Redundant and Secure Time and Frequency Transfer through Fiber-Optic Networks for Quantum Applications and PNT beyond GNSS

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NATO IST-SET-198-RSY on Quantum Technology for Defence and Security

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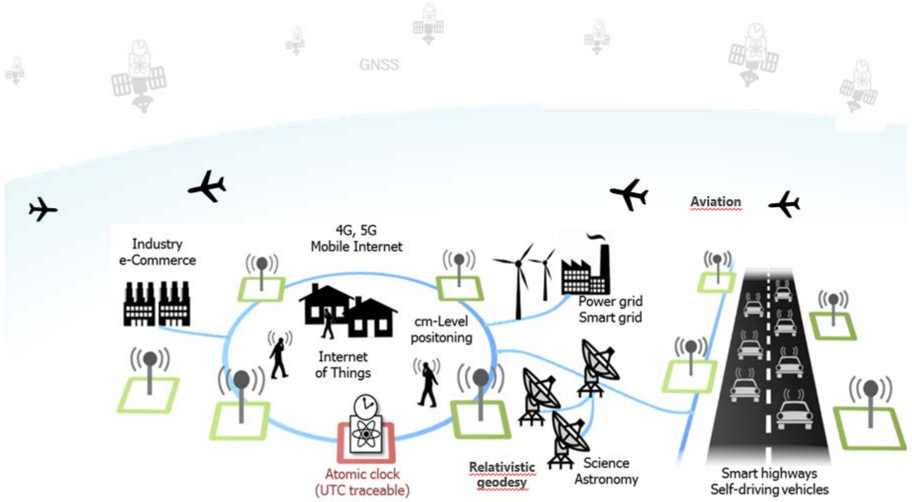
Research carried out with support from

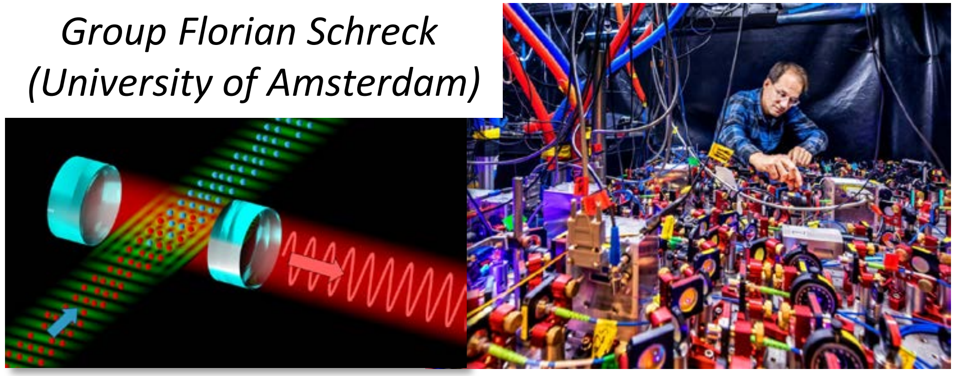
Our research

Networks for extremely accurate **time** and **frequency** distribution:



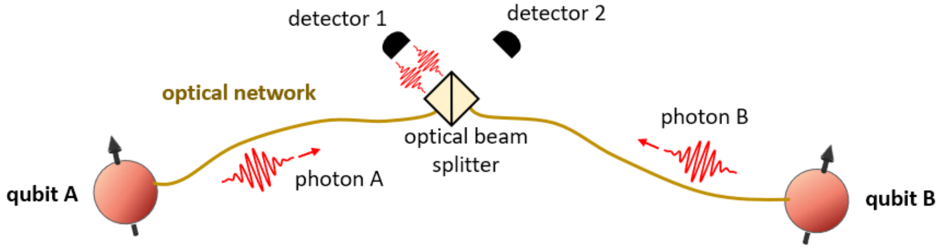
1. Networked GNSS-backup systems with performance beyond GNSS
   Koelemeij et al., *Nature* **611,** 473 (2022)

Group Florian Schreck (University of Amsterdam)



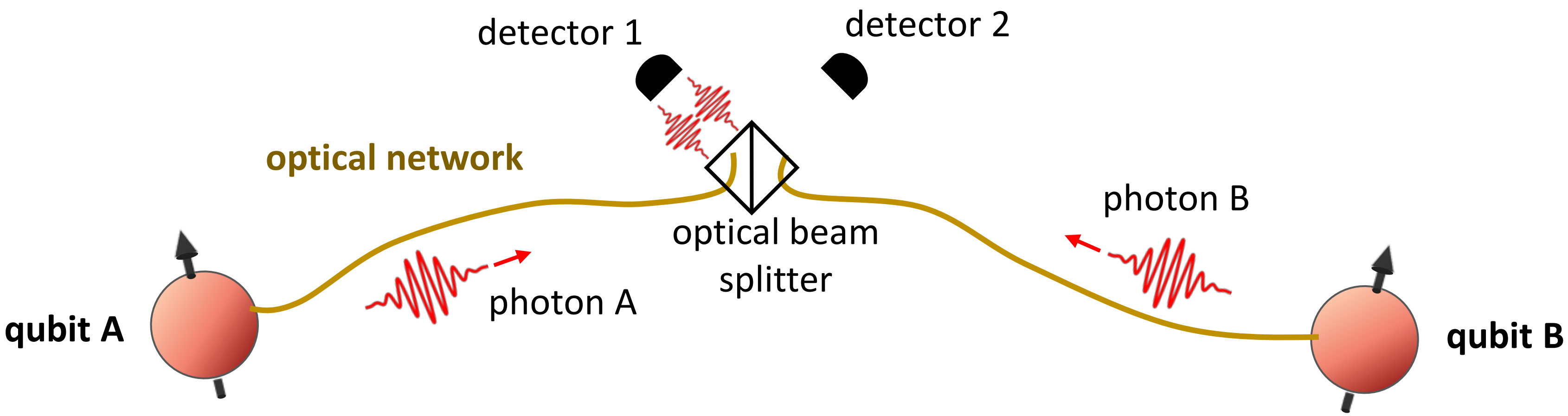
2. Connecting optical quantum clocks (e.g. for gravitational potential sensing)

3. Time synchronization of quantum network nodes



Why is timing important for quantum networks?

- Quantum networks:
  - Now: Quantum Key Distribution (QKD) – secure exchange of quantum information (**photons**)
  - Future: networks of entangled **qubits and photons** for distributed quantum information processing



- Quantum information processing requires **entangling** qubits A and B
- Entanglement achieved if two photons arrive at the same detector
  - **but only if** two photons are **indistinguishable**: same color, **same arrival time**
- *In practice: photon emissions must be timed within 0.1 nanosecond**

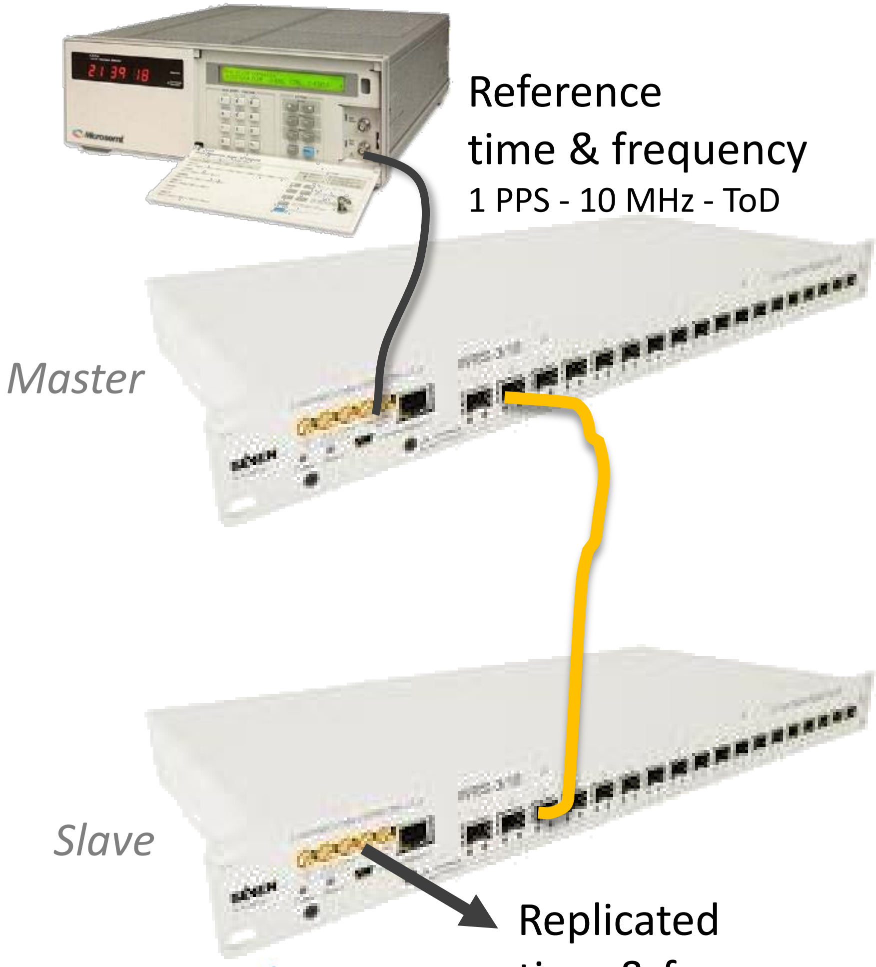
* Moehring et al., *Nature* **449,** 68 (2007); Stolk et al., *PRX Quantum* **3,** 020359 (2022)

0.1 nanoseconds timing precision…

… requires equipment in large-scale networks (fiber-optic, satellite, …) to be time-synchronized to within 0.1 ns

- Most existing large-area timing technology cannot provide such precision
  - ✘ NTP (network time protocol): 1 millisecond at best (= 1 million nanoseconds)
  - ✘ Precision Time Protocol (PTP/IEEE 1588): several tens of nanoseconds at best
  - ✘ Global Navigation Satellite Systems (GNSS): a few nanoseconds error at best
  - ✓ White Rabbit (CERN) can provide 0.1 ns, in the form of Gigabit Ethernet network equipment!

White Rabbit network time distribution



White Rabbit http://www.ohwr.org/projects/white-rabbit

- Data, time & frequency distribution system originally developed for (and by) high-energy-physics research facilities (notably CERN/LHC)
- Open-source, open-hardware network equipment for optical **Gigabit Ethernet**

+

- Optical **subnanosecond time distribution**: measurement and correction for round-trip delay

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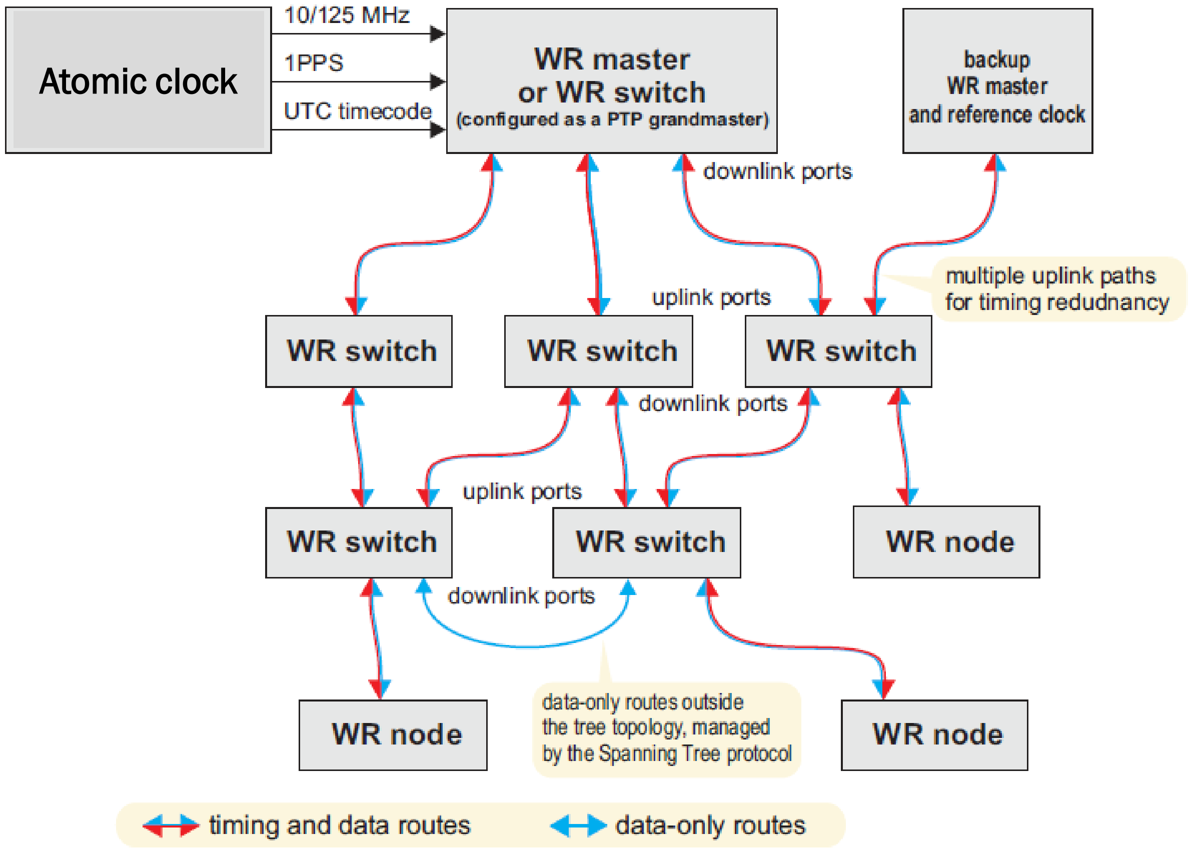
White Rabbit networks (see also: IEEE 1588-2019)

White Rabbit residual network time error <1 ns

http://www.ohwr.org/projects/white-rabbit



Graph: WR project website

0.1 nanoseconds timing precision

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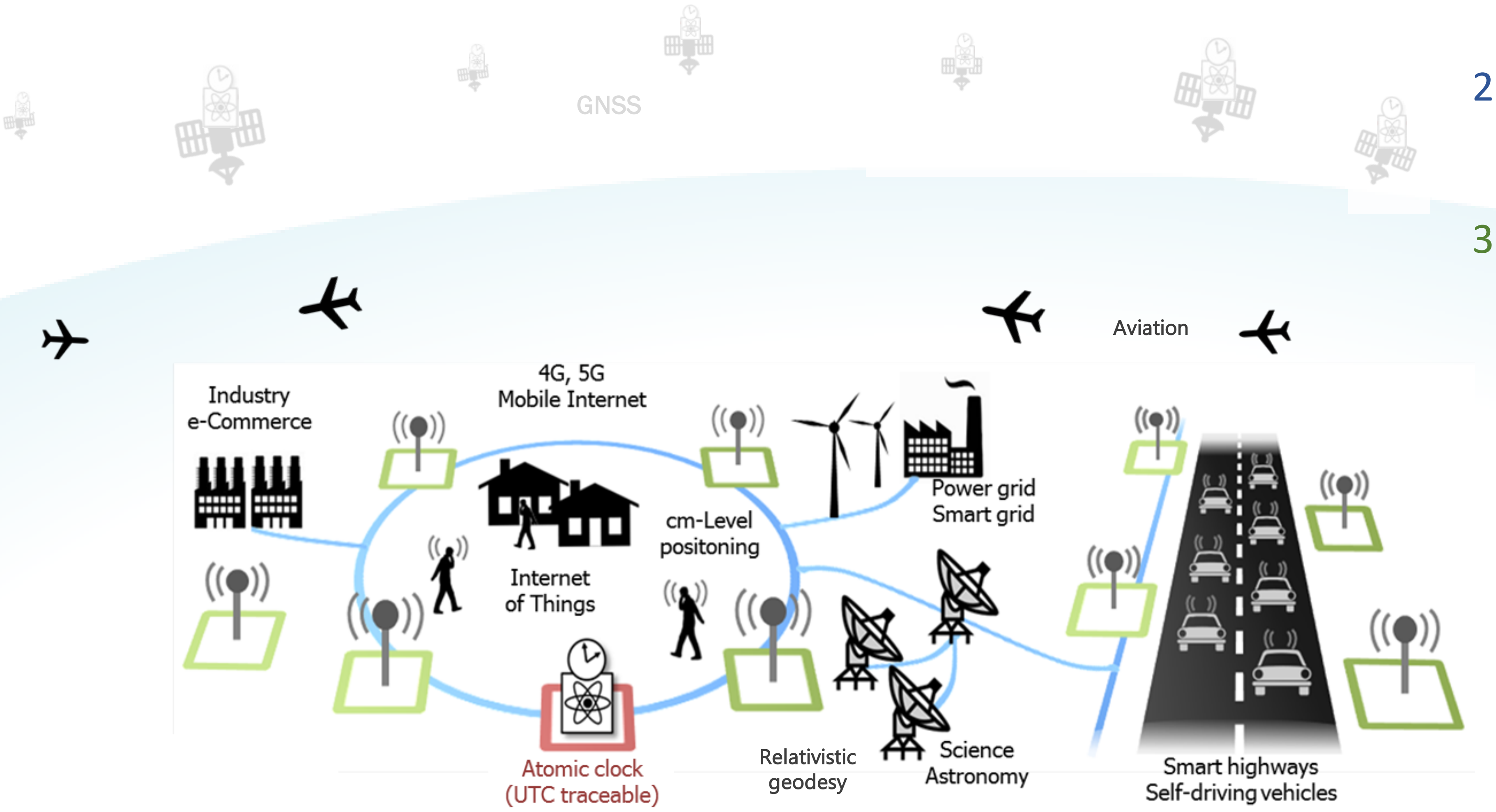
- For photons travelling at speed of light (299 792 458 m/s): 0.1 ns ⇔ 3 cm
  - Same for radio waves, transmitted by e.g. mobile network base stations
  - **Can we build a WR-based PNT network with cm-level precision?**

    ⇒ **YES** (see e.g. Koelemeij et al., *Nature* **611,** 473 (2022), Tiberius et al., *ION NAVIGATION* **70**(3), 589 (2023)

Subnanosecond, centimeter terrestrial PNT network

(collaboration with Delft University of Technology, VSL Delft, and private partners)



1. Reference atomic clock
2. Subnanosecond time through fixed network
3. Wireless network for decimeter-level positioning (TDoA)

No dependence on satellites in space

Secure (fiber-optic) connections

Received signal power 10^6 times that of GNSS

Subnanosecond, centimeter terrestrial PNT network

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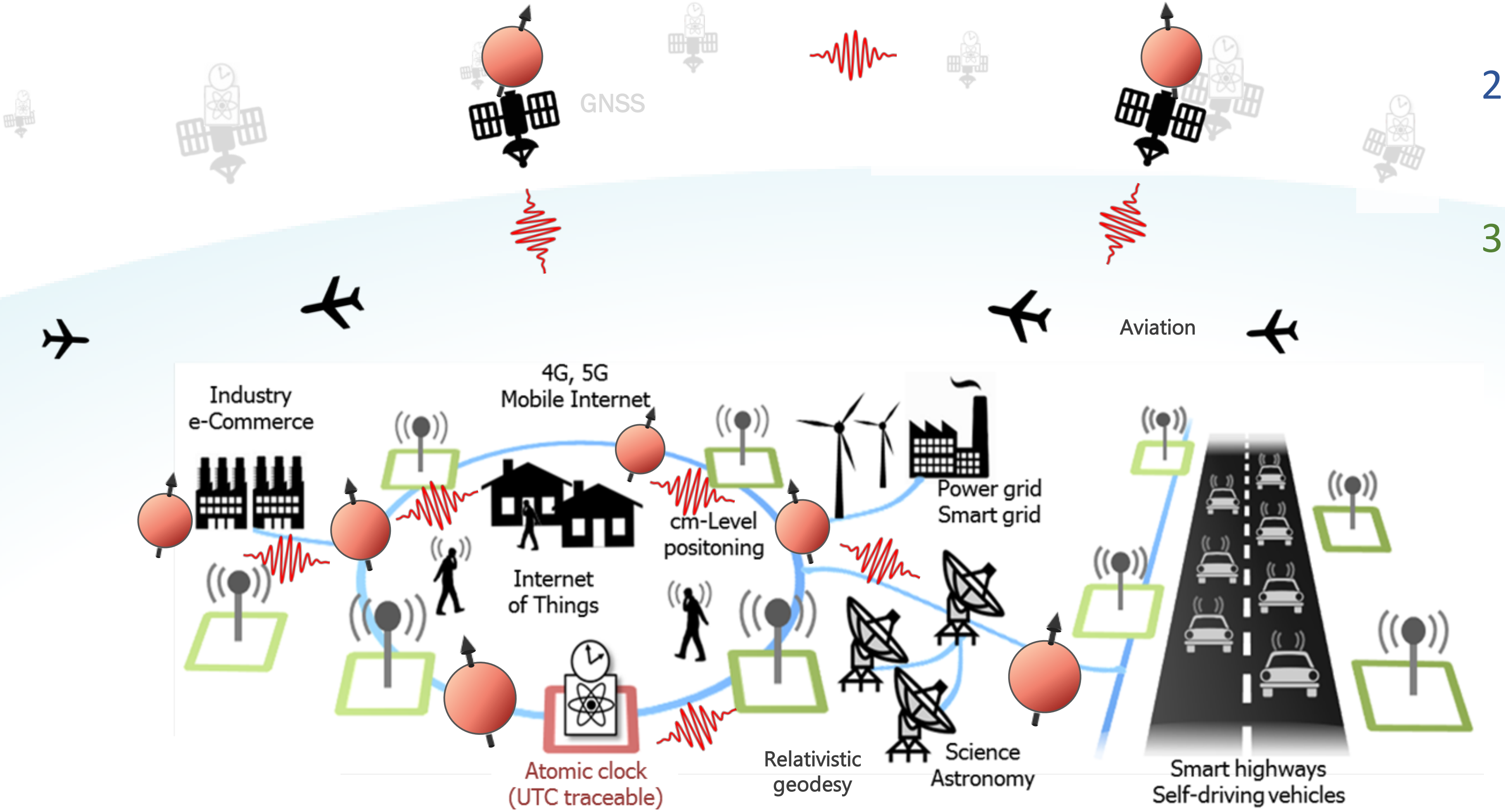
Back-up system for PNT through GNSS

Could also support quantum networks and distributed quantum computing



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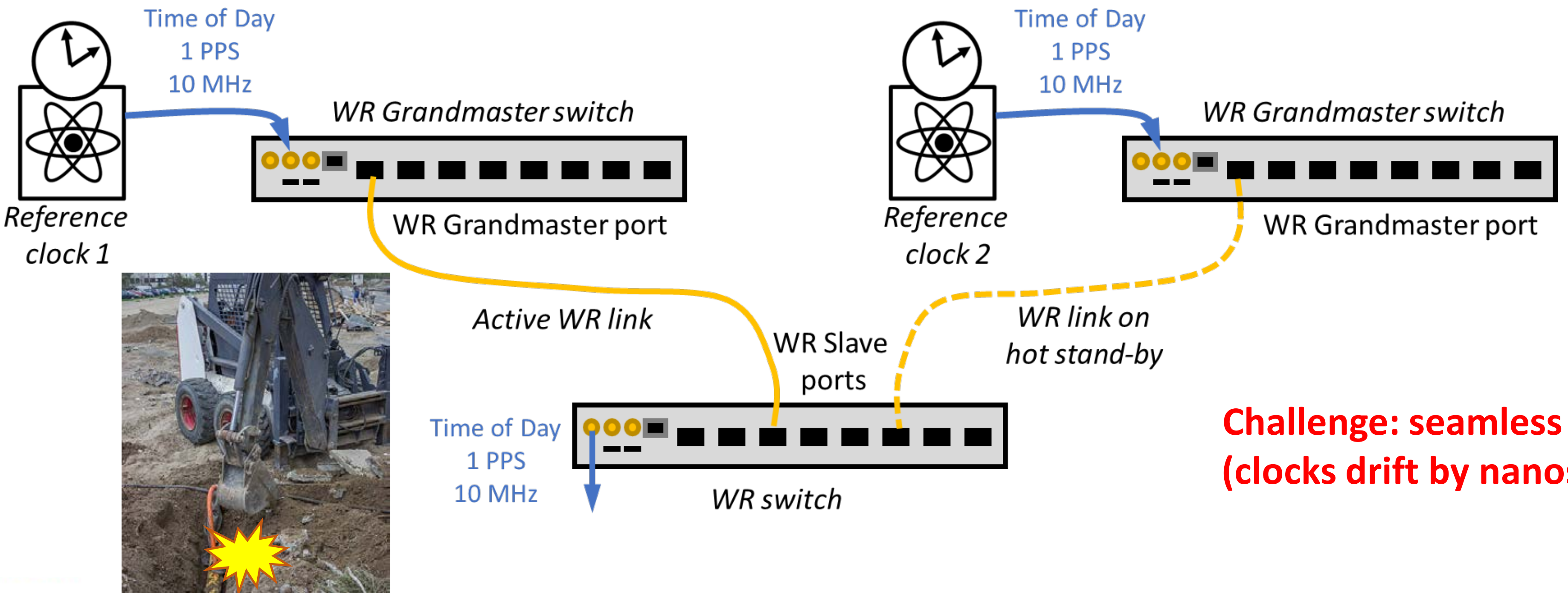
Redundancy and fail-over

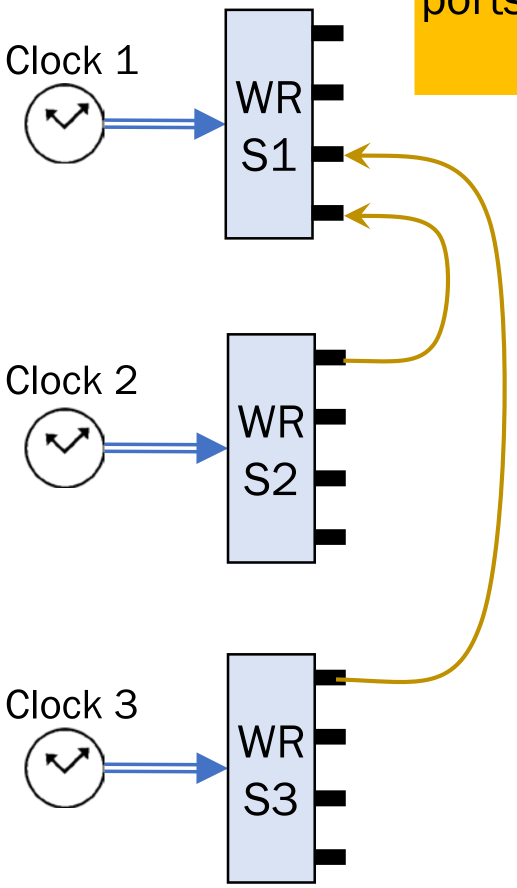
- GNSS backup & quantum networks: security and reliability are of the essence, and so must be timing accuracy, availability and integrity
- BUT: WR designed for single reference clock: single point of failure
- Need for redundant clocks and paths + fail-over mechanisms



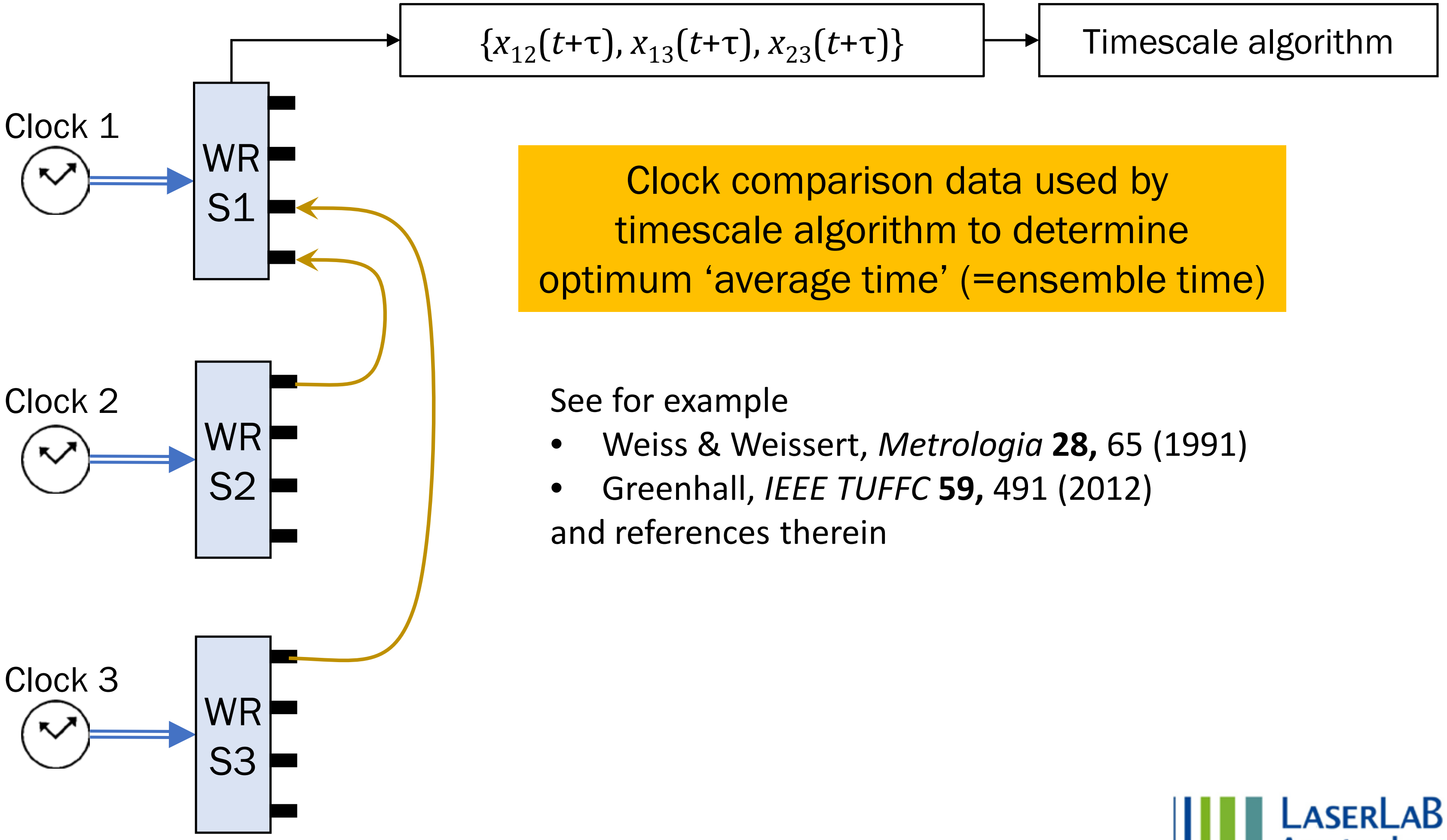
Challenge: seamless fail-over (clocks drift by nanoseconds)

Network timescale based on a clock ensemble

WR switch measures time/phase differences between WR slave ports, and between slave ports and its own LO (which is locked to Clock 1)
$\Rightarrow \{x_{12}(t+\tau), x_{13}(t+\tau), x_{23}(t+\tau)\}$



Network timescale based on a clock ensemble



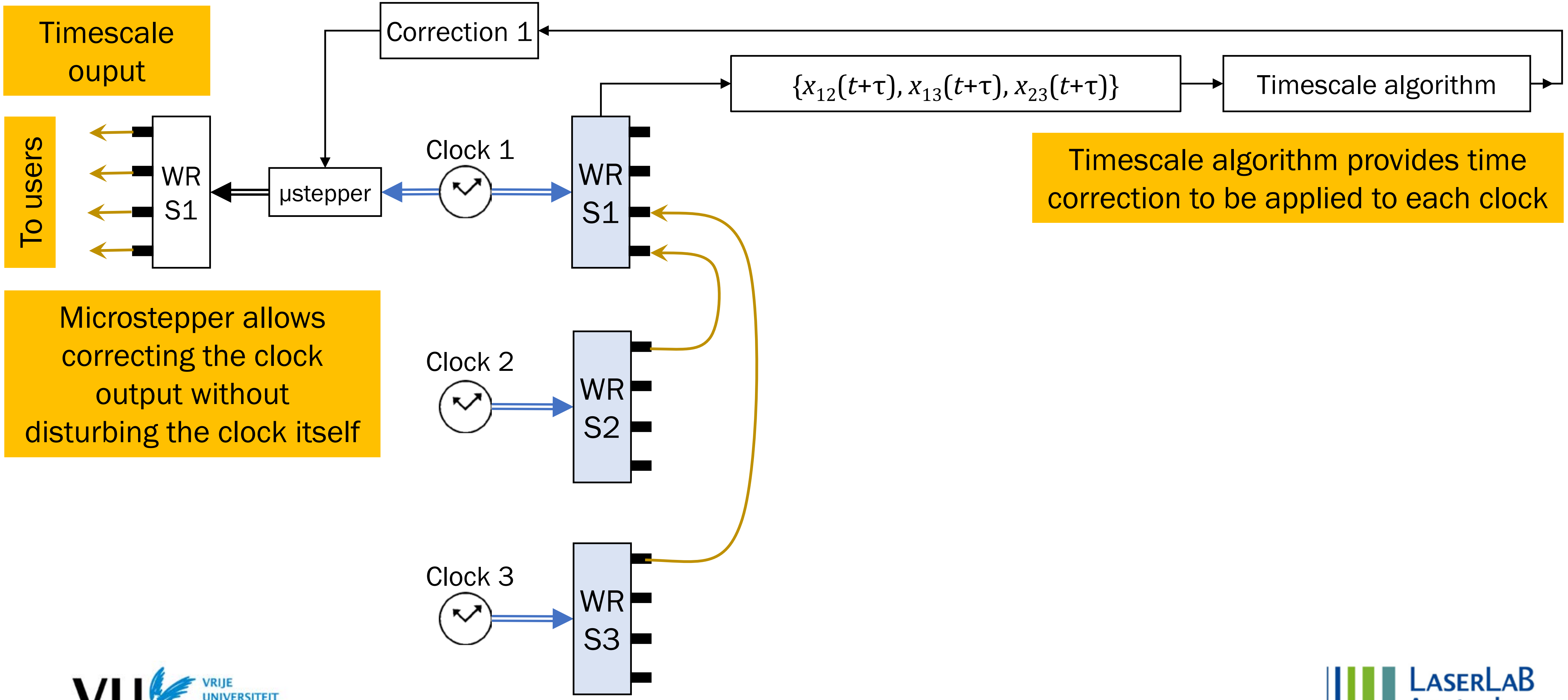
Clock comparison data used by timescale algorithm to determine optimum ‘average time’ (=ensemble time)

See for example

- Weiss & Weissert, *Metrologia* **28,** 65 (1991)
- Greenhall, *IEEE TUFFC* **59,** 491 (2012)

and references therein

Network timescale based on a clock ensemble



Timescale algorithm provides time correction to be applied to each clock

Microstepper allows correcting the clock output without disturbing the clock itself

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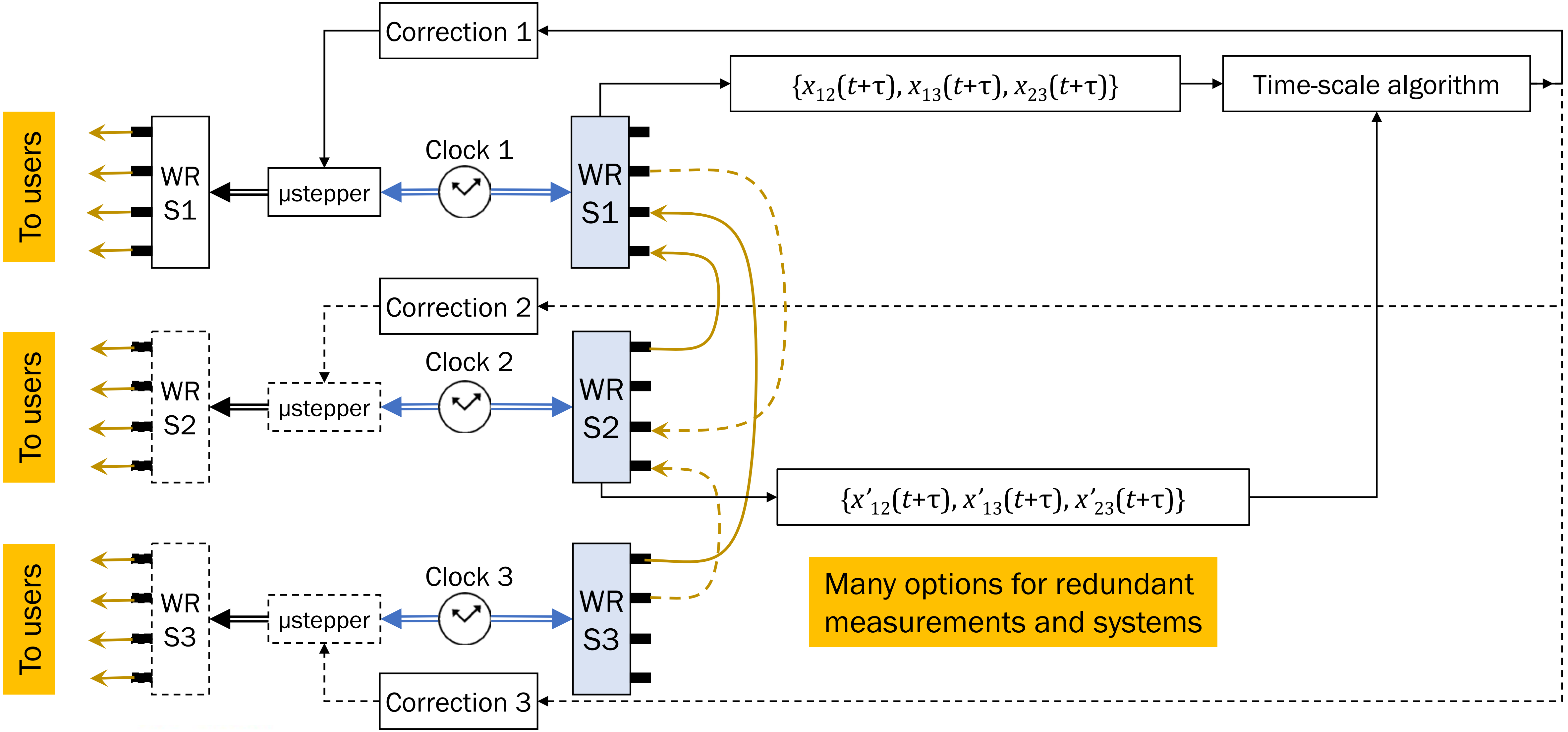
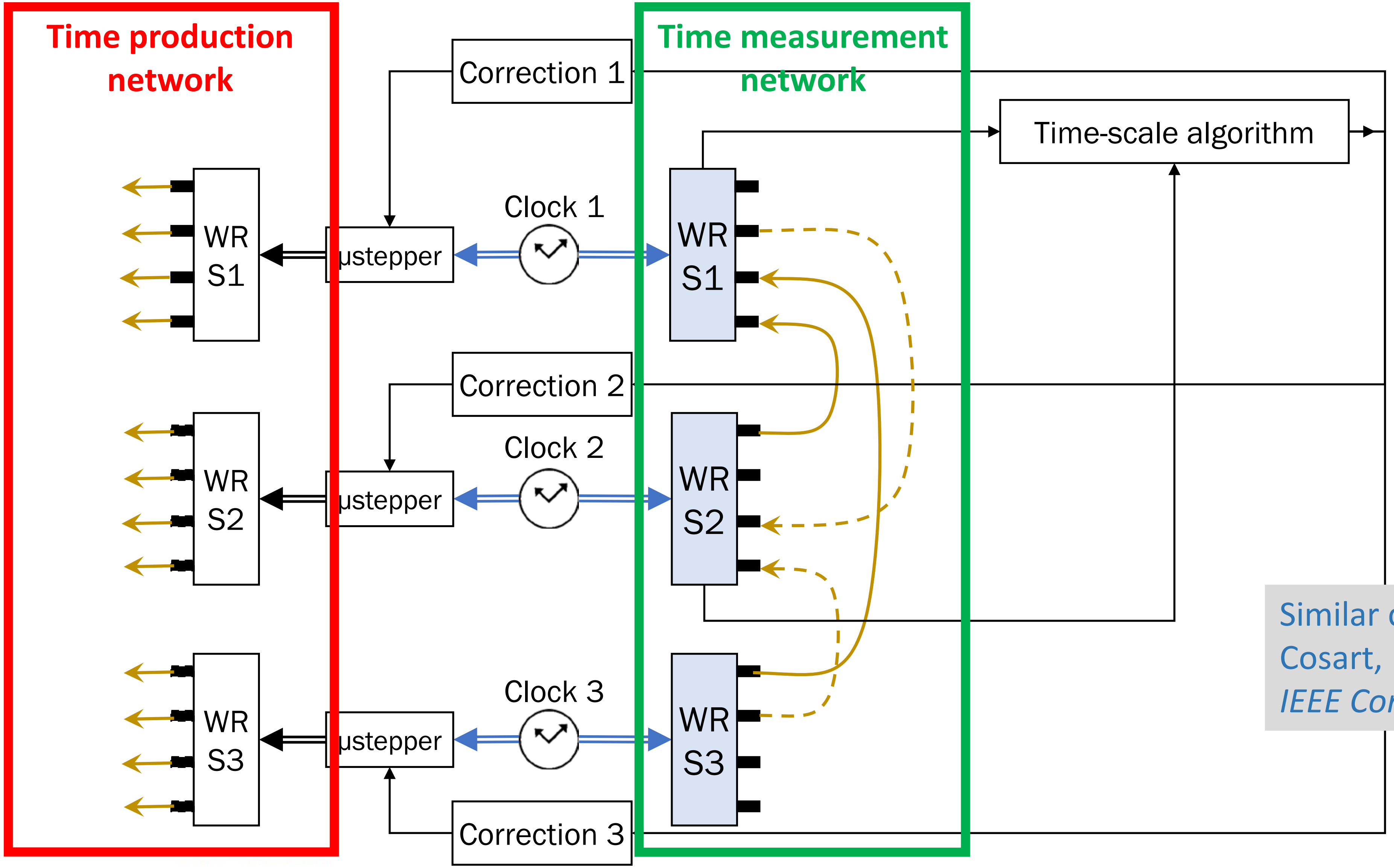
Extensions for increased redundancy



Many options for redundant measurements and systems

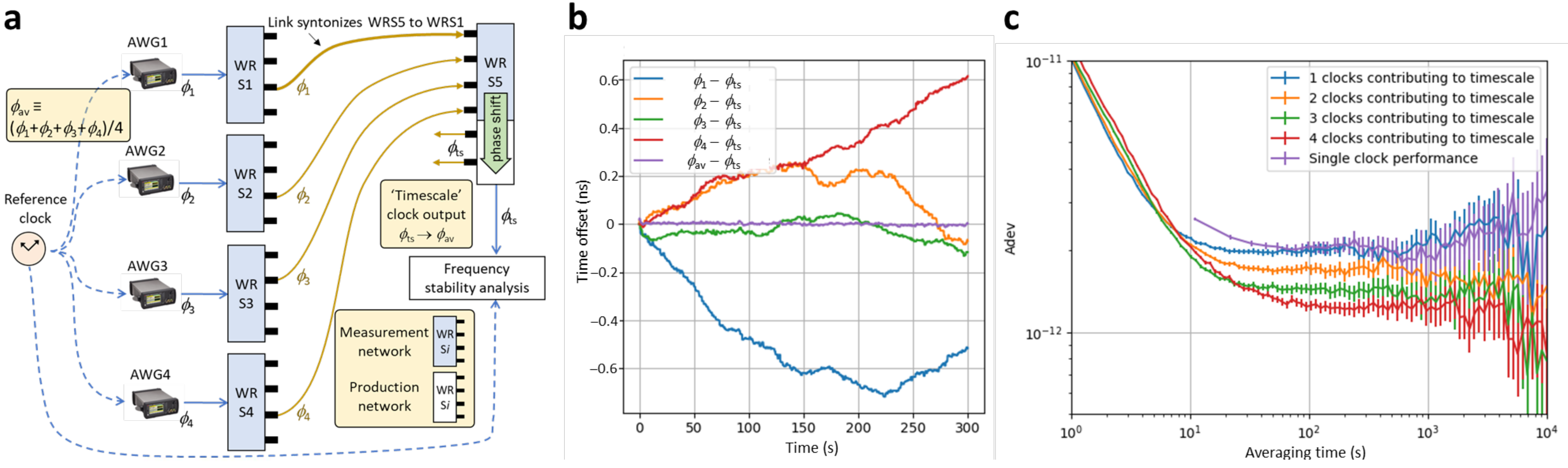
Time measurement and time production networks



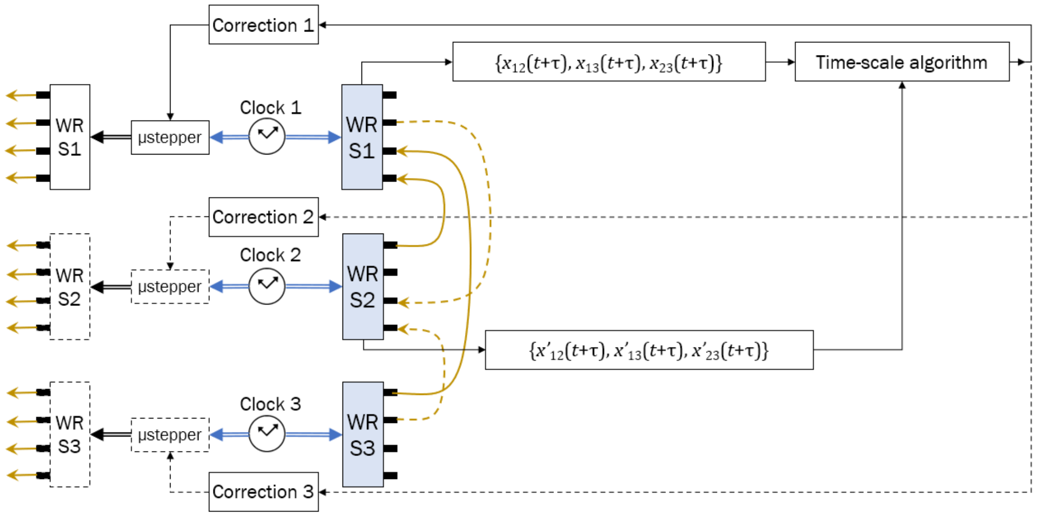
Similar concept proposed by Cosart, Imlau, Zampetti *IEEE Comms. Mag.* April 2023, p.28

Proof-of-principle clock ensemble

- Measurement network monitors four 'clocks'
- Algorithm: simple mean of clock times ⇒ improves stability of production network time



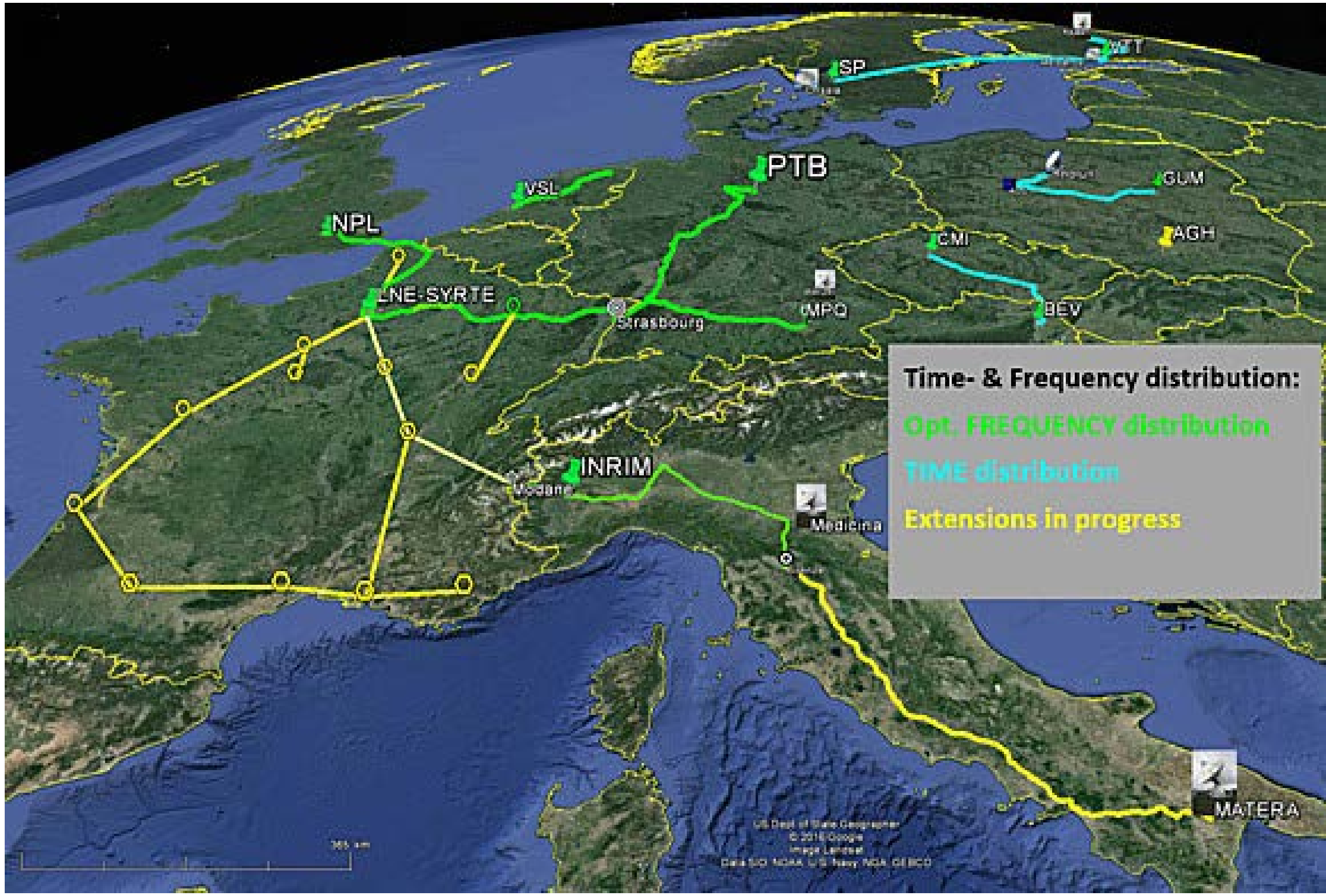
What's next?



- Under development: sophisticated algorithms
  - More stable clocks assigned larger weight
  - Anomaly detection & fail-over mechanisms
- Aim: dynamical and flexible algorithm, connect any number of clocks, performance better than any single clock at all averaging times
- Scalable and accurate source of assured subnanosecond network time
  - PNT applications beyond GNSS
  - Quantum network timing
- Future definition of UTC, GNSS ground segment timescale, …?

What about optical (quantum) clocks?

- Clocks with >18 digits of accuracy*
- Applications: timekeeping, PNT systems, chronometric levelling**
  - 1 cm height difference ⇔ 10^{-18} frequency shift
- WR not stable enough to transport/compare such clocks through fiber
- Method to compare optical clocks: ultrastable laser through optical fiber



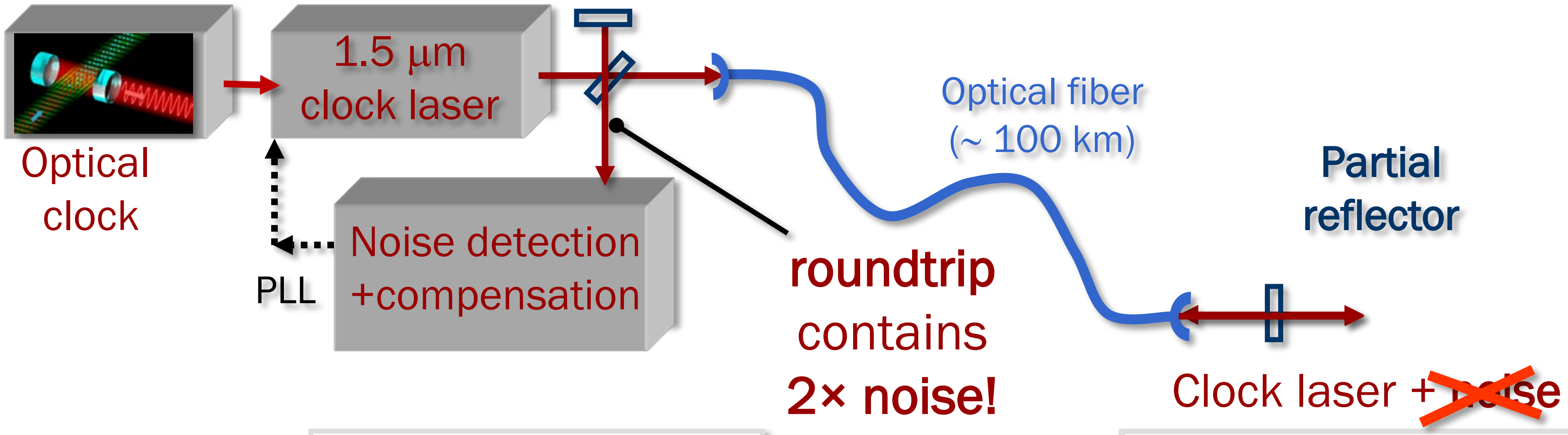
* Brewer et al., Phys. Rev. Lett. 131, 059901 (2019)
Chou et al., *Science* **329, 1630 (2010)
Takano et al., *Nat. Phot.* **10,** 662 (2016)

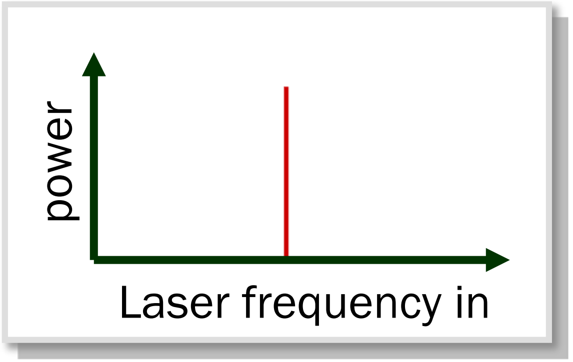
Mehlstäubler et al., *Rep. Prog. Phys.* **81,** 064401 (2018)
Grotti et al., *Nat. Phys.* **14,** 437 (2018)

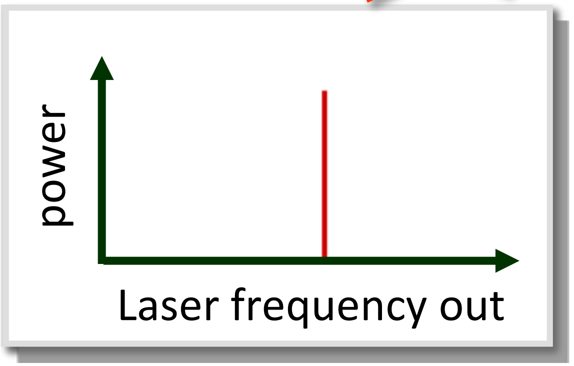
Optical path length stabilization

Compensation of frequency fluctuations due to optical path length fluctuations*:

*L.-S. Ma, P. Jungner, J. Ye, J.L. Hall, *Opt. Lett.* **19**, 1777(1994)







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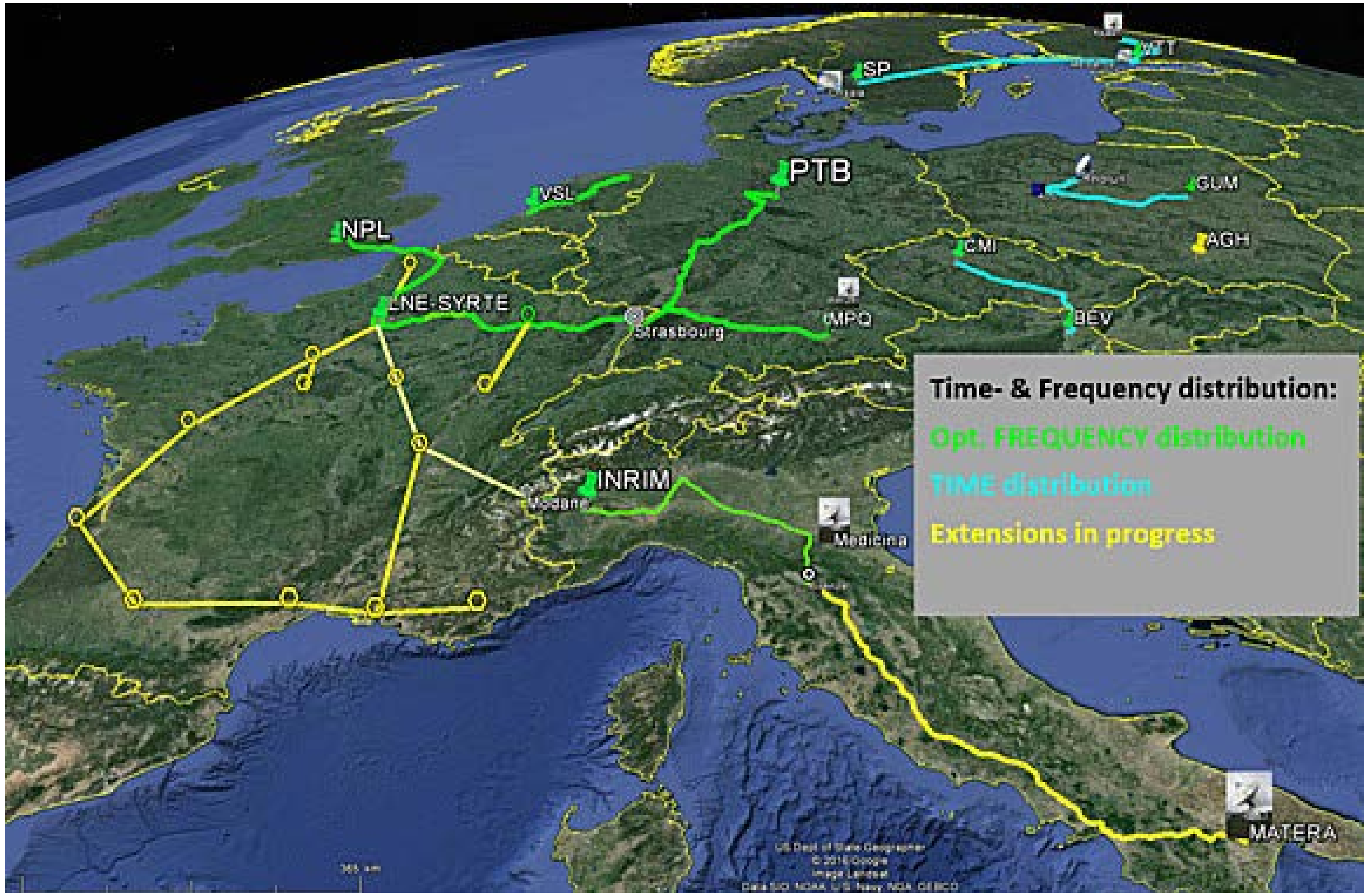
  - 1 cm height difference ⇔ 10^{-18} frequency shift
- WR not stable enough to transport/compare such clocks through fiber
- Method to compare optical clocks: ultrastable laser through optical fiber
- Methods exist***, but
  - Multiple access could be improved
  - No encryption/security measures known to authors



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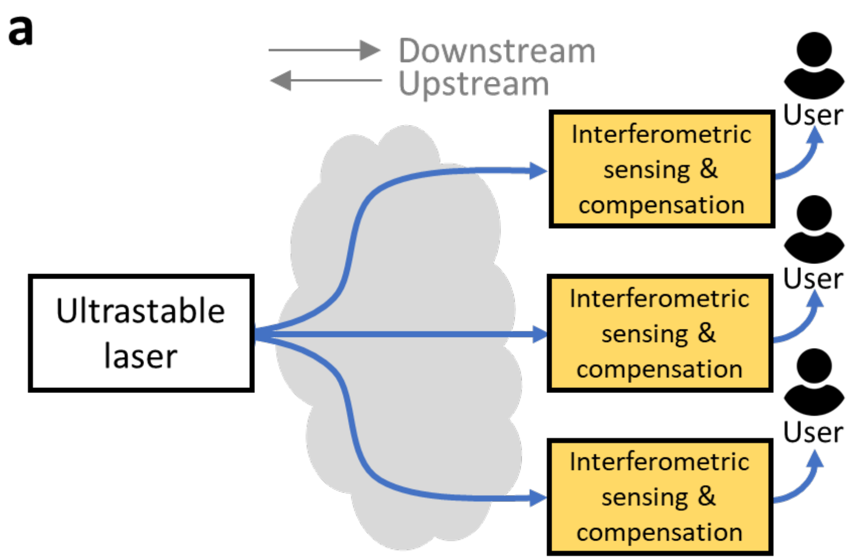
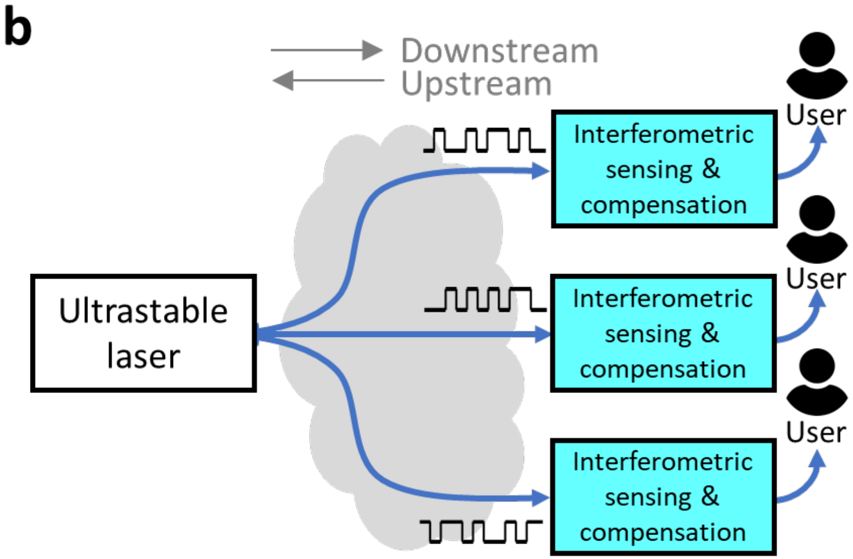
***Lopez et al., *C. R. Phys.* **16,** 531 (2016); Grosche, *Opt. Lett.* **39,** 2545 (2014).

Code-division multiple access (CDMA)

- Existing methods: anyone can use/eavesdrop the ultrastable signal
- CDMA (inspired by mobile networks):
  - Users need to have a key to demodulate the signal
  - Cross-user interference reduced (improves scalability and frequency stability)



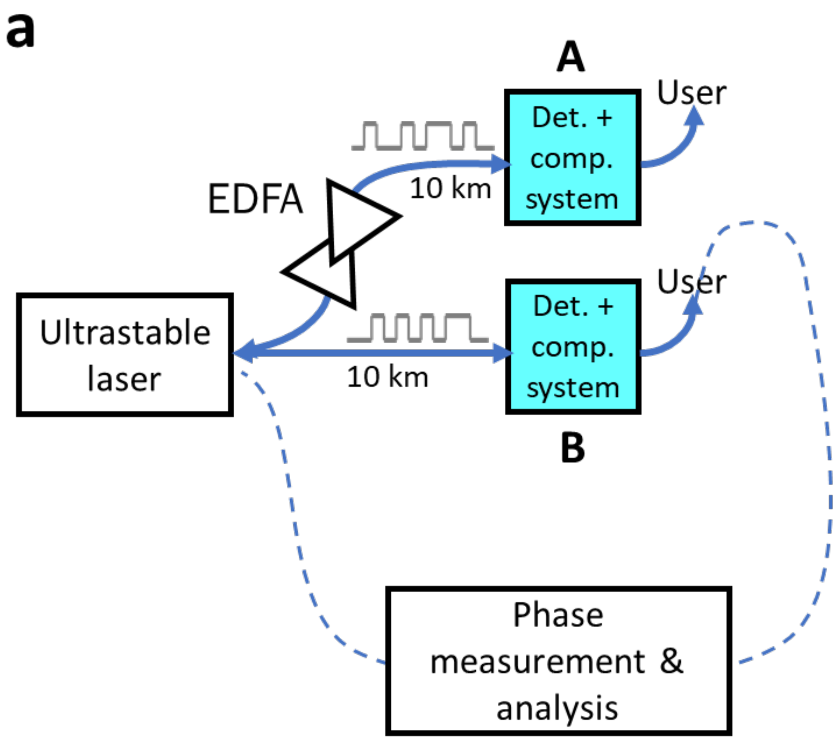
Schediwy et al., *Opt. Lett.* **38,** 2893 (2013)

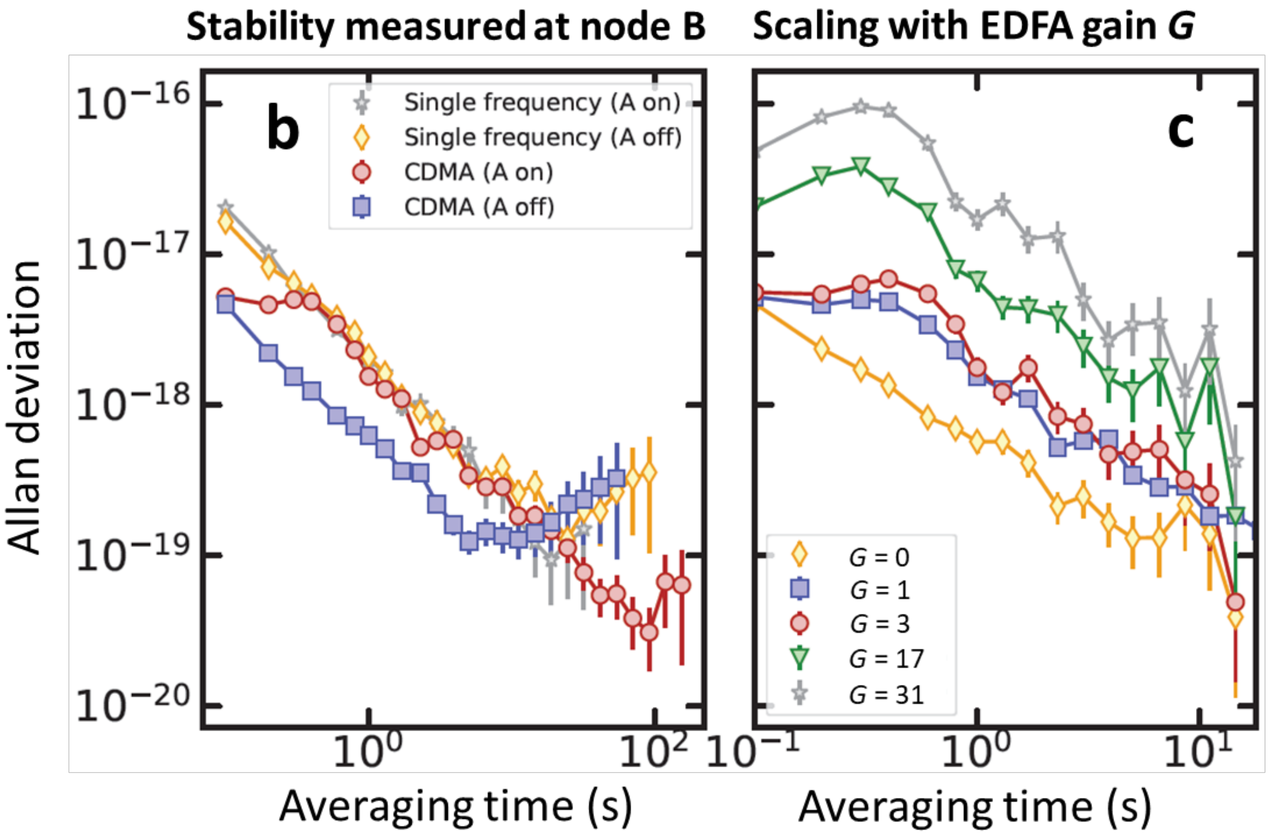


This work

Results

- Proof-of-principle experiment: CDMA works! $\Rightarrow$ encryption possible
- Limited stability degradation when scaling up to several tens of nearby users



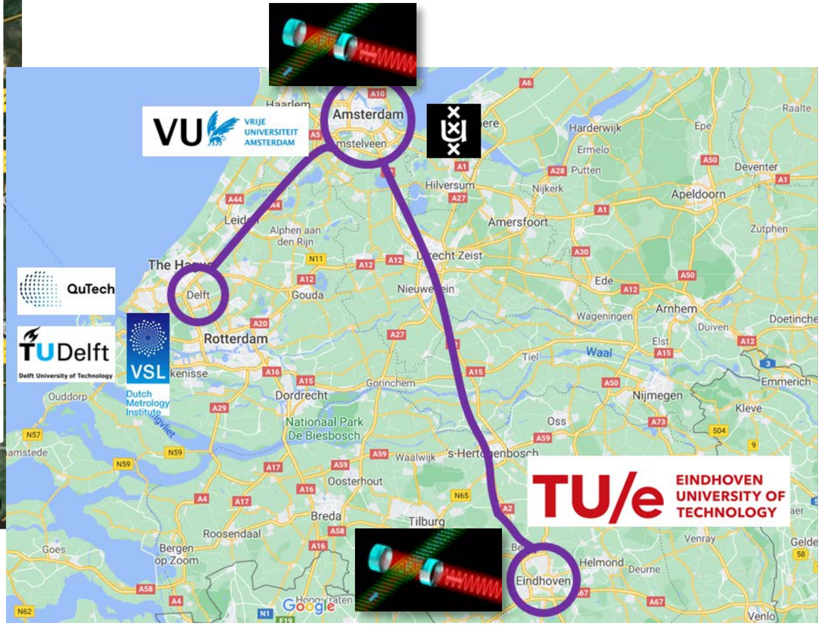


Our local fiber-optic testbed (WR + ultrastable laser)

Quantum Delta the Netherlands

SURF

Quantum.Amsterdam



Summary & outlook

- Accurate & secure time and frequency for quantum networks and PNT systems
  - New quantum-network-based PNT techniques?

- (Encrypted) ultrastable laser could also serve as reference wavelength for qubit photon conversion to universal quantum wavelength (indistinguishable photons!)

- Terrestrial networked PNT systems, e.g. on offshore wind energy farms
  $\Rightarrow$ GNSS-independent communication + positioning of maritime drones?

Thank you!

Questions: j.c.j.koelemeij@vu.nl

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Sumit Sarkar

Philippe Bouyer

Florian Schreck

TNO

Hugo Gelevert

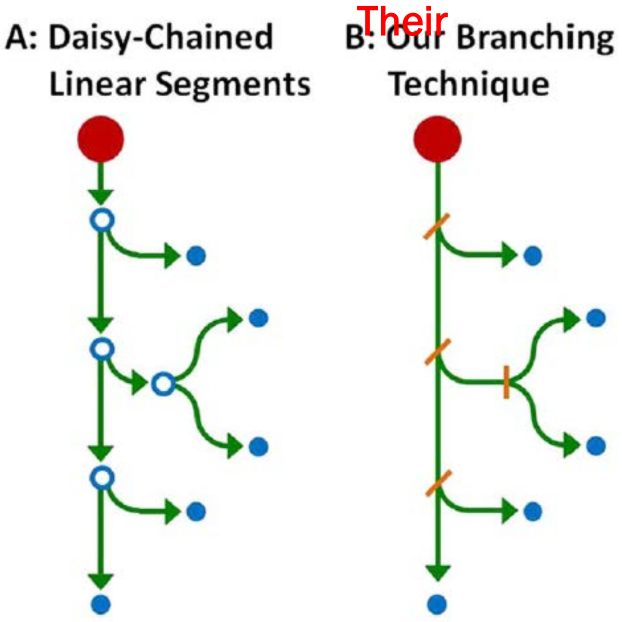
SURF

Rob Smets

Sander Klemann

Extra slides

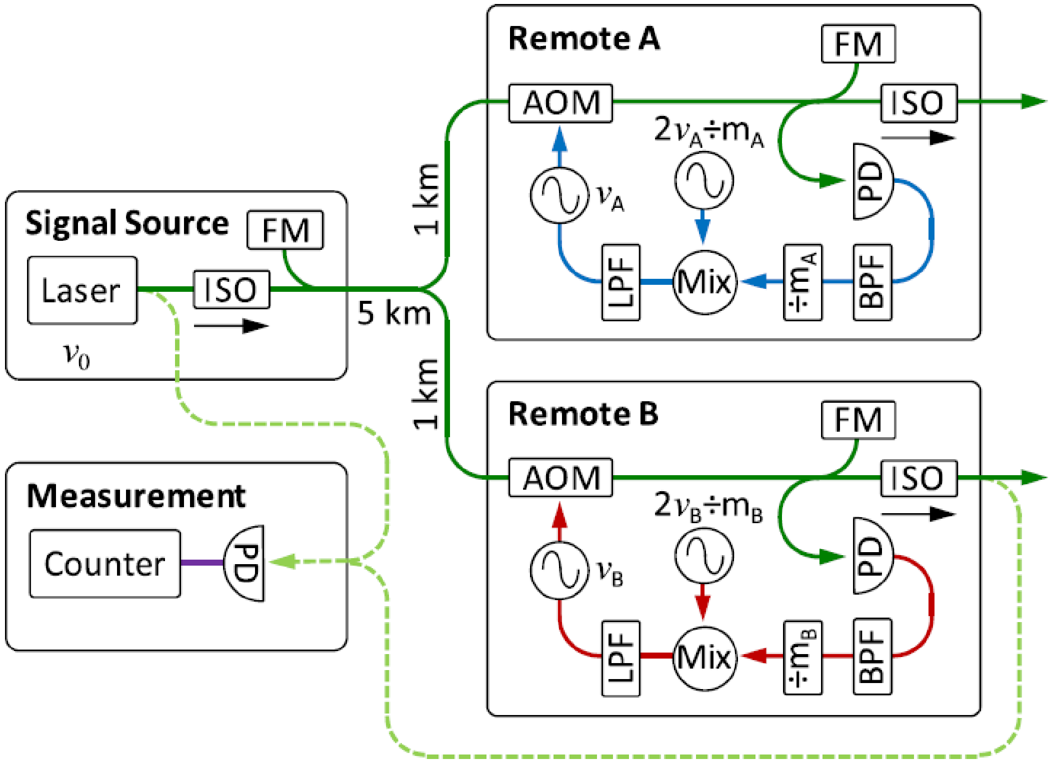
Frequency transfer via branched networks



August 1, 2013 / Vol. 38, No. 15 / OPTICS LETTERS 2893

High-precision optical-frequency dissemination on branching optical-fiber networks

Sascha W. Schediwy,[1,*] David Gozzard,[1] Kenneth G. H. Baldwin,[2] Brian J. Orr,[3] R. Bruce Warrington,[4] Guido Aben,[5] and Andre N. Luiten[1,6]



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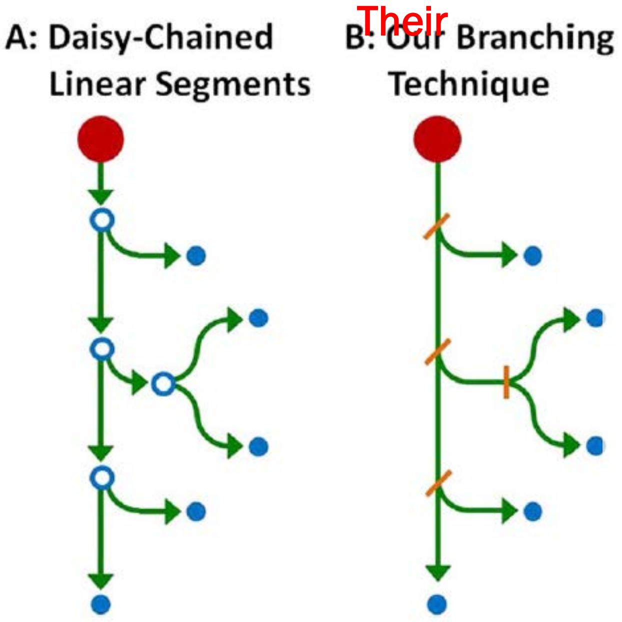

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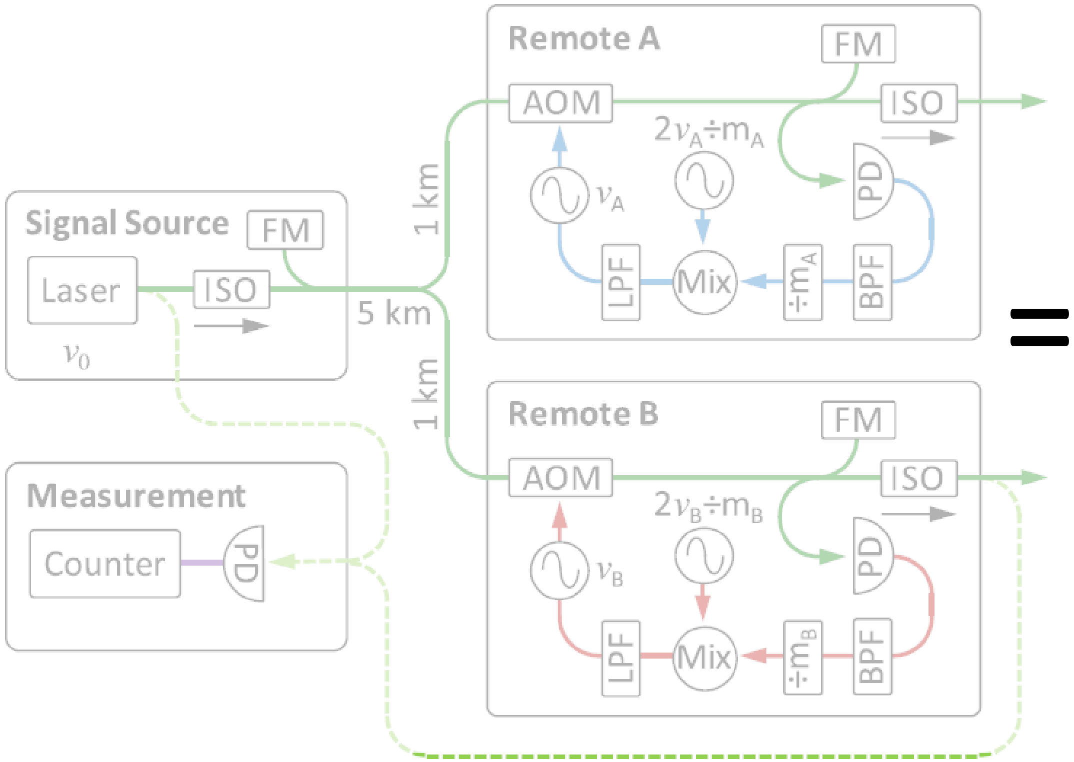

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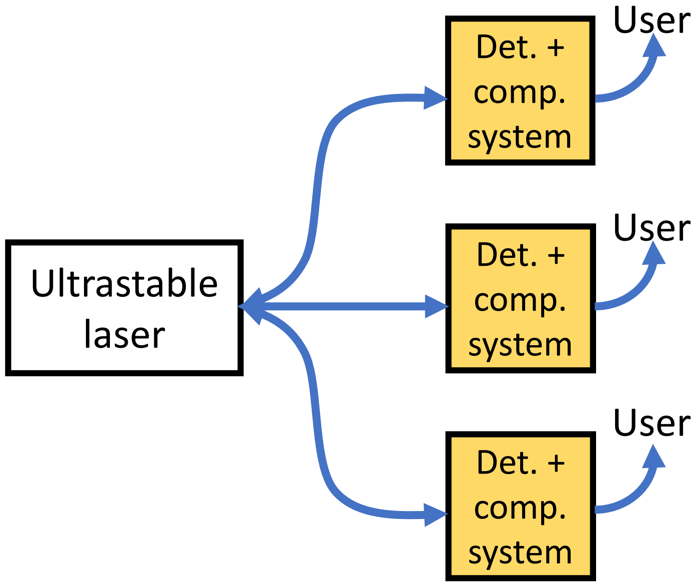
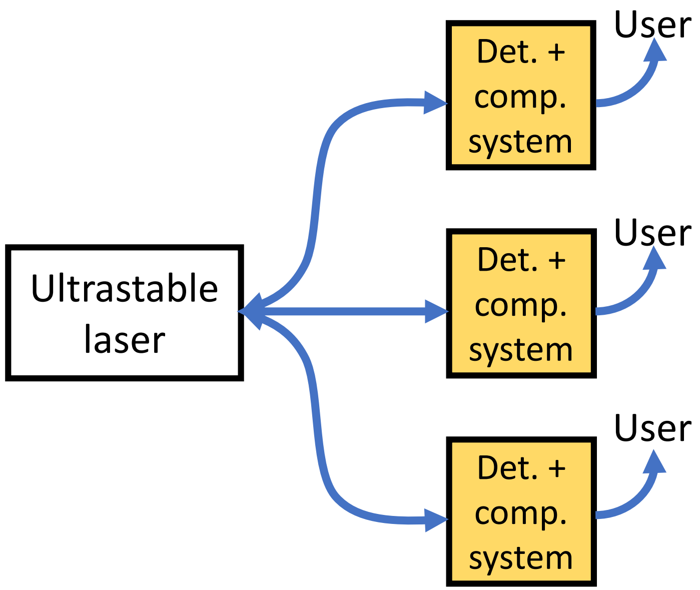


Avoiding user-to-user interference

