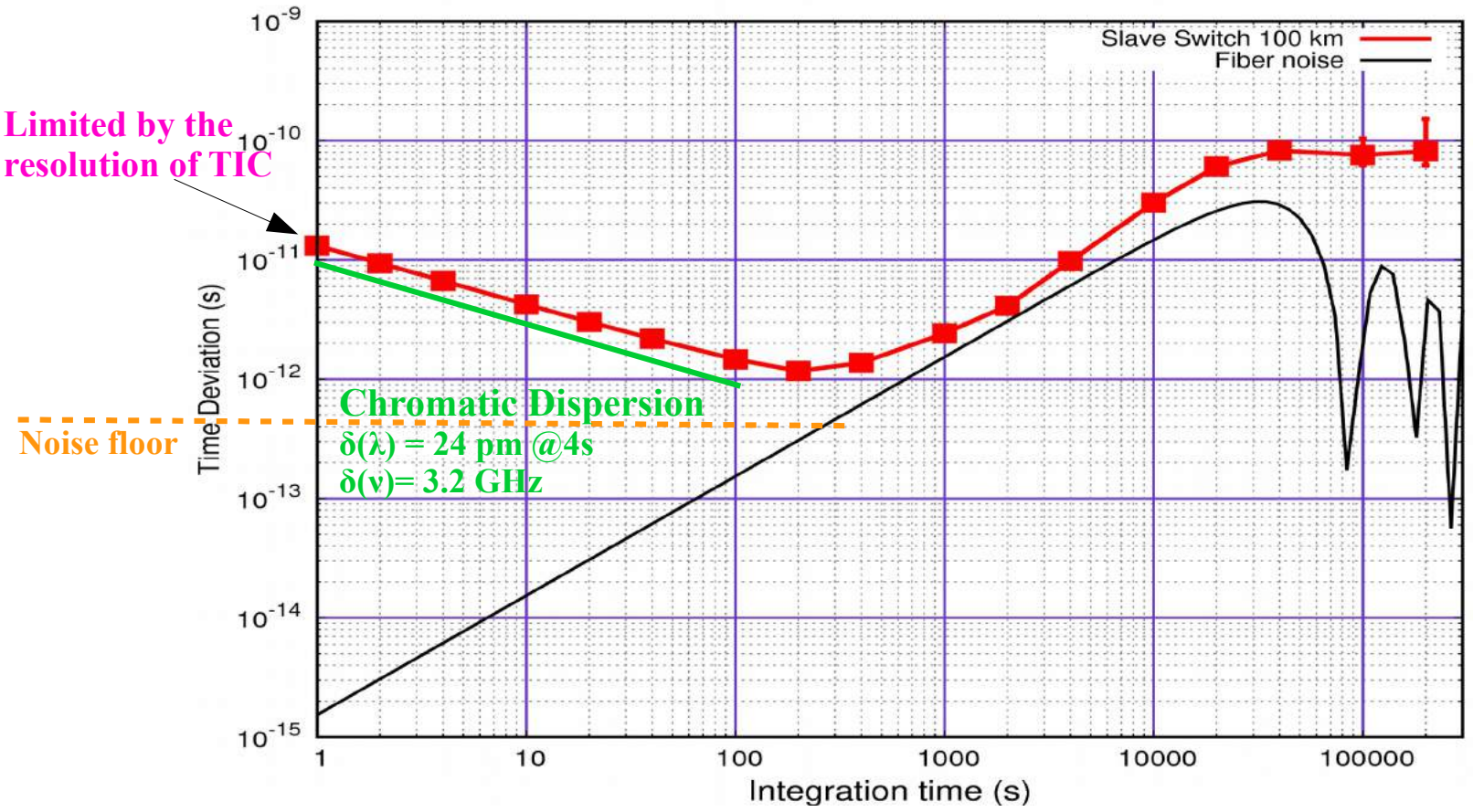


* BW of measurement=1 Hz

The linewidth of the emitters

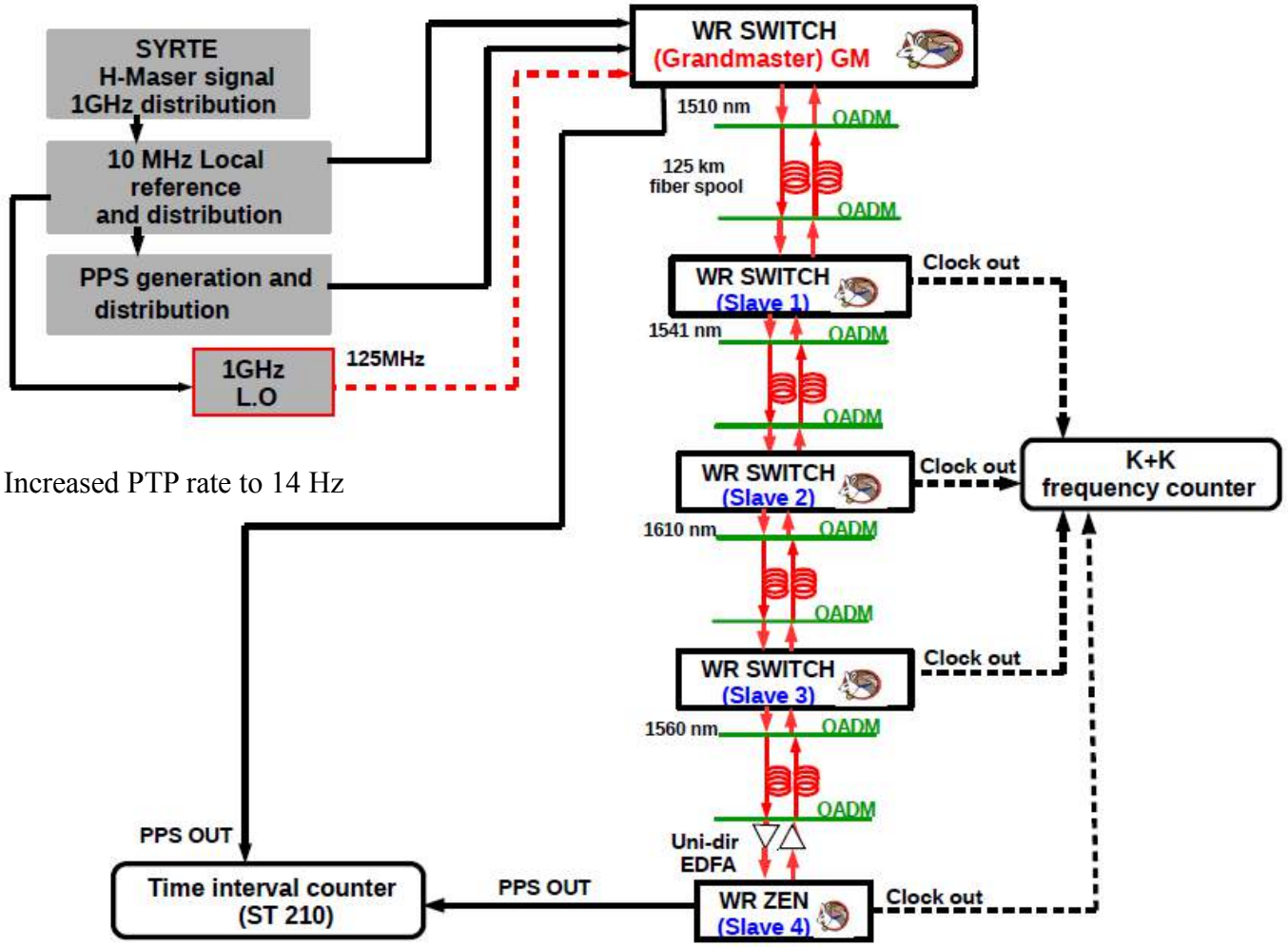


