OPNT
Optical Positioning, Navigation and Timing

Sub-nanosecond synchronization of wide-area networks through White Rabbit

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Also affiliated with VU University Amsterdam

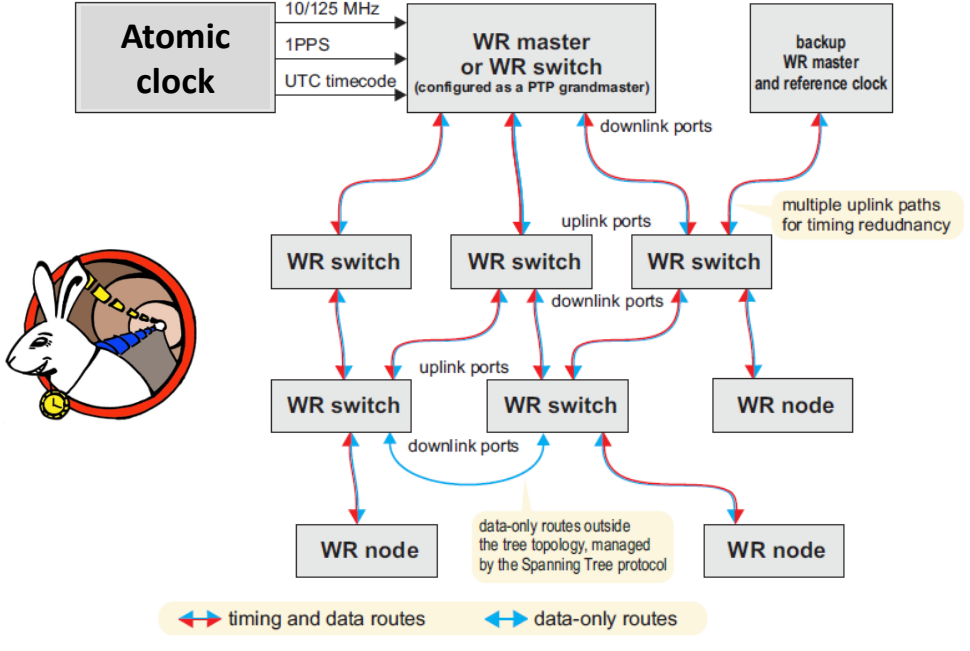
opnt. TIME PROVISIONING

Outline

- White Rabbit intro
- OPNT building blocks for long-haul White Rabbit
- Recent results
- Outlook: sub-nanosecond, centimeter-accuracy terrestrial PNT systems

CERN's White Rabbit

- CERN required Ethernet and timing at the LHC with a precision ≤1 ns
- 'Community effort' gravitating around particle-physics research labs, but also many others
- 'Upgraded' IEEE1588 : **White Rabbit (WR)** http://www.ohwr.org/projects/white-rabbit



Graph: WR project website

Gigabit Ethernet + (sub)ns timing

Range: 10 km

Can handle thousands of nodes

Essential: send signals in both directions through the same optical fiber

Open source software/hardware

Incorporated in IEEE 1588-2019 HA profile

The Netherlands: White Rabbit hotspot

WR academic research activities in The Netherlands (2010 - present)

- **Nikhef high-energy physics institute**
  - Introduced famous WR bitslide mechanism
  - WR for submarine KM3NeT neutrino telescope
  - Absolute delay calibration techniques*,**
- **VU University (later: spin-off company OPNT)**
  - Long-haul, low-noise implementations of WR**,***
  - WR over WDM installed/live fiber-optic networks
  - WR for optical metrology/data acquisition infrastructure LaserLaB VU
- **VSL Delft (NMI)**
  - Nanosecond UTC dissemination over long-haul WR links**
- **SURFnet (NREN)**
  - Long-haul WDM WR for academic research (particle physics, radio astronomy)**
- **ASTRON/JIVE**
  - WR for radio astronomy (VLBI, LOFAR and SKA)

*H.Z. Peek *et al.*, Opt. Express **26,** 14650 (2018)
E.F. Dierikx et al., IEEE TUFFC **63, 945 (2016); T.J. Pinkert et al. (in preparation)
***C. van Tour and J.C.J. Koelemeij, NRAO ngVLA memo #22 (2017)

OPNT

- Optical Positioning Navigation Timing
- Spin-off founded early 2014 (VU University Amsterdam)
- Open source and proprietary WR software/hardware
- Supporting hardware: bidirectional optical amplifiers, optical filters
- Focus:
  - Carrier-grade HW, maximum compatibility
  - Long-haul WDM methods to facilitate deployment and operation in live networks
  - SLA-enabling features (redundant links and hardware, network management system)

Timing Switch

Timing Node

Timing Amplifier (bidirectional)

Timing Filter
Alien λ, WDM, other

Recent results

PoC in live core network Vodafone Netherlands

- Five locations along a 320 km ring
- Optical fiber carrying live core traffic
- End points co-located: timing verification!
- Time offset between end points < 1 ns

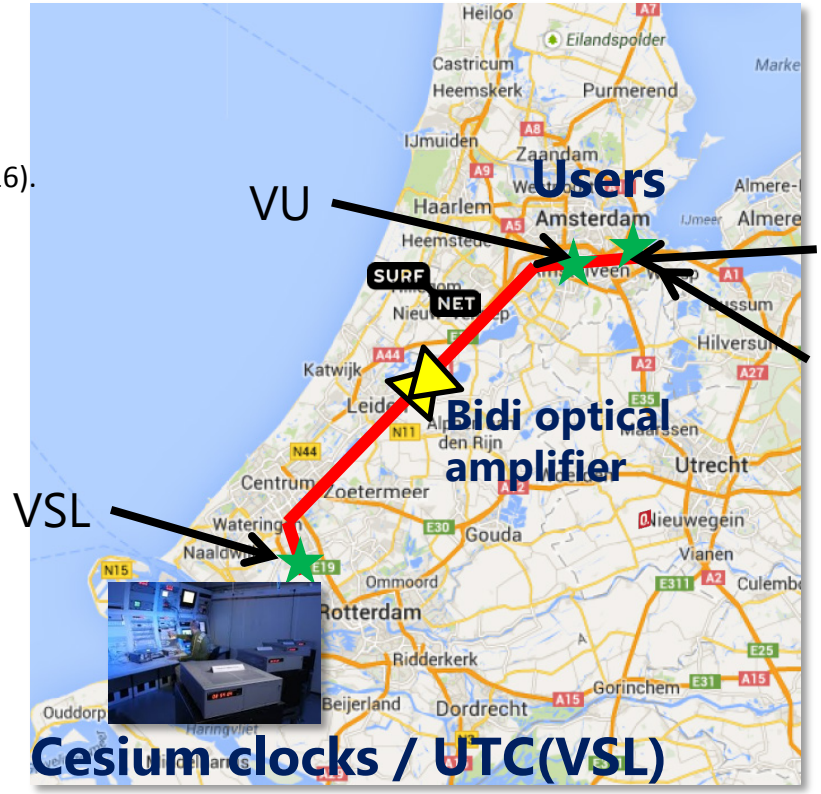
UTC link VSL Delft - Nikhef Amsterdam

- 2× 137 km of dark optical fiber (SURFnet)
- CWDM (1470 nm + 1490 nm)

E. Dierikx *et al.* , *IEEE Trans. Ultrason., Ferroelect. Freq. Control,* **63**(7), 945-952 (2016).

TABLE I. TIME OFFSET OF THE 2 × 137 km WR LINK

Description	Delay (ns)	Unc (ns)
Link VSL - Nikhef		
Amplifier delay asymmetry	0.58	0.2
Dispersion G655 fiber 122 km	1.56	4.0
Dispersion G652 fiber 15 km	5.26	0.5
Slave-master delay measured at Nikhef	61.06	1.0
Link Nikhef - VSL		
Amplifier delay asymmetry	-5.58	0.2
Dispersion G655 fiber 122 km	1.56	4.0
Dispersion G652 fiber 15 km	5.26	0.5
Slave-master delay measured at VSL	-68.76	1.0
Residual time offset	3.39	8.2

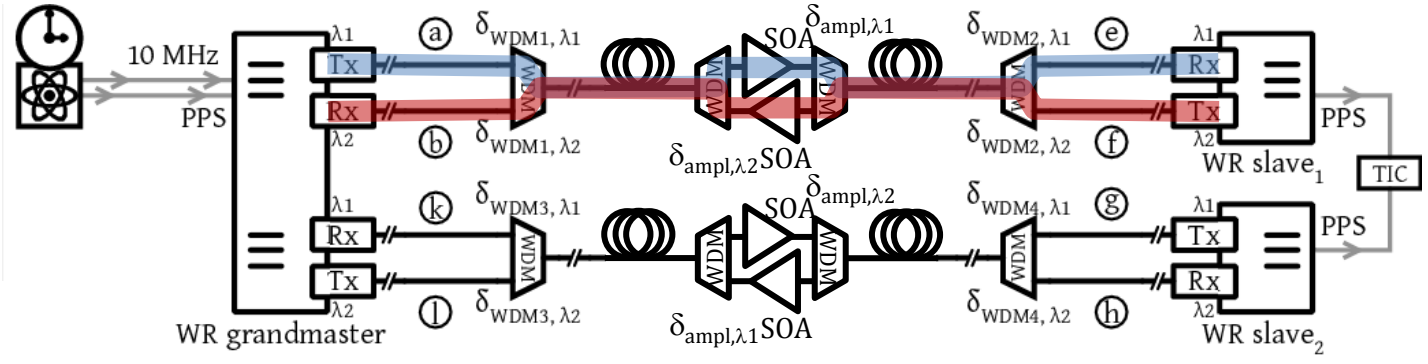


Chromatic dispersion delay calibration

- (Chromatic) Dispersion is main source of differential delays (and timing errors) on long fiber spans (~1 ns/nm per 100 km)
- WR takes this into account through the fiber delay asymmetry parameter α :

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

Dispersion leads to timing errors…



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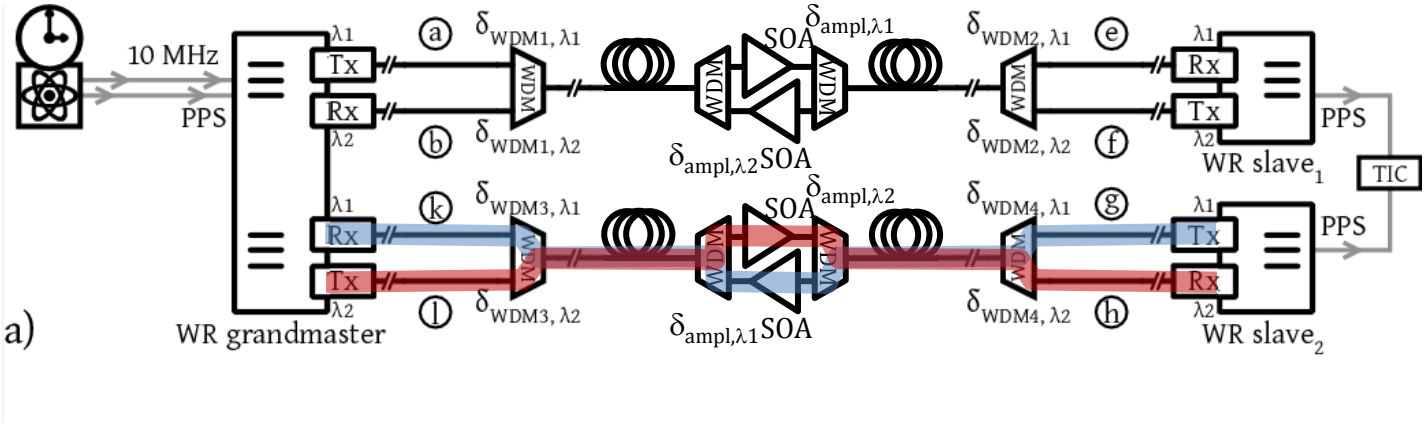
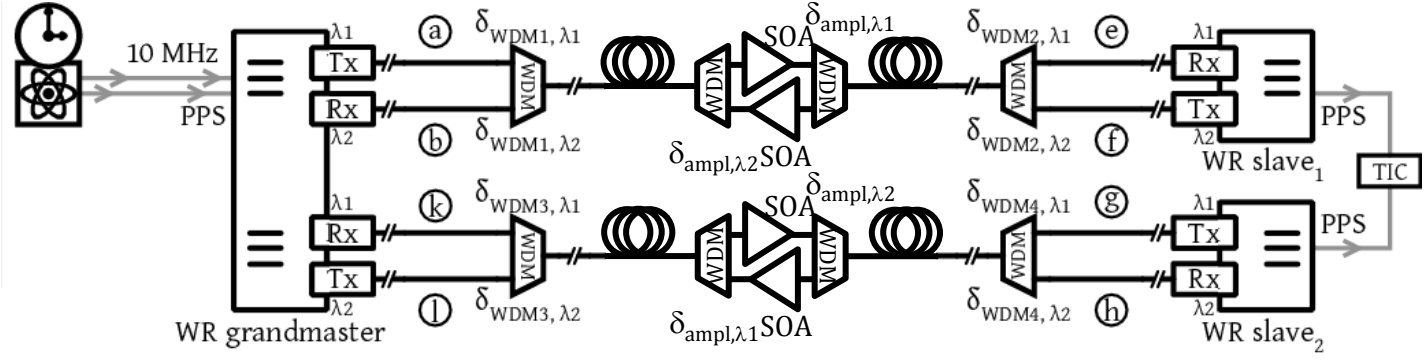
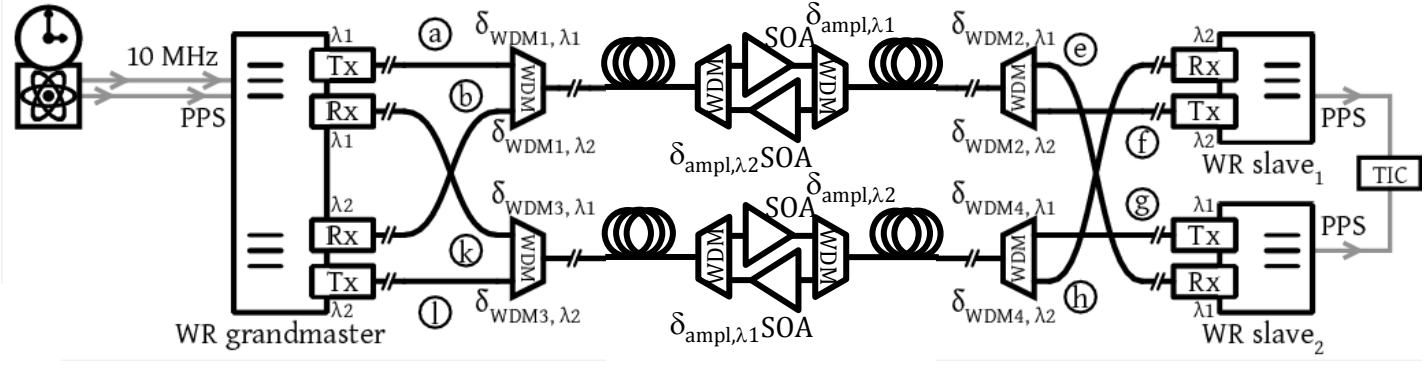


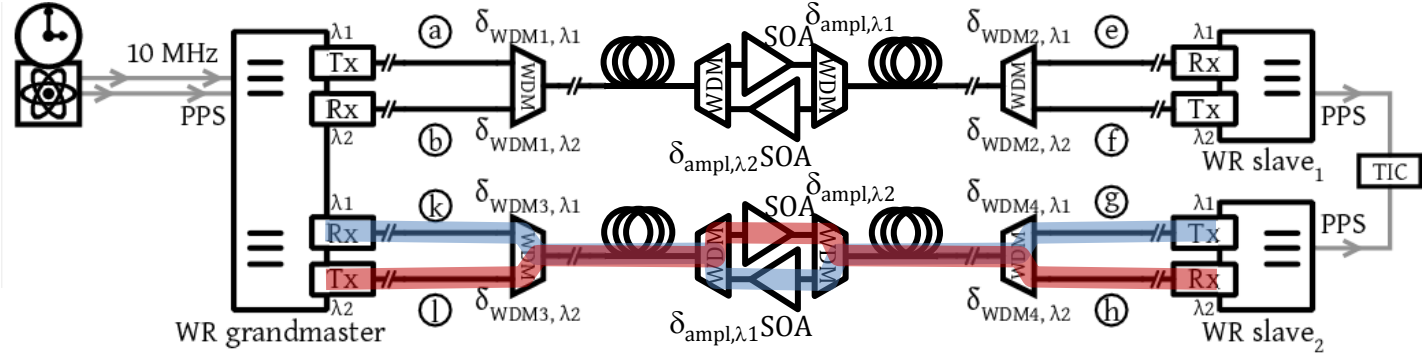
In-situ α calibration



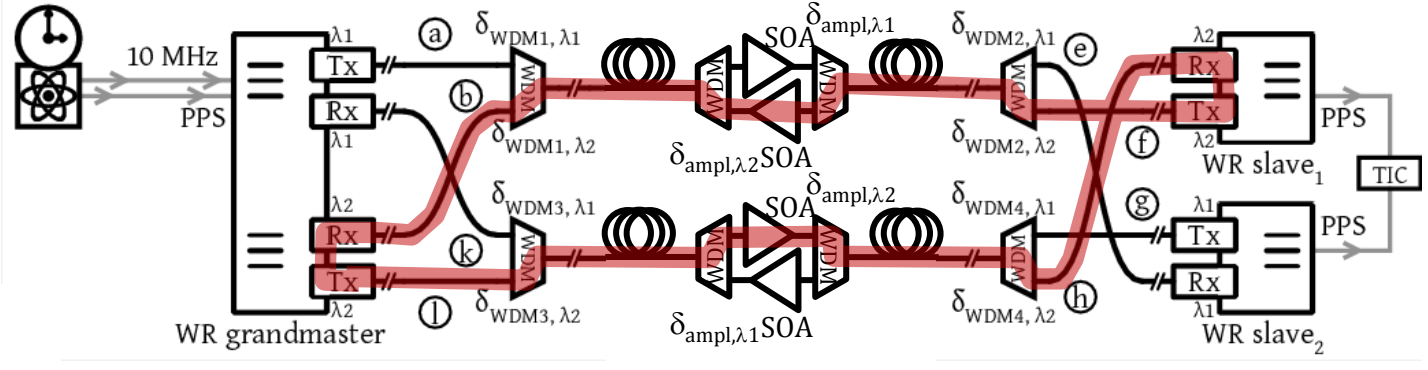
Let's try a different arrangement (by Henk Peek, Nikhef):



In-situ α calibration



Configuration changes only needed at end nodes – leave fiber link unaltered!



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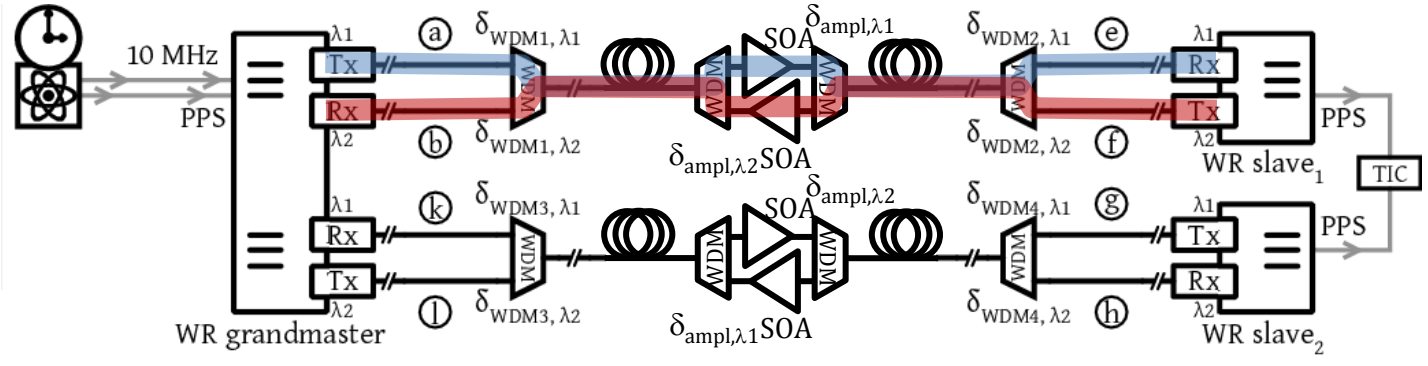

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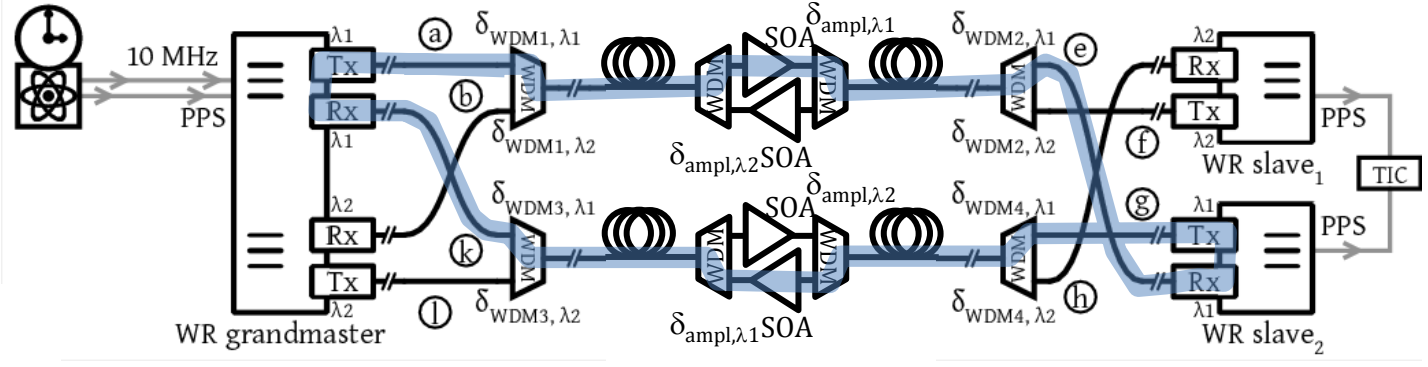
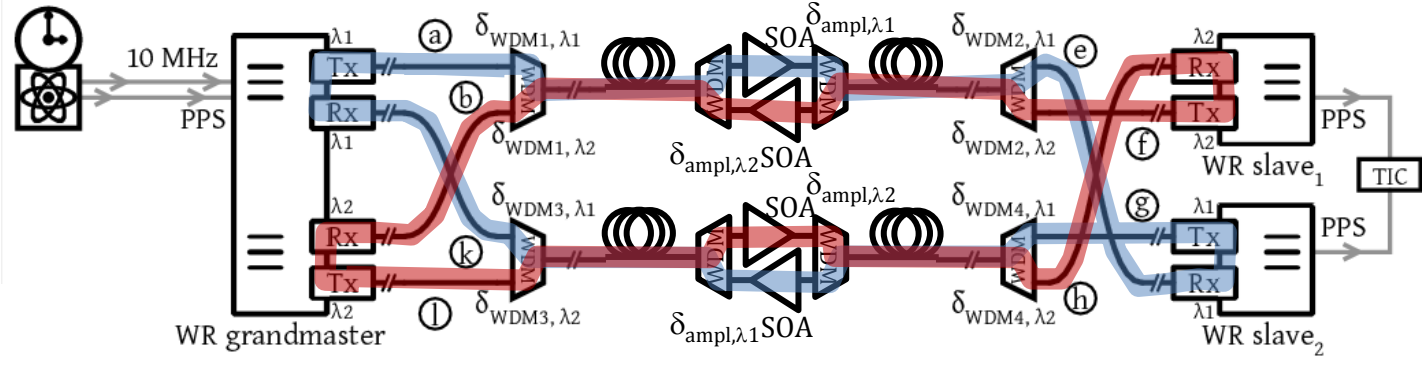


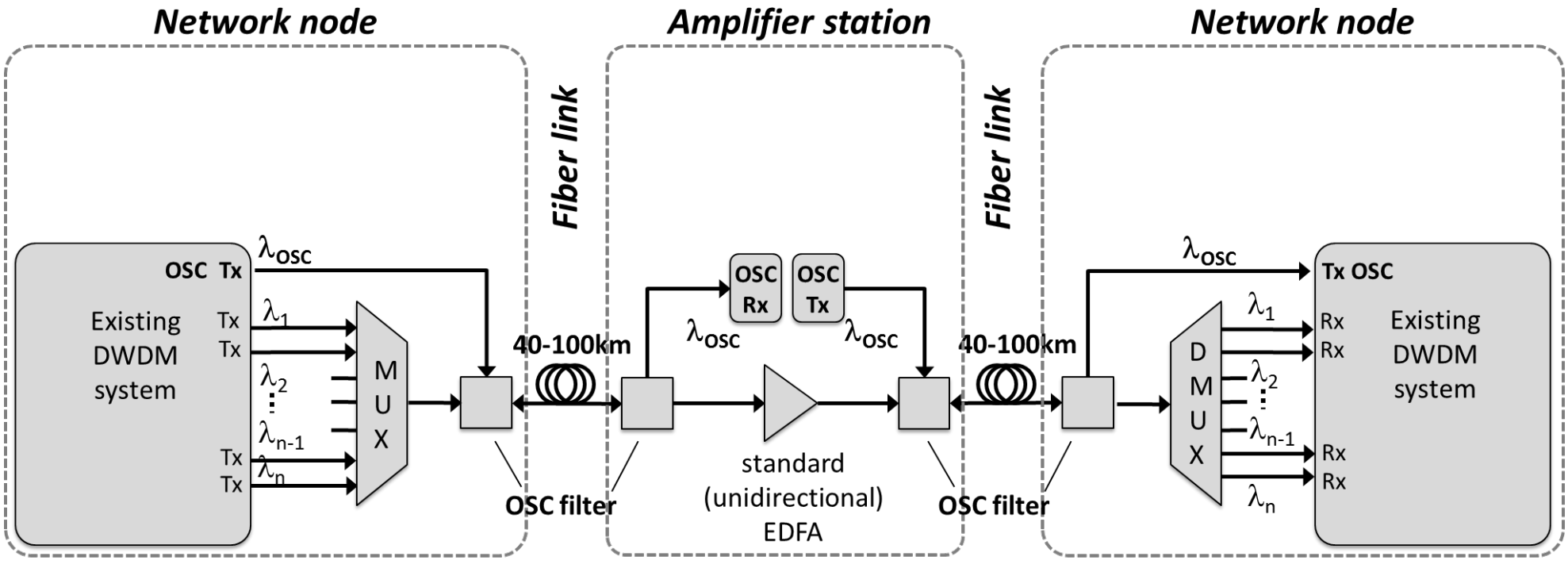
In-situ α calibration

- **Fractional round-trip time difference gives us α**
  - Assumption: fibers have same dispersion properties
- Test (not in 137 km link but 2x 50 km spooled fiber): After correcting for α, time offsets of the two links are **35(6) ps and 38(7) ps**…
- Uncertainty to be studied further, but likely < 500 ps

T. J. Pinkert, H.Z. Peek, P.P.M. Jansweijer, E. Dierikx, R. Smets, JK, *in preparation*

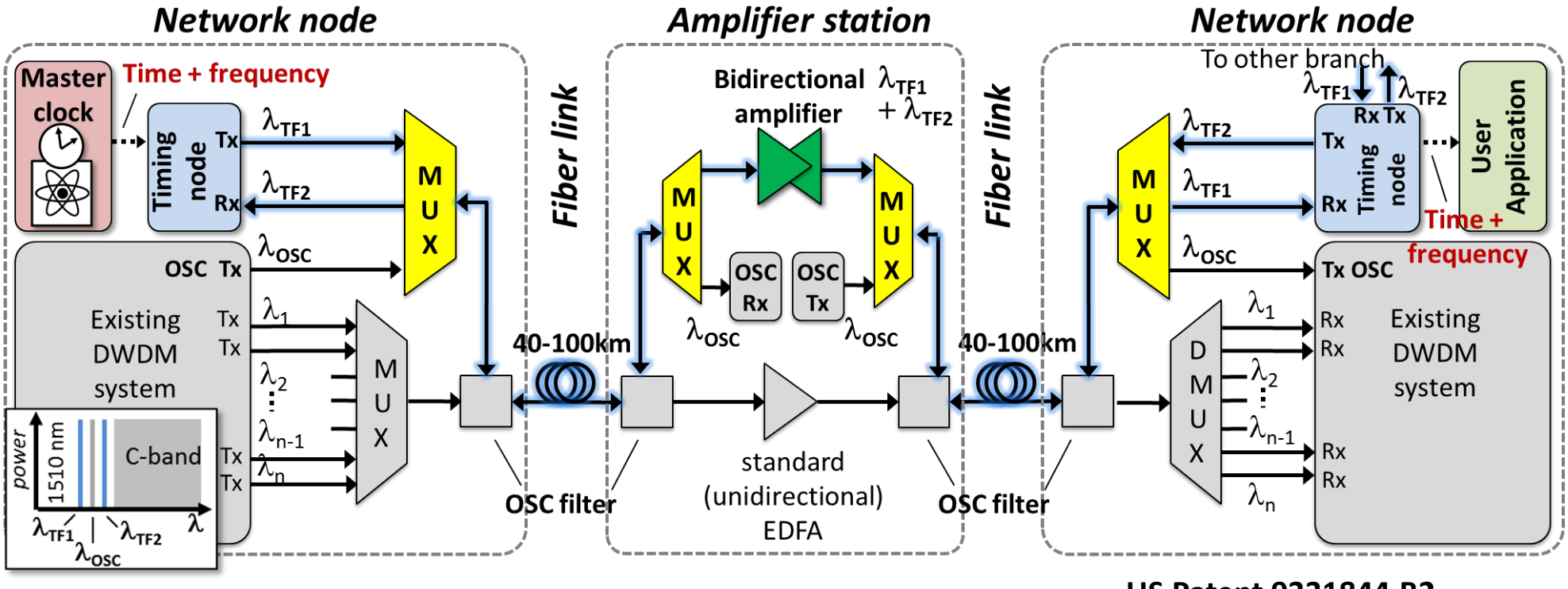


Timing through C band DWDM systems



(duplex fiber, return link not shown)

Timing through C band DWDM systems



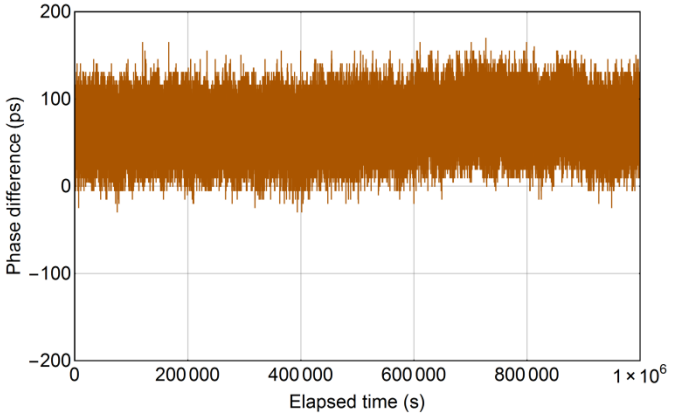
US Patent 9331844 B2
R. Nuijts, JK

Similar WDM solutions demonstrated by others, e.g.
LPL and Observatoire Paris, France
http://www.refimeve.fr/index.php/en/ressources/publications/partners-of-refimeve.html

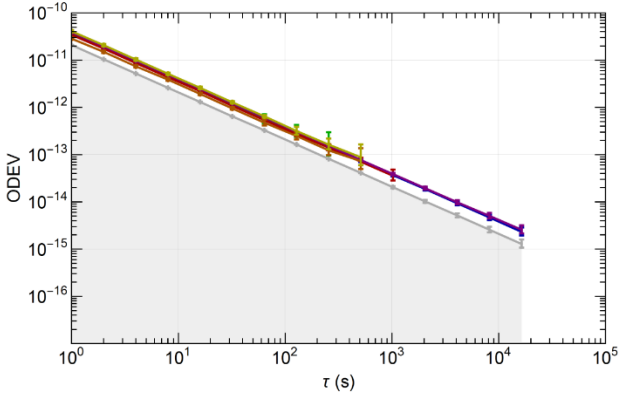
Interoperability tests

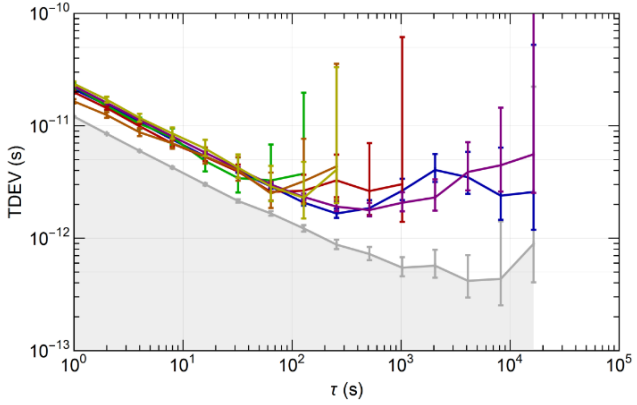
- Demonstrated interoperability with DWDM systems of six vendors
- Two in the field, four in the lab
- Over distances up to 200 km, mean time offsets below ±100 ps routinely achieved after calibration
- 1 PPS output measurements: ~20 ps RMS jitter (partly TIC)

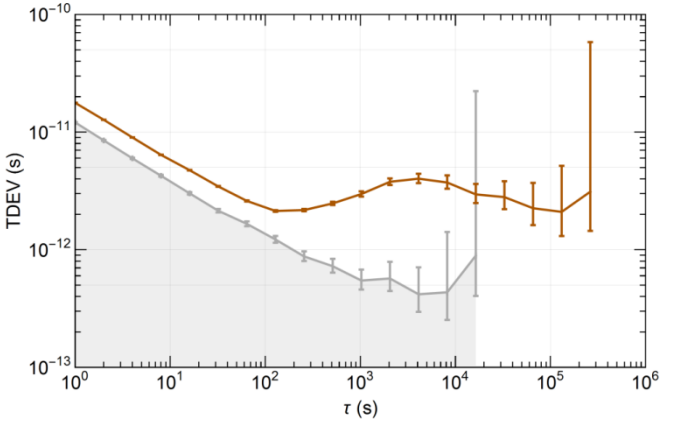
11-day run



Stability for 4 different DWDM setups



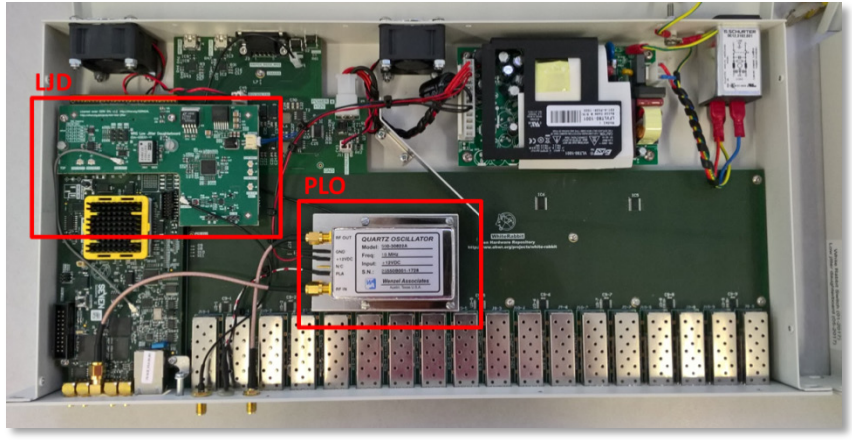




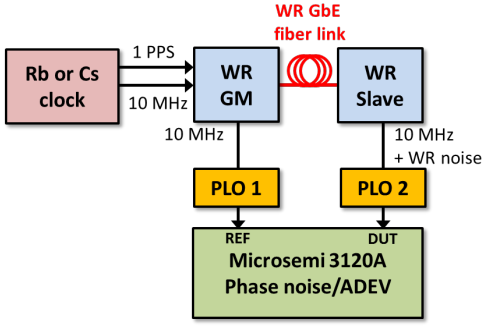
Low-jitter White Rabbit

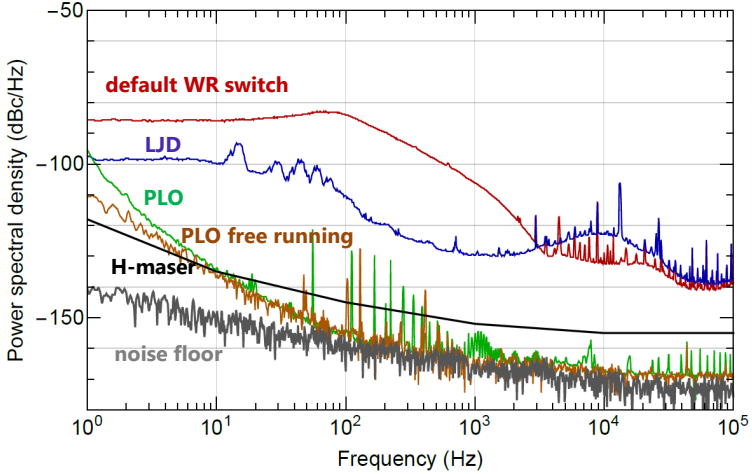
- Based on work* by Mattia Rizzi et al. (CERN) ⇒ WR switch with low-jitter daughterboard (LJD)
- Extended with clean-up oscillator (PLO)
- ADEV **4×10^{-13} @ 1s** and **5×10^{-16} @ 5000s**
- RMS jitter 0.18 ps (1 Hz - 100 kHz)

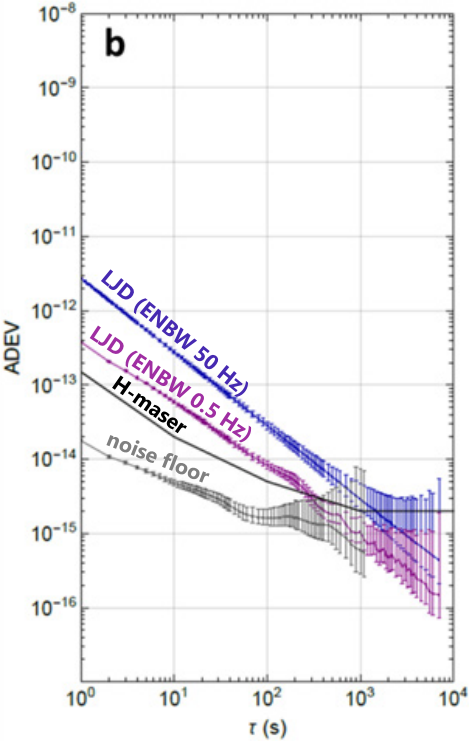
*https://www.ohwr.org/projects/wr-low-jitter



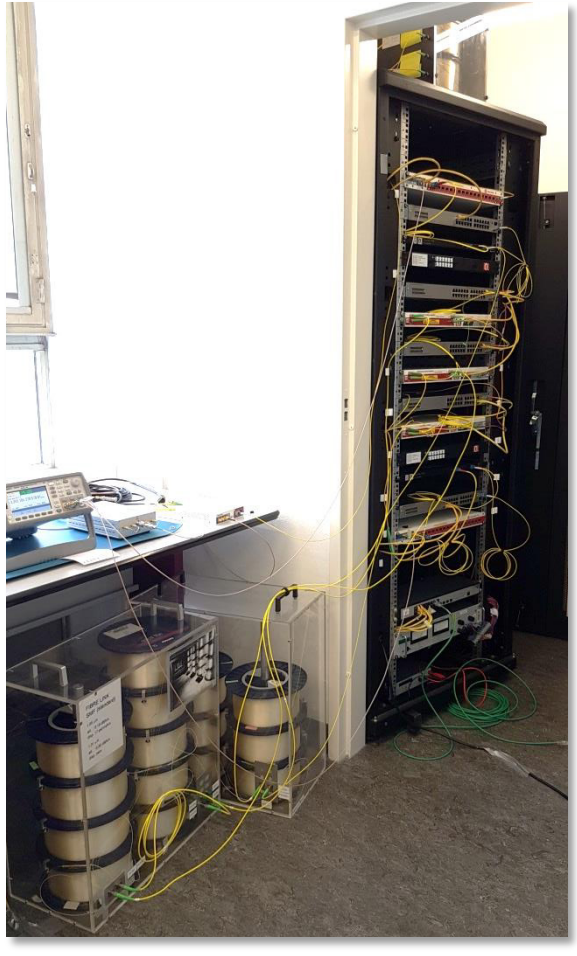
C. van Tour and J.C.J. Koelemeij, NRAO ngVLA memo #22 (2017)
https://library.nrao.edu/public/memos/ngvla/NGVLA_22.pdf

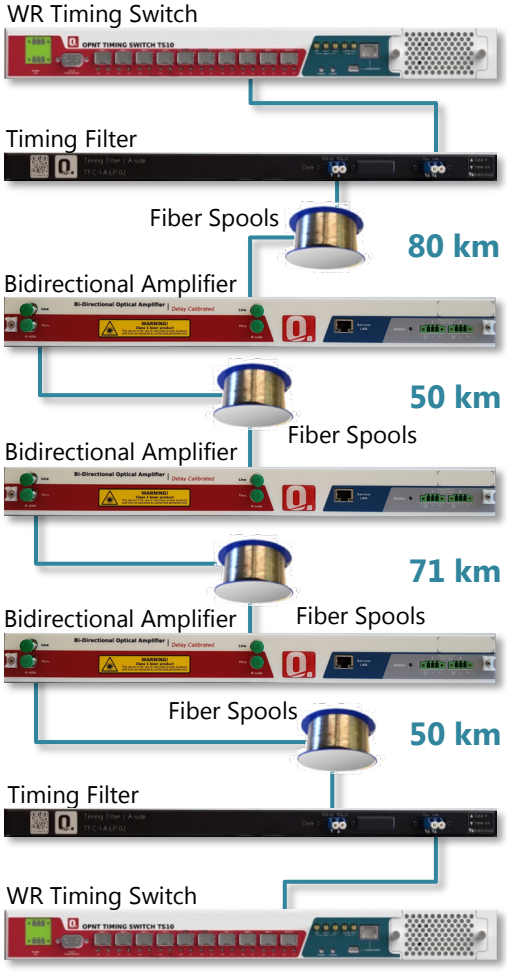






251 km link with cascaded amplifiers

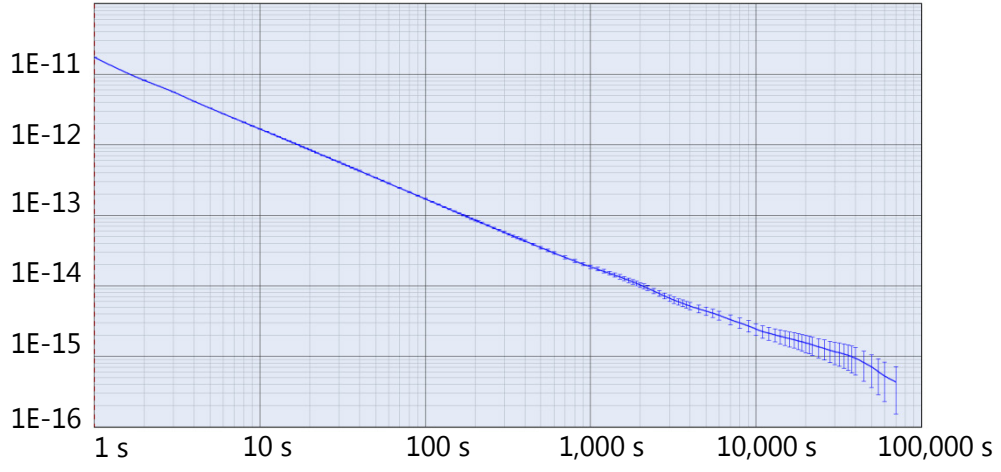




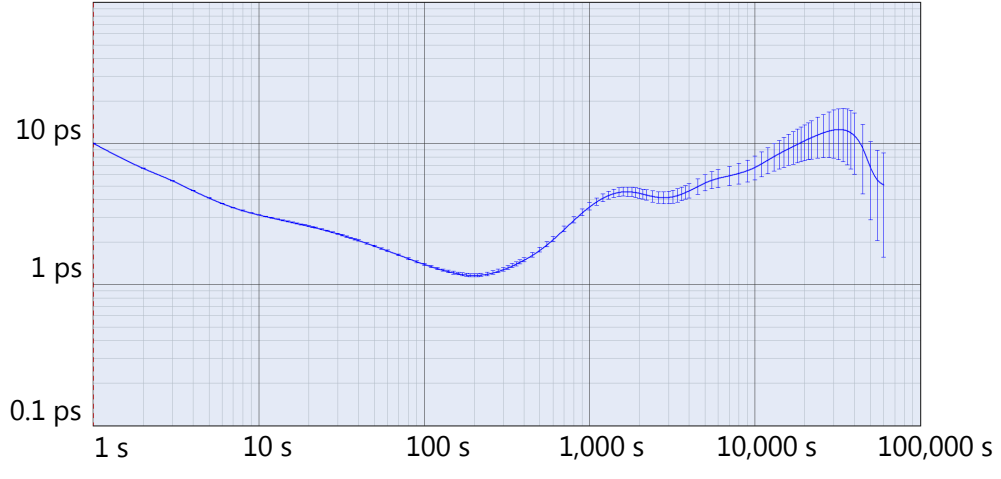
- Delay asymmetry calibration procedure suited for field deployment
- End-to-end time offset after calibration: **-77 ps**
- Statistical uncertainty: **9 ps**
- Systematic uncertainty: **TBD**
  - Estimate: **< 0.2 ns**

251 km link with cascaded amplifiers

ADEV



TDEV



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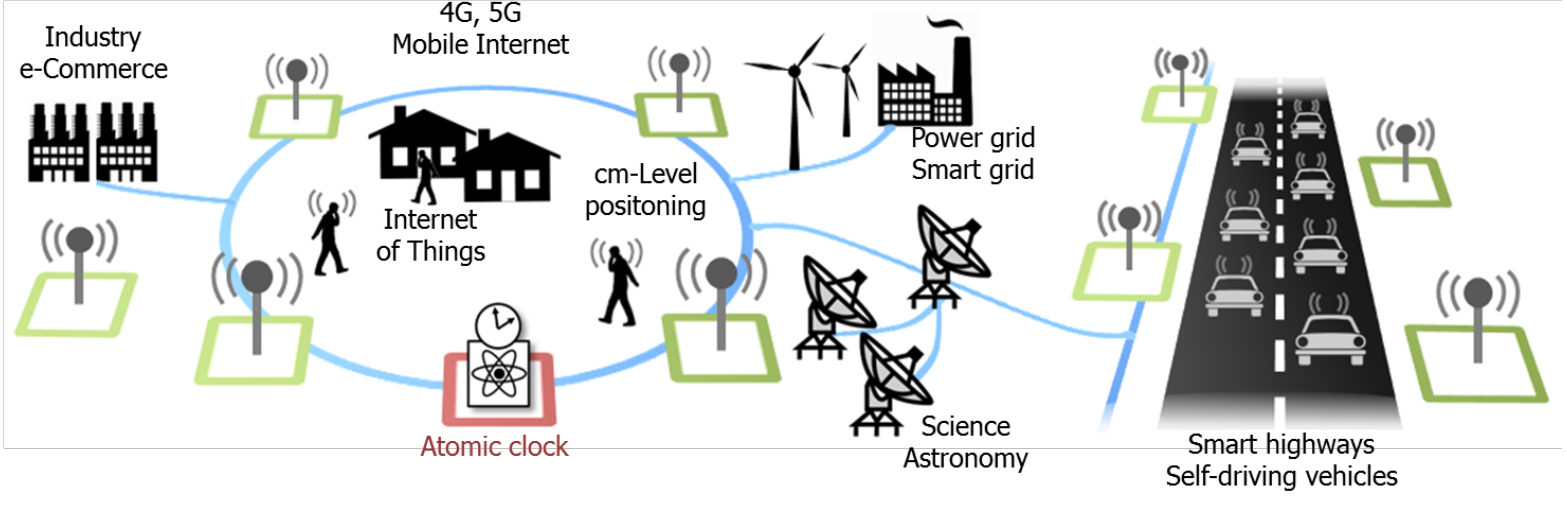
Summary / WR benefits

- ✓ End-to-end ‘OSC type’ WR timing solutions in existing networks (in field and in lab)
- ✓ Practical installation and delay calibration methods allowing ~ 0.1 ns uncertainty
- ✓ Low-noise WR gear (approaching H-maser performance)
- ✓ Cascaded optical amplifiers for long all-optical spans (251 km between two WR switches)
- ✓ Time offsets below 0.1 ns even for long links and long measurement runs
- ✓ WR / IEEE 1588-2019 HA:
  - ✓ Accurate (beyond GPS)
  - ✓ Stable (beyond Rb/Cs clocks)
  - ✓ Insensitive to network traffic load
  - ✓ Backward compatible with PTPv2

Outlook: nationwide terrestrial PNT networks

- Vision: long-haul core network (WR/IEEE 1588-2019 HA) with PTPv2 towards edges
- National terrestrial time infrastructure also useful for 5G mobile, finance, Smart grids, autonomous driving and indoor positioning with < 0.1 m accuracy
- Integrate wireless positioning signals into 5G signal structure and bands(?)
- Topics addressed by SuperGPS project (with Delft University of Technology, KPN, VSL, a.o.)



Credits

- **Team @ OPNT**
- OPNT Advisors (Mr. Jeffrey K. Harris, Mr. Jean Pierre Aubry) and independent Board Member (Dr. Niel Ransom)
- Investors (Cottonwood Technology Fund, KPN Ventures)
- Partners...

... and funding agencies: