ELECTRONICS & DEFENSE

White Rabbit ZEN & Z16 Calibrations

29 March 2023

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Agenda

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Chapter 3

Network & Calibration

WR: Introduction

- **White-Rabbit Ethernet + ~ PTP Boundary clock with SyncE support.**
  - Tree, ring topologies or any other Ethernet architecture but be aware that BC imposes E2E M-S link utilization (scalability = number of WR port at the WR-switches level).
- **WR performance is like having SecureSync wired to your slave.**
  - It also bring additional resiliency capabilities to scattered GNSS receivers.
- **WR can be use for accurate time transfer (PPS) and frequency dissemination (Radio over Ethernet) for distributed applications**
  - When the link asymmetry can not be estimated/measured, the accuracy can be degraded. WR is still able to operate with high stability ~10 ps and it provides much more stable PPS output than any PTPv2 profile, all without suffering PDVs accuracy degradation or other penalties due to the number of hops or timestamp precision limitations.

WR: Networks & Calibration

- **White-Rabbit Ethernet + ~ PTP Boundary clock with SyncE support.**
  - Tree, ring topologies or any other Ethernet architecture but be aware that BC imposes E2E M-S link utilization (scalability = number of WR port at the WR-switches level).
- **The physical layer encode the clock and the phase difference associated with the link propagation delay**
  - Any in-the-middle element that destroy the L1 syntonization will make impossible to provide the White-Rabbit precision and accuracy (
    - WR will not lock or will provide just PTP-like performance).
  - Any in-the-middle element that add an unknown delay or asymmetry in the propagation signals will destroy the accuracy (we can always calibrate and model its contribution into the Alpha asymmetry coefficient, so accuracy is preserved).
- **The WR deployment process should cope with the previous considerations.**

Lets see how!

WR: Networks & Calibration

- The packet time techniques could provide a precise value of the RTT (Round Trip Time) but obtaining an accurate synchronization means isolate the $delay_{MS}$ (Master-Slave delay).

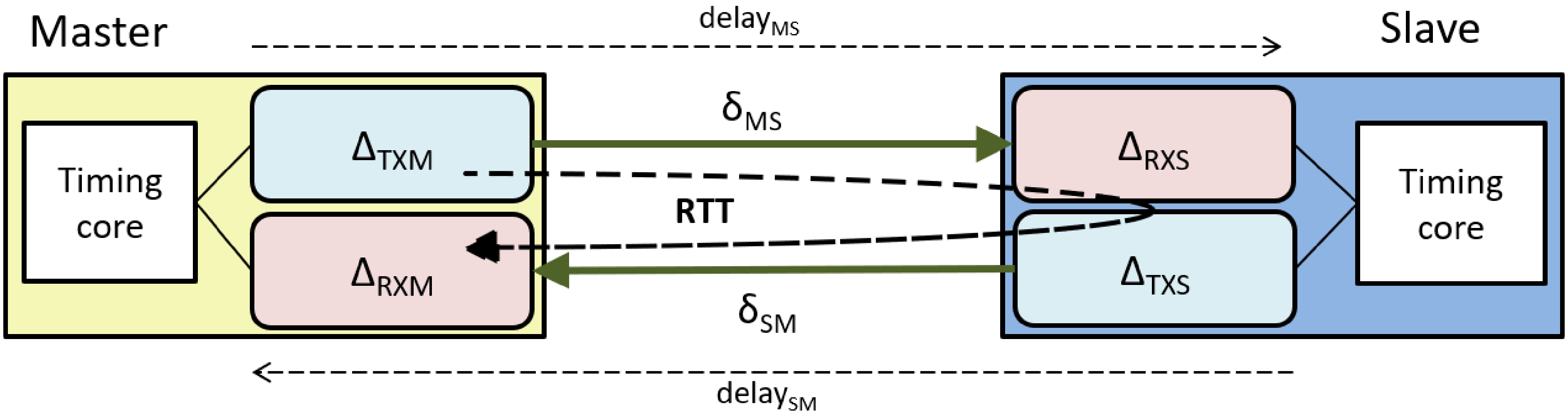
- The problem is not easily resolvable because there is not a simple relation between the RTT and the $delay_{MS}$.

$$delay_{MS} = \Delta_{TXM} + \delta_{MS} + \Delta_{RXS}$$
$$delay_{MS} = \Delta_{TXS} + \delta_{SM} + \Delta_{RXM}$$
$$RTT = delay_{MS} + delay_{SM}$$

→ The asymmetries increase the difficulty of solving the $delay_{MS}$ value. Equipment delays + asymmetry coefficient try to deal with this problem.