Time transfer performance for a 100 km WR link and its limitations



* BW of measurement=1 Hz

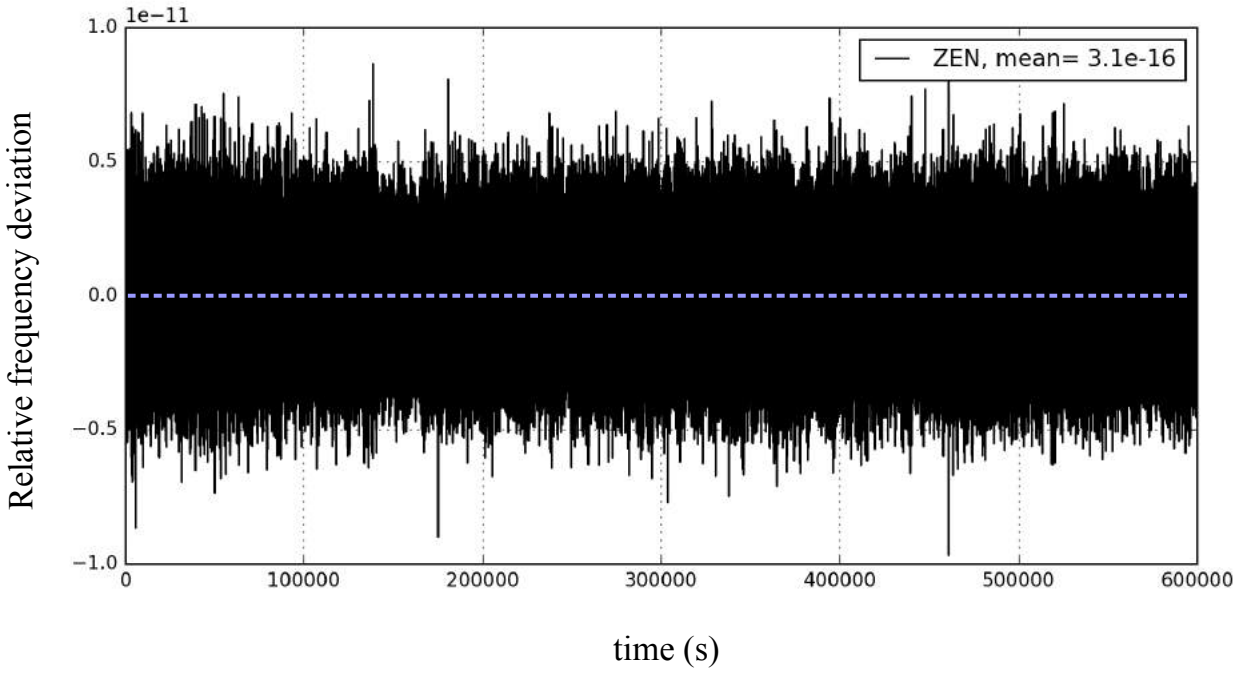
A cascaded 500 km WR link



Increased PTP rate to 14 Hz

The first 500 km 4-span cascaded WR link
ZEN -10 MHz clock out
(K+K counter)

Accuracy for frequency < 1E-15



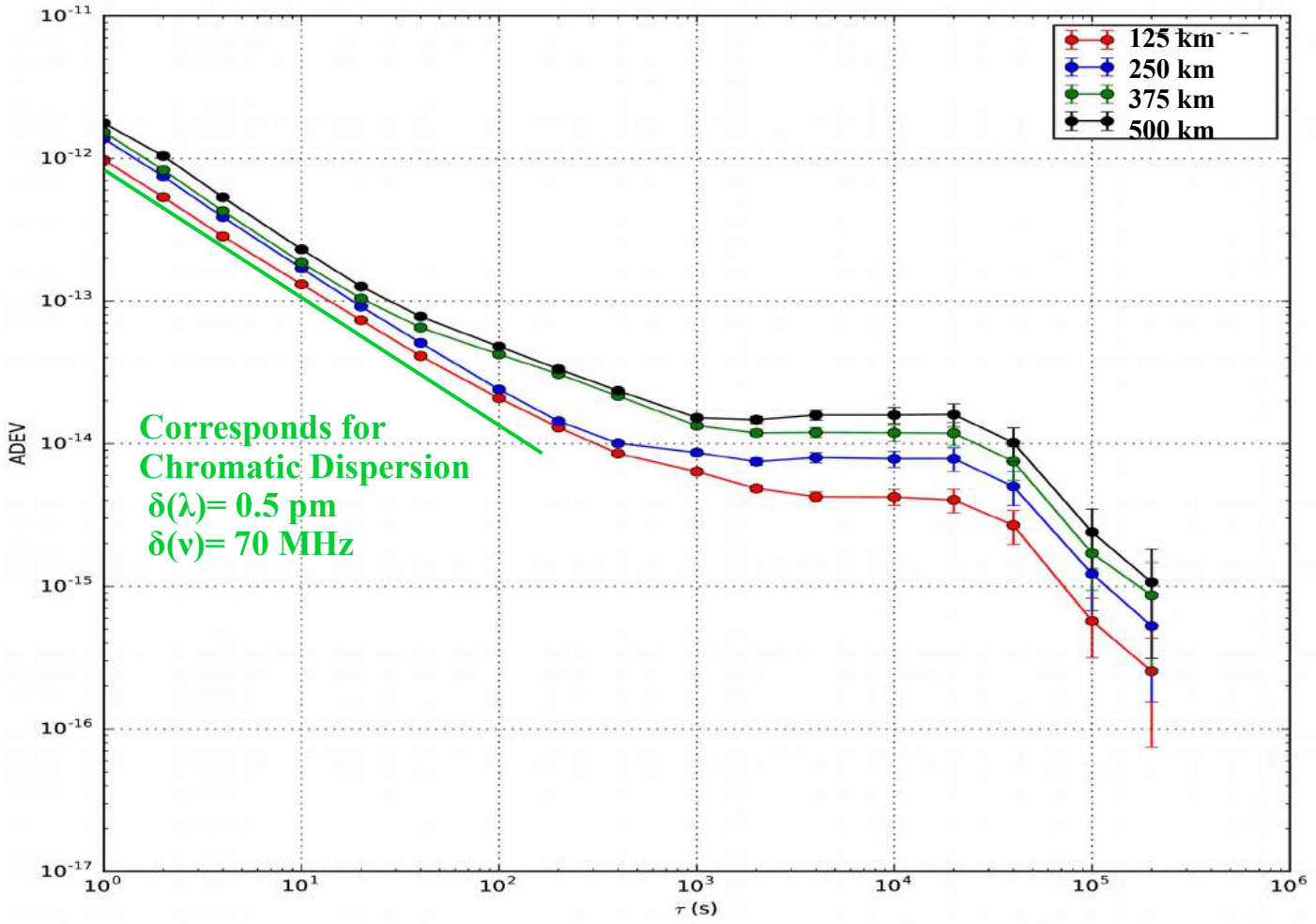
Λ gate time = 1s

7 days of measurement

* BW of measurement=0.5 Hz

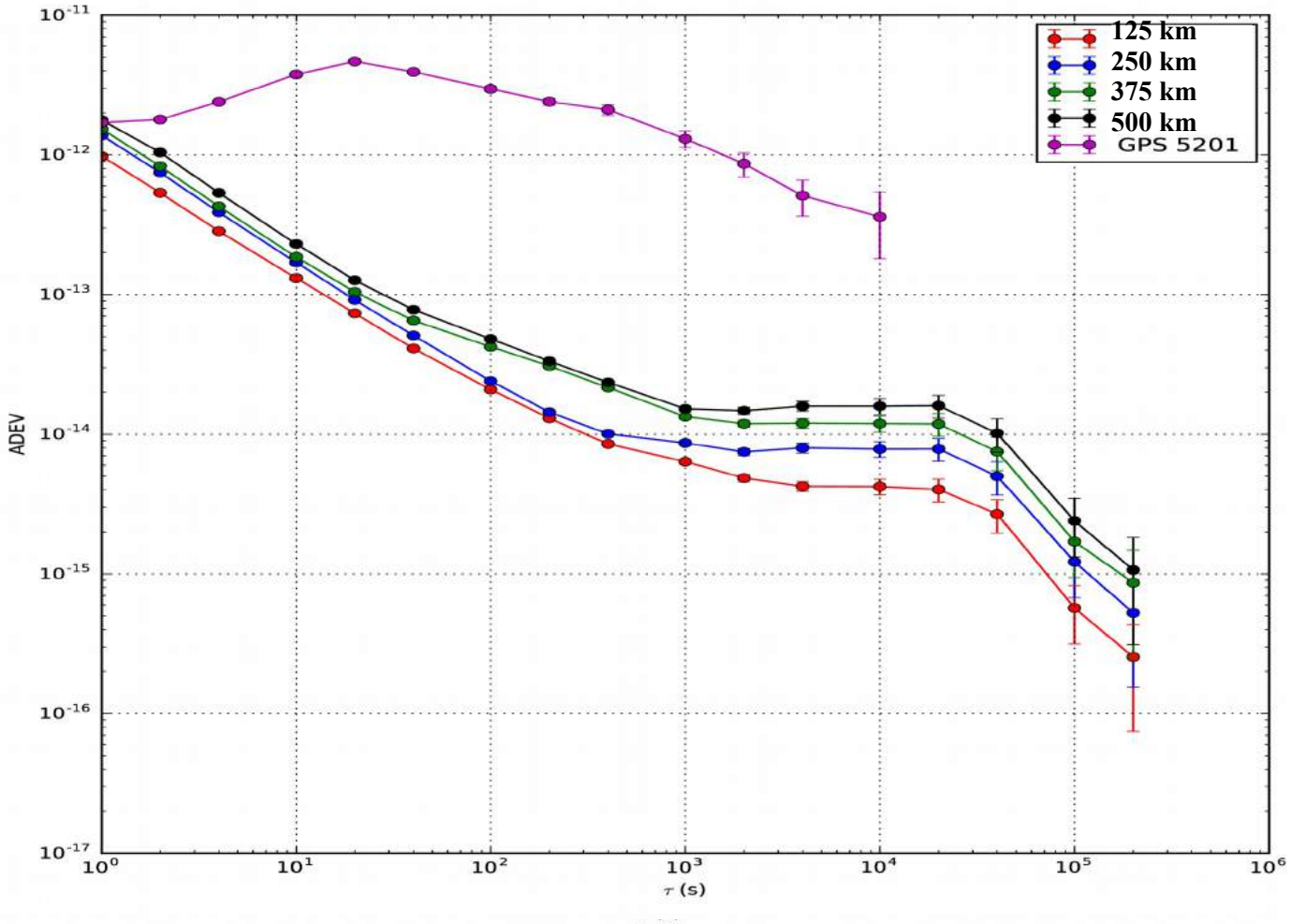
The first 500 km 4-span cascaded WR link

Allan Deviation at each span



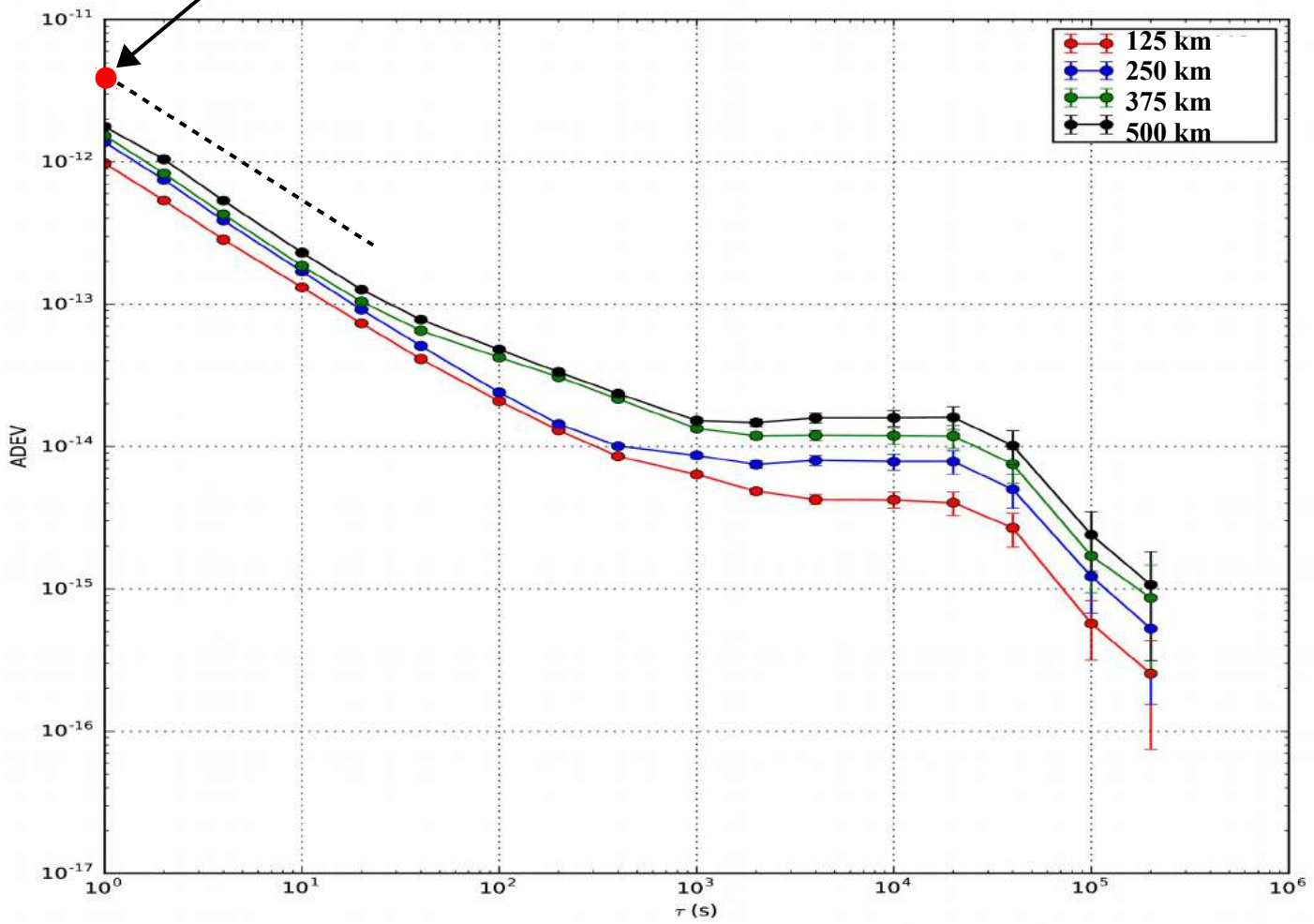
Λ gate time = 1s

The first 500 km 4-span cascaded WR link
Comparison with GPS



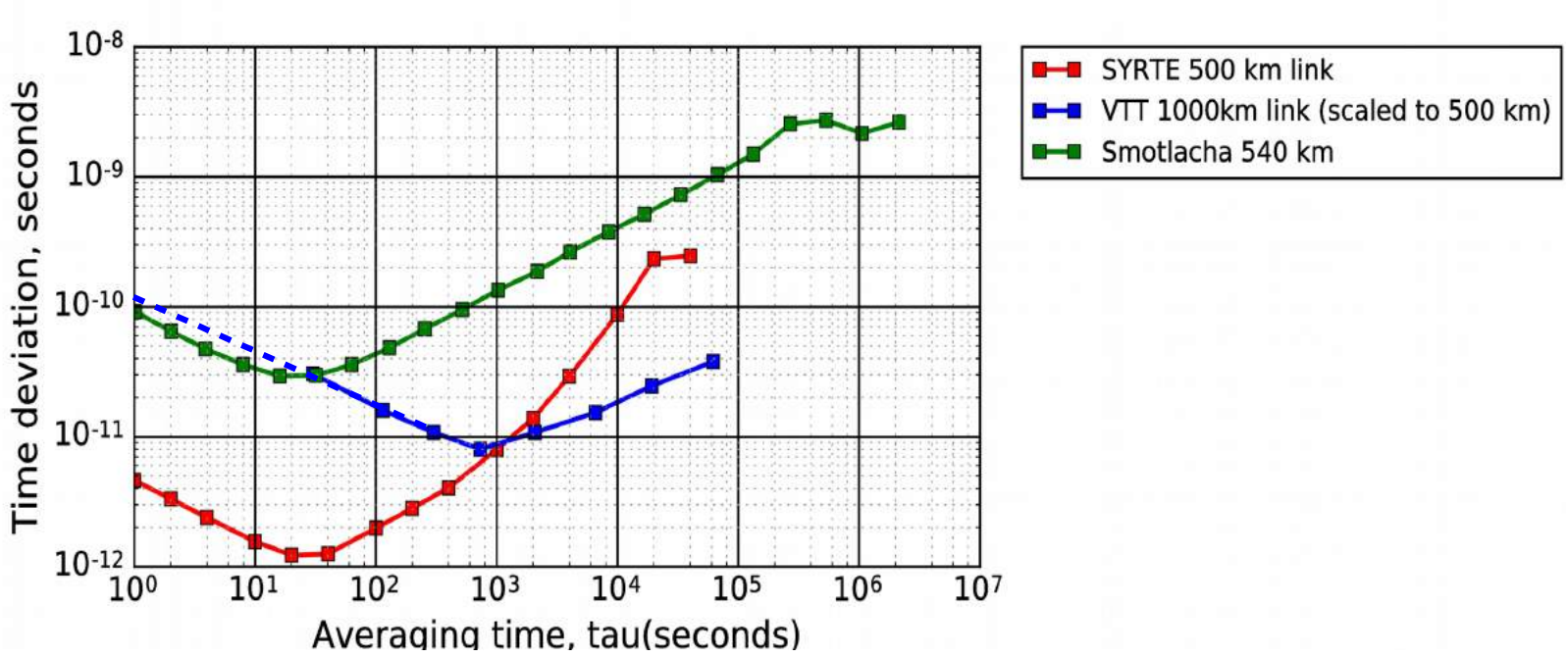
The first 500 km 4-span cascaded WR link

Scaling to the Paris to Besançon link
(4 spans, about 250 km each)



The first 500 km 4-span cascaded WR link

Time deviation comparison with infield applications



* BW of measurement=1 Hz

Conclusions

- Improved the White Rabbit Switch stability (in Grandmaster mode) by more than one order of magnitude for 0 euro!
  - ➢ The improved performance is only limited by the switch hardware.
- The bandwidth of the slave is optimized : improved by a factor 3 (0 euro)
- We evaluated the performance of a 500 km cascaded White Rabbit link for long range time and frequency dissemination.
- We have demonstrated frequency transfer stability at the level of 2×10^{-15} over 1 day of integration time. No shift within the statistical uncertainty.
- Time deviation reaches a minimum of 1.5 ps at short integration time.
- The limitations for the time performance are chromatic dispersion (emitters stability) and fiber thermal noise…
  - ➢ The end-user equipment has to follow...

Perspectives

- **Time and frequency dissemination at a national scale:**
  - **A WR link between Paris to Besançon (UTINAM) using active telecom fiber network in collaboration with RENATER.**
- **Looking for practical solutions to be implemented in field for determining time accuracy/calibration of the link.**

Thank you for your attention!