WR: Networks & Calibration

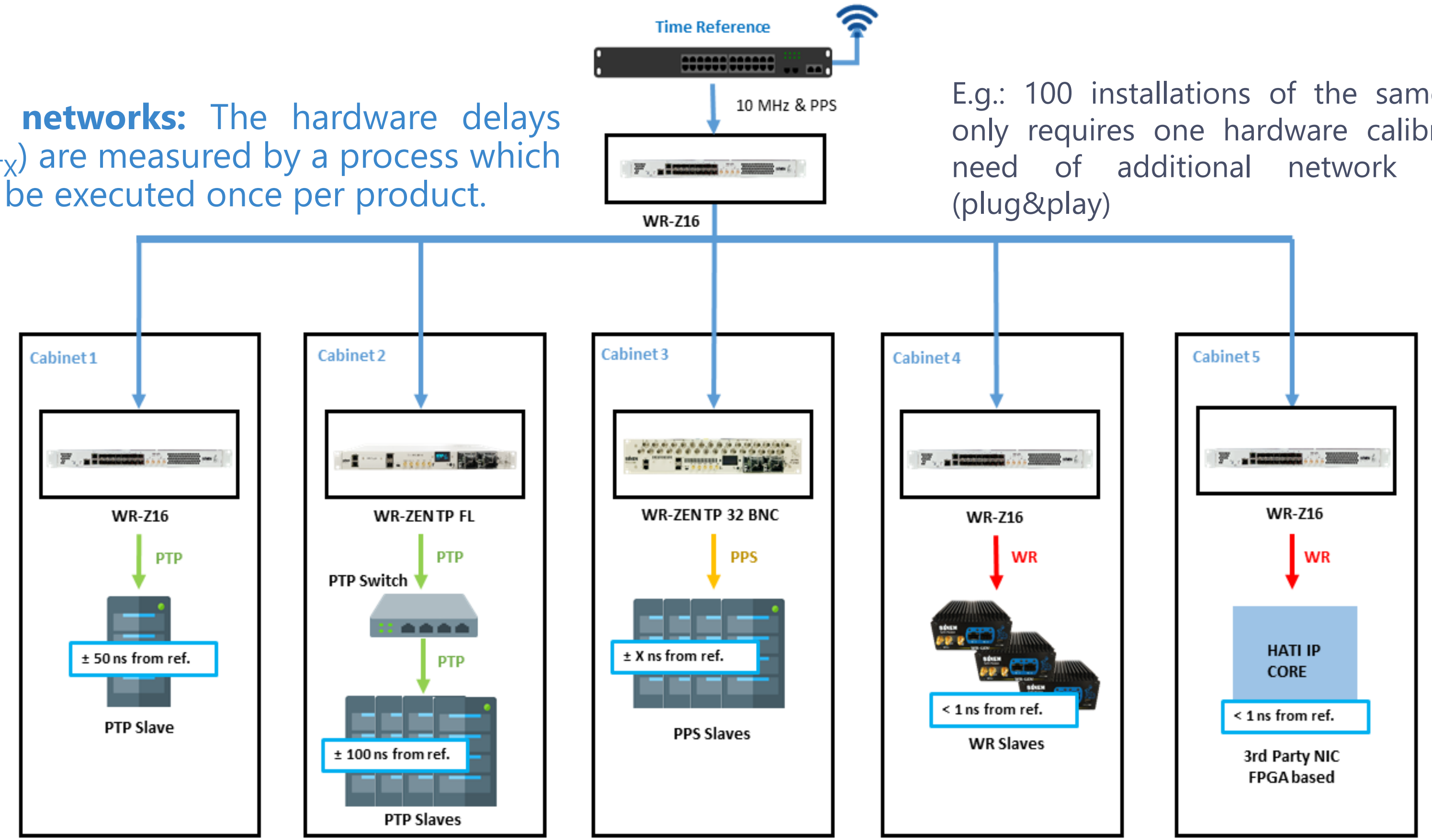
- **PROBLEM:** Default WR network model is too simplistic (equipment delays + wavelength asymmetry).
- Networks can be very heterogeneous, specially on the long-haul scenario. DWDMs, EDFA, DCMs, etc.. or two different RX/TX fibers, add significant asymmetry!



Network scenarios: Local network < 10 Km

1. Local networks: The hardware delays (Δ_{RX} & Δ_{TX}) are measured by a process which needs to be executed once per product.

E.g.: 100 installations of the same element only requires one hardware calibration. No need of additional network calibration (plug&play)



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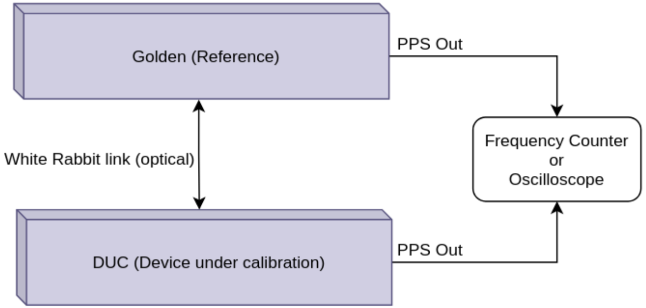
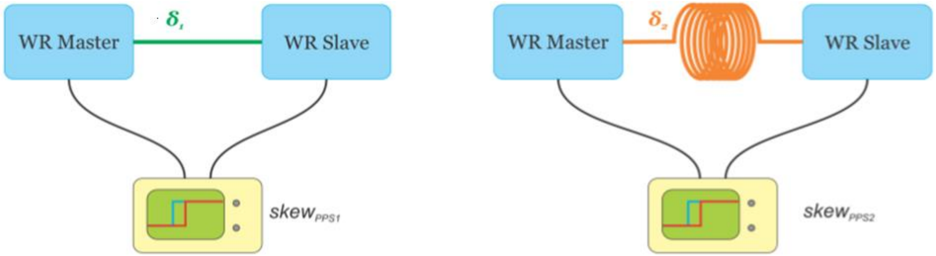
Local network calibration



Supported SFPs
AXGE-1254-0531
AXGE-3454-0531
AXGD-1254-0531
AXGD-3454-0531
SFP-GE-BX120 1490nm/1550nm
SFP-GE-BX120 1550nm/1490 nm



- **It is based on the "CERN approach", this is the used method. It requires to use a "golden device" (it is a relative calibration method).**
- **Only bidirectional optical fiber links is supported.** Board, gateware and optical fiber asymmetry delays are jointly computed. Modularity is not possible (only aggregated delays are estimated). Any uncertainty source like the one associated to reboot power cycles or the one associated with the unit of the SFPs we use may degrade the calibration → a problem for long distance links!
- **It works only for metro networks (<40Km).**
- **Calibration accuracy ~100 ps (<10 Km)**

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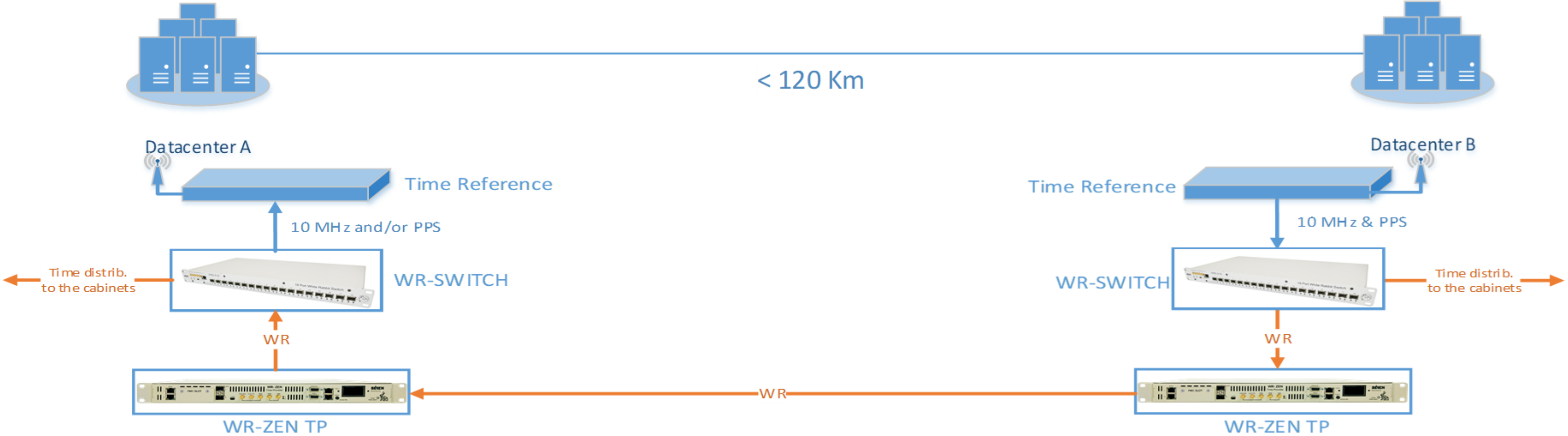
Network scenarios: metro network ~100Km

2. Metro network: point to point link with only an optical fiber between the two WR devices. May require theorical or experimental alpha estimation for link deployment.

1. **Bidirectional SFP → Local network method**

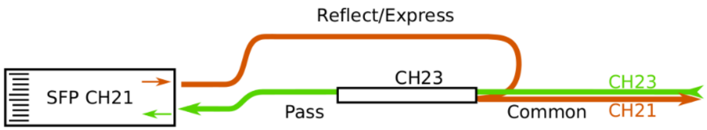
Length	α (factory)	α (experiment)
50 cm	100 ps	200 ps
20 km	4 ns	160 ps
80 km	15 ns	780 ps

2. **Bi-fiber & bidirectional metro-link scenarios → Feasible without accuracy issues**

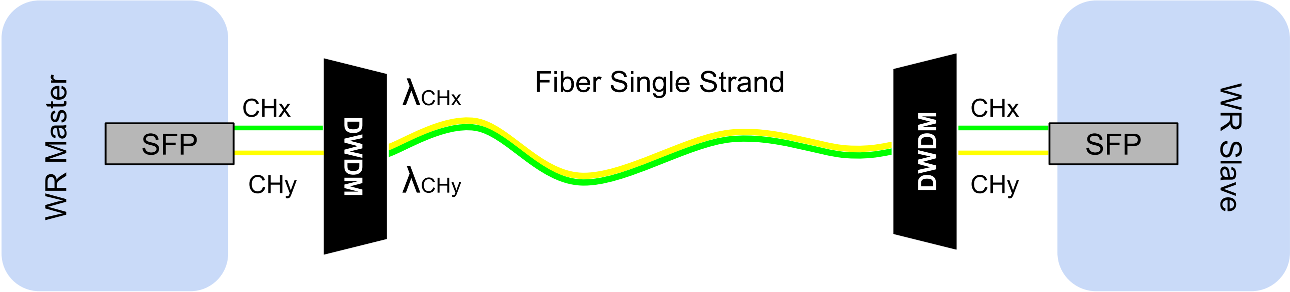


Metro link improvement: simple network calibration using long Haul over WR BIDI DWDM

- **Fixed latency of WR equipment calculated using local calibration WR Model**
- **Resolves/reduces calibration problems of tech and "complex" OF networks:**
  - Uncertainty of the wavelength of BiDi SFPs
  - Uncertainty of characteristics among OF vendor
  - α in networks with mixed version of OF (G652b/d)
- **Reduces impact of wavelength asymmetry: $\alpha DWDM \sim 10^{-6} < \alpha BiDi \sim 10^{-4}$**



We use **DWDM-SFP1G-30.33** 80-100 Km
Example: C23, C56, C59 … channels



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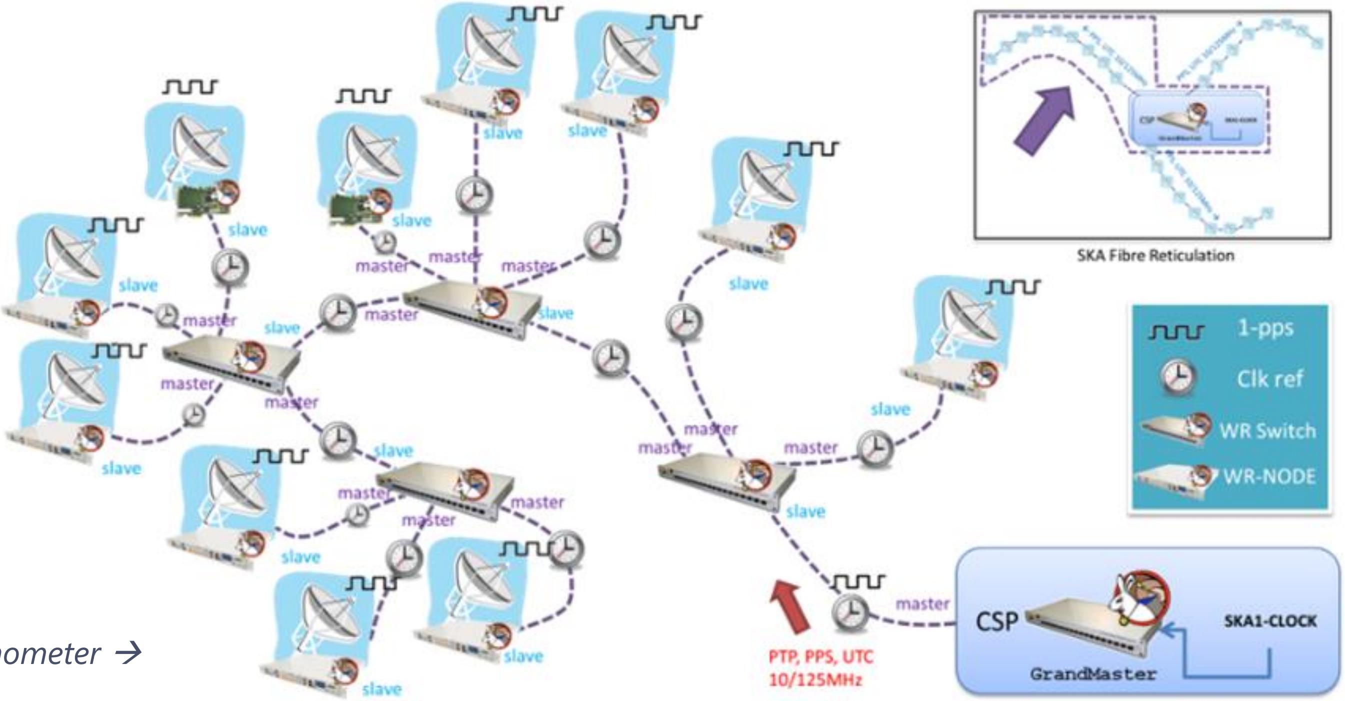
SKA telescope use case

- **Under high-environmental changes (ΔT~20°C) the synchronization is below 400ps (peak-to-peak).**

We have built a very expensive thermometer →



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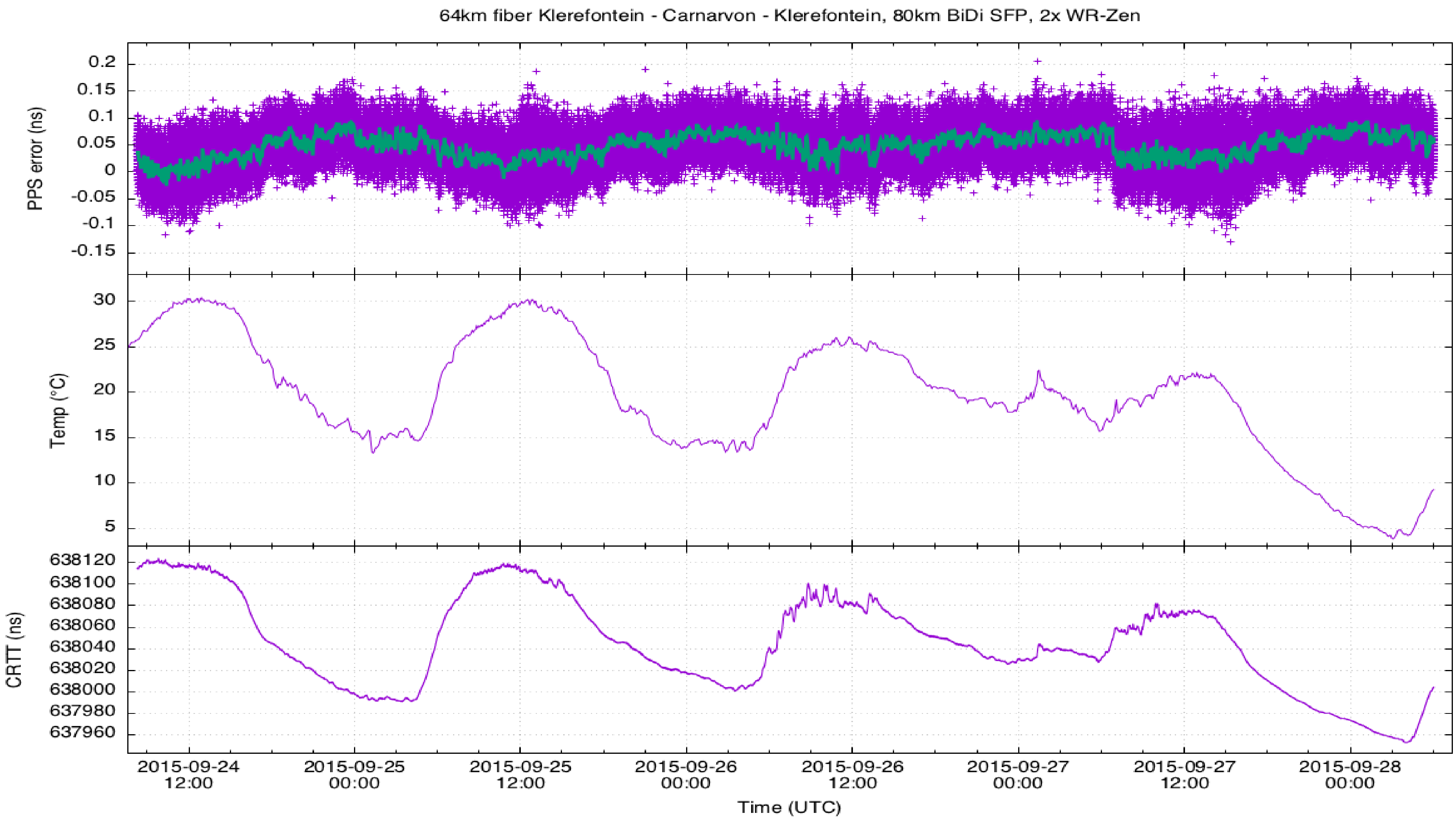


64km fiber Klerefontein - Carnarvon - Klerefontein, 80km BiDi SFP, 2x WR-Zen
PPS error (ns)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Temp (°C)
30
25
20
15
10
5
CRTT (ns)
638120
638100
638080
638060
638040
638020
638000
637980
637960
2015-09-24 12:00
2015-09-25 00:00
2015-09-25 12:00
2015-09-26 00:00
2015-09-26 12:00
2015-09-27 00:00
2015-09-27 12:00
2015-09-28 00:00
Time (UTC)

SKA uncertainty budget estimation

- **SKA-MID: Uncertainty (left) + worst case (3 links with 173 Km total distance)**
  - Requirement is 2 ns (1.5 ns for UTC time transfer).
  - Sagnac effect compensation is required

Source	Calculation	Contribution (ps)
Delay Calibration		10
Link Restart		75
Received power variation		30
Dispersion (α)	15% of 1.1ns	165
Wavelength Uncertainty	0.1nm * 20ps/nmkm * 80km	160
Fibre temperature	80km * -1.3fs/kmK * 25K	3
TC of WR-Zen	3.75ps/K * 25K	94
TC of WR-SW	8ps/K * 1K	8
THD on CLOCKS interface		50
Total		**595**

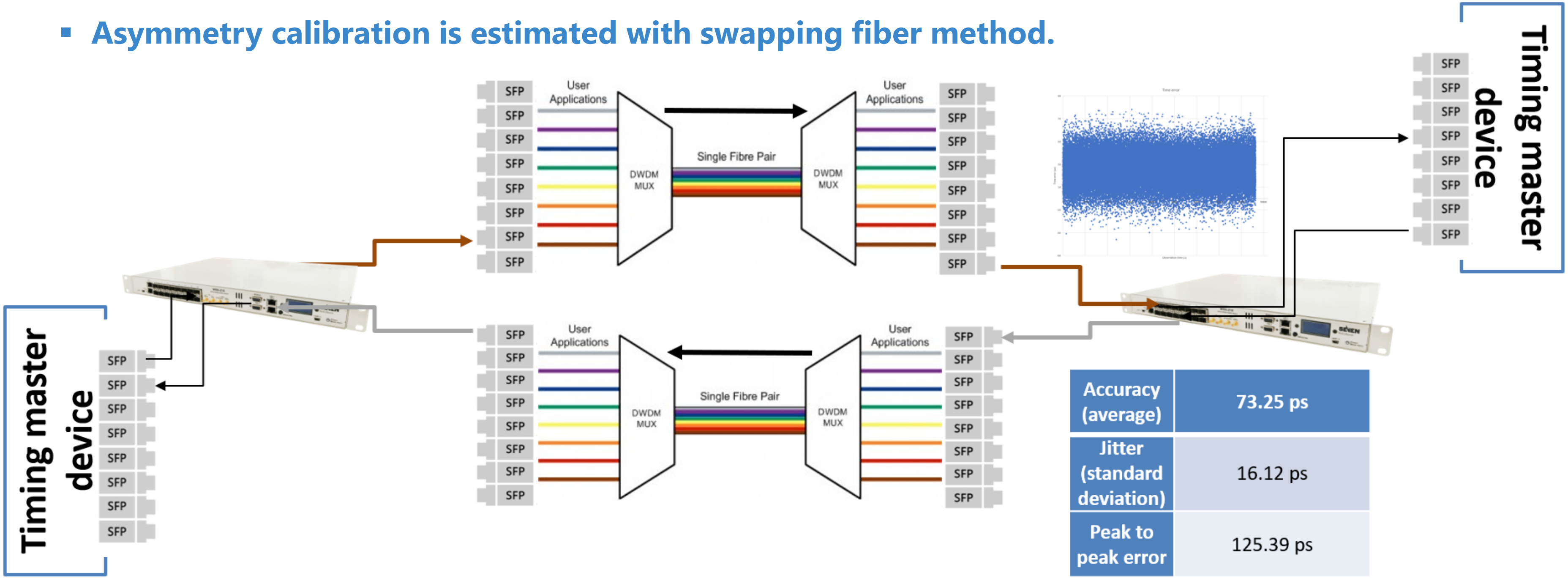
Table 10: Uncertainty budget on 80km links

Source	Calculation	Contribution (ps)
Delay Calibration	3* 10ps	30
Link Restart	3* 75ps	225
Received power variation	3* 30ps	90
Dispersion (α)	15% of 2.4ns	375
Wavelength Uncertainty	0.1nm * 173km * 20ps/nmkm	346
Fibre temperature	173km * -1.3fs/kmK * 25K	6
TC of WR-Zen	3.75ps/K * 25K	94
TC of WR-SW (TFR)	8ps/K * 1K	8
THD on CLOCKS input		50
Total		**1224**

Table 11: Uncertainty budget on the worst-case link in SKA1-Mid

Metro link with bifiber link topologies

- Support for WDM networks with two fiber (one per direction) but not unidirectional elements in the optical path (like EDFAs).
- Asymmetry calibration is estimated with swapping fiber method.



Accuracy (average)	73.25 ps
Jitter (standard deviation)	16.12 ps
Peak to peak error	125.39 ps

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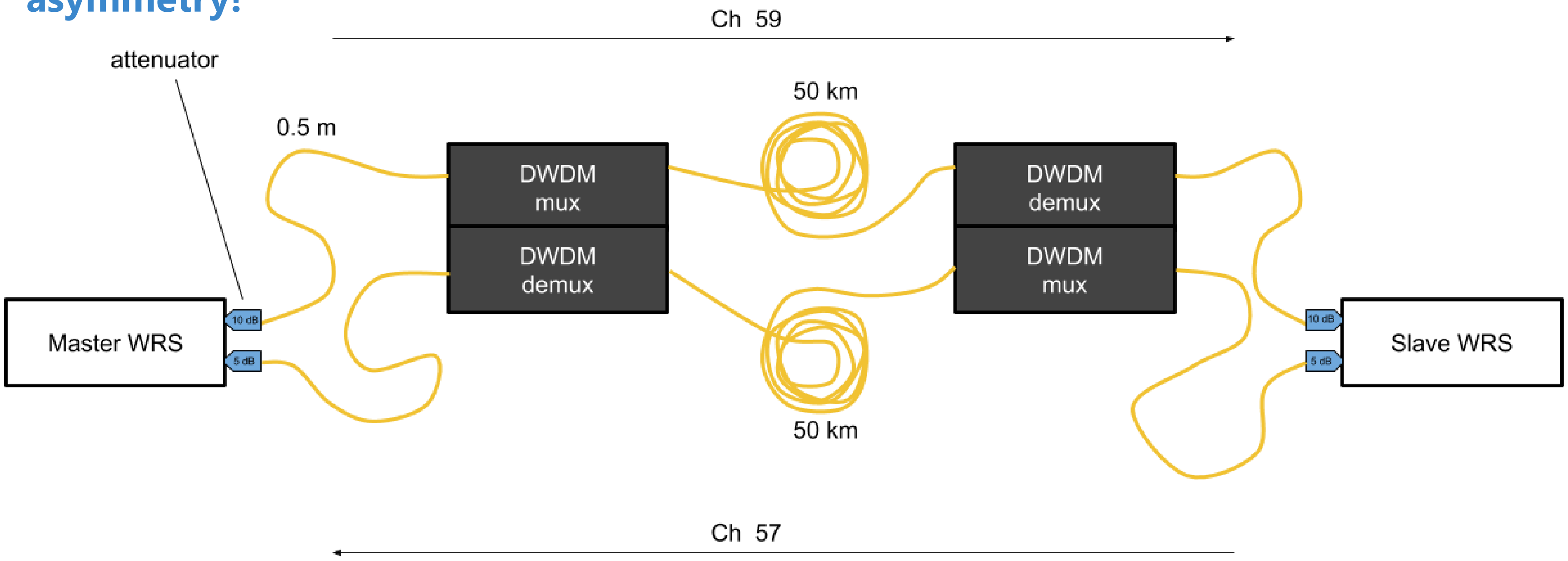
Metro link with bifiber link topologies

- **Bidirectional WDM connection through 50 km fiber: be careful with attenuator asymmetry!**



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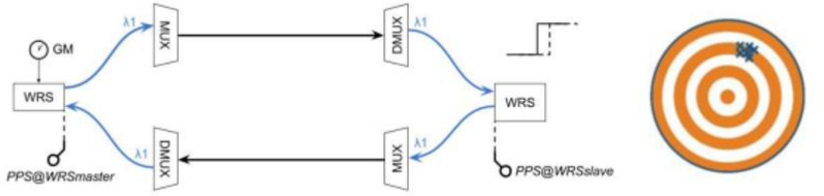
Long Haul WR Calibration
Fiber Swap Method

- **In-situ calibration impossible due to the great separation between WR nodes**
- **Different lengths in the paths is possible.** Example: 100ns (26 m) en 50Km.
- **Different wavelength dispersion compensation not needed: use same wavelength**
- **Any deviation is caused only by the fiber's length differences**
- **Slave PPS is compared with a stable PPS reference**

NOTE: You need to swap fiber in master & slave nodes (and having a proper stable reference in the master side. Implement this method requires a GPS receiver (or clock) in both ends and somebody to perform both swapping operations (or ready to drive from one site to the other place)



After tx/rx fiber swapping:

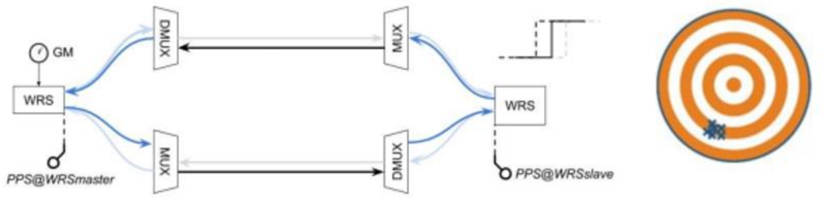
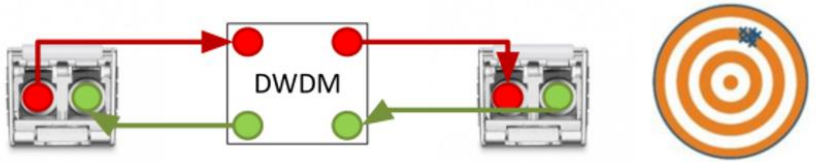
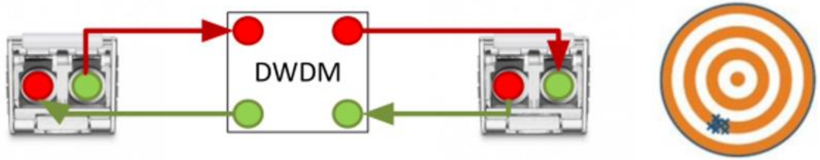
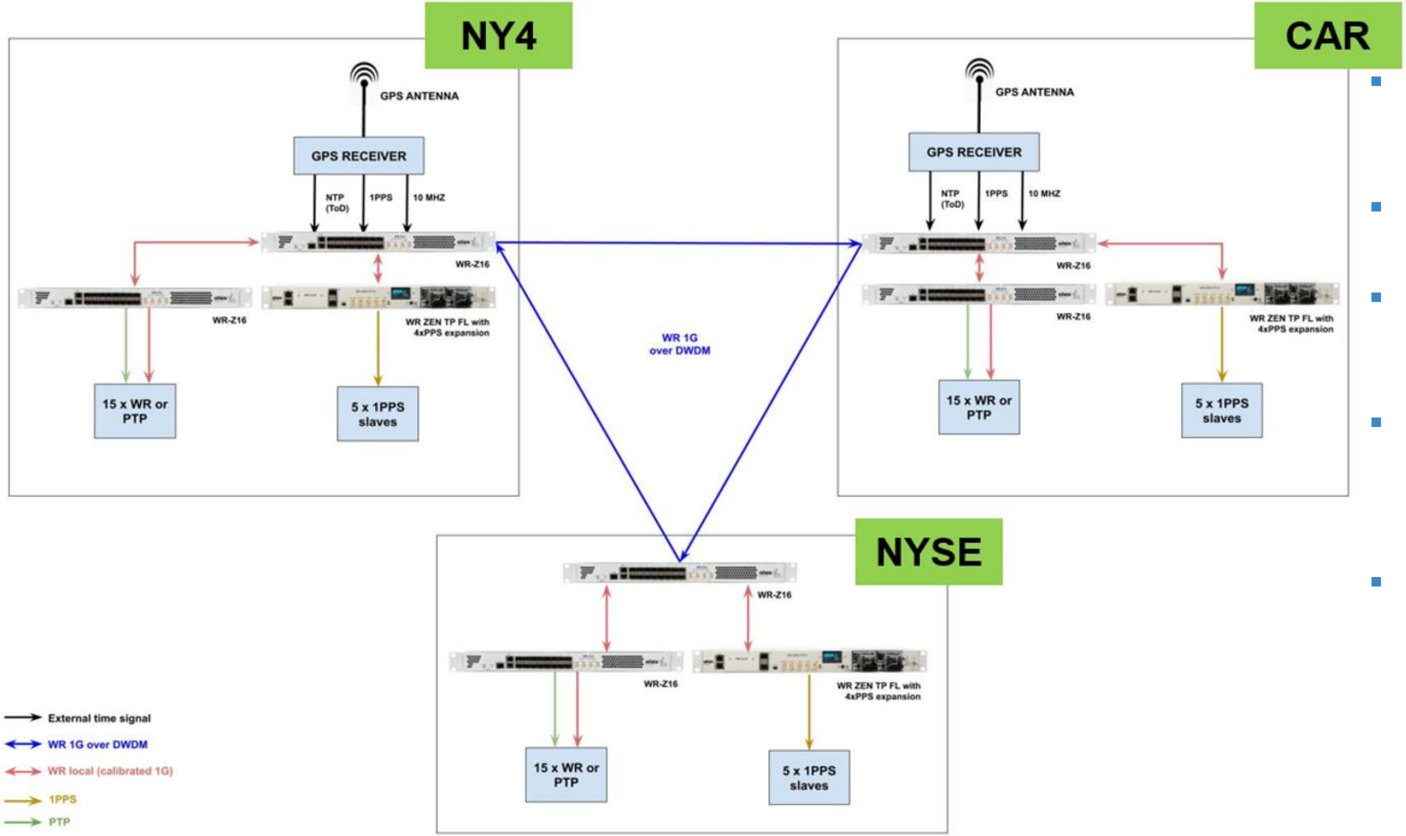


Figure 2.17: Fiber swap calibration technique





Use case: Metro Area Network



- Long distance sub-ns time transfer in metro area (100km approx.)
- DWDM support to avoid using dedicated links.
- On-site calibration service. Closing the triangle to verify calibration procedure.
- Network resiliency based on multiple time sources (at least two are available on each location)
- Optional Expansion cards to provide multiple 1PPS outputs from the same device (WR ZEN TP FL)

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Network scenarios: long haul networks 100Km+

3. Long haul network: In-situ calibration impossible due to the separation between nodes.

- The length of the network impose amplification and the utilization of elements such as unidirectional EDFAs, DCMs, mux/transponder or bidirectional amplifiers.
  - Note that we require that all the devices in the network (active or passive) have a fully deterministic behavior. **SyncE has main compatibility requirements to keep WR functionality (precision)**.
- Calibration alternatives
  - GNSS techniques can be used to easily compare Master-Slave offsets in a black box approach. Suitable for all kind of network with passive or active optical equipment (fixed asymmetry) but with performance limited by the GNSS receiver (calibration and augmentation techniques are required)
  - Bidirectial amplifiers approach: requires to modify the infrastructure provider network to add these elements (not best choice for many fiber providers due to the risk of back-reflections)
    - Alternatively, amplifiers can be replaced by a cascade of WR links (only suitable for multiple metro-link approaches but not a real long-haul link)

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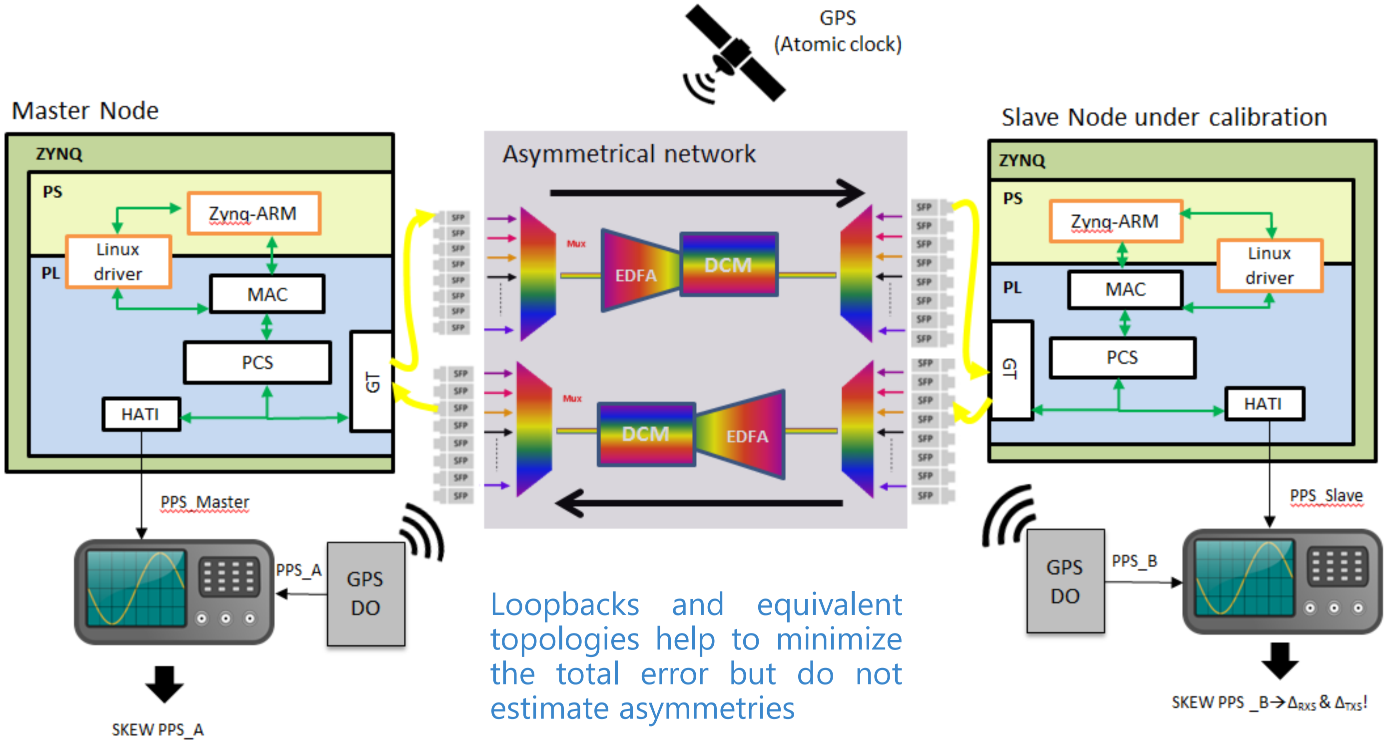
GNSS-based blackblox Calibration

- Calibration by a GPS device: Calibration based on the portable clocks or GPSDOs for **a long-haul network calibration**.
- Calibration accuracy = GNSS time transfer accuracy.



SKEW PPS _B→Δ_{RXS} & Δ_{TXS}!

Loopbacks and equivalent topologies help to minimize the total error but do not estimate asymmetries

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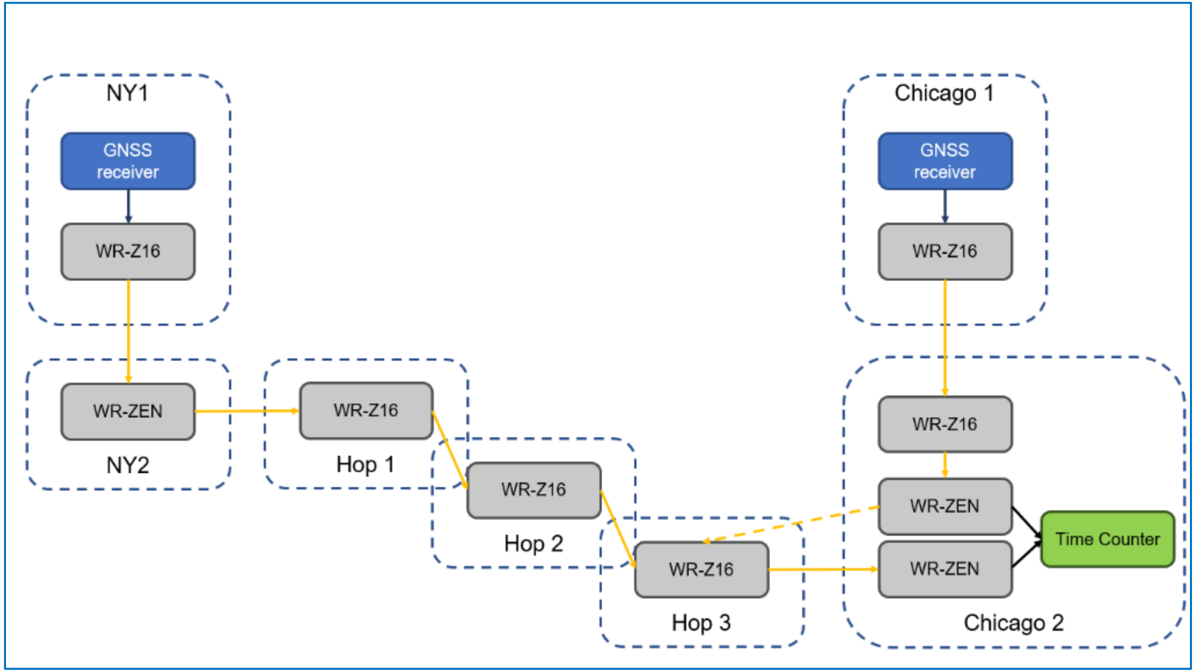
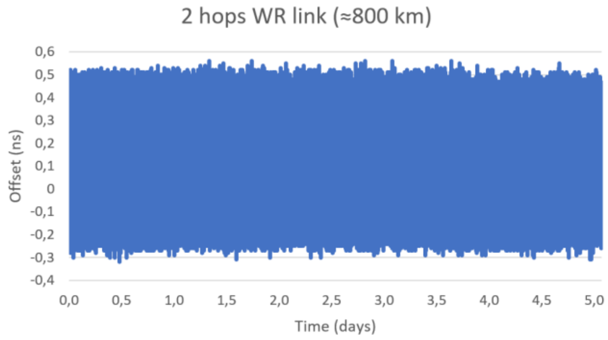
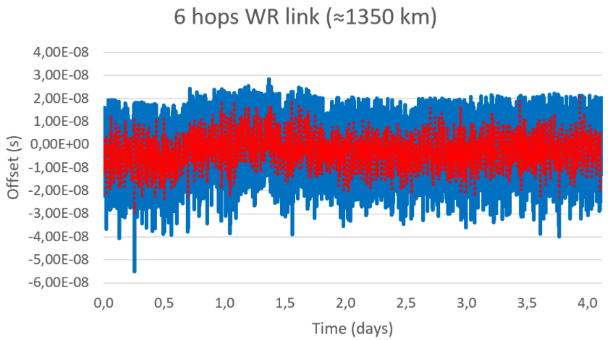
Largest WR link deployed: 1350 Km

- Cascade set of WR devices (many metro link, no real long distances. Calibration verified using calibrated GPS receivers







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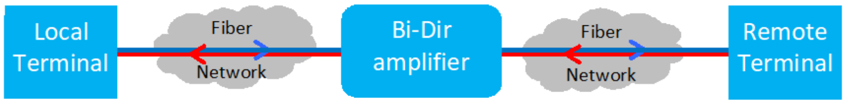
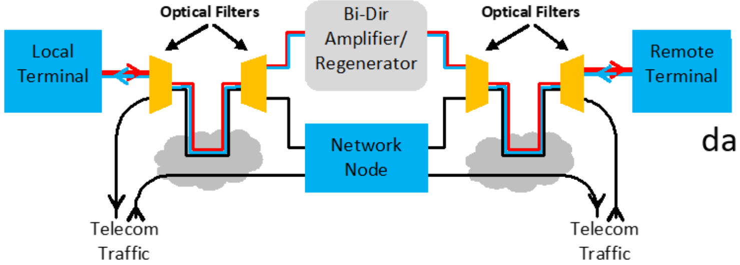
Bidirectional amplifier alternative

- Metrological time transfer solutions achieve ultra-high performance but require dark fibers or dark channels with bidirectional amplifiers. Examples:

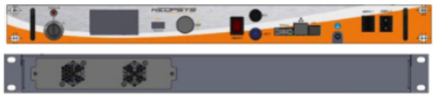
dark fiber

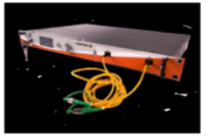


Metrological preferred solutions !



dark channel (alien wavelengths)





- These are expensive solutions with low TRL (Technology Readiness Level) and costly calibration and operation. Not easy to install on existing networks (owned by telecom operator or network provider)
- Bidirectional amplifiers are problematic, not well integrated on optical network infrastructures
- Use WR enabled devices for signal regeneration

Note: Keopsys bidi-amplifiers tested with deterministic behavior and fixed asymmetry (~ 2 ns)

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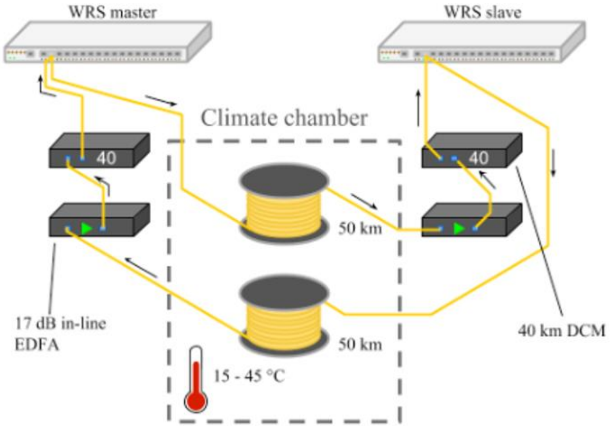
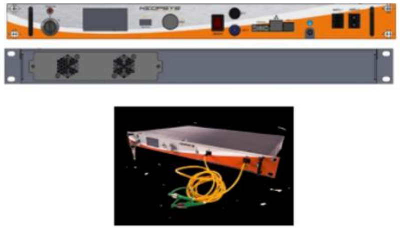
Metro/Long Haul networks: full devices characterization alternative

- **Most long-distance links requires amplification, dispersion compensation or wavelength changes that add to the optical fiber other elements that break WR asymmetry model and you need to add them to alpha.**
- **One deployed, impact on asymmetry is not possible to determine. All devices contributions and fiber characteristics should be known in advance (deterministic behavior determined and asymmetry measured in the lab before deployment) .**
  - Otherwise, the only way to calibrate the link is to use a black-box approach as the only feasible method. Temperature changes can be an issue.



Bidi-amplifiers as alternative to EDFAs.



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Questions?

Manuel Rueda
Customer Support & QA Engineer
Safran – Navigation & Timing
manuel.rueda@nav-timing.safrangroup.com

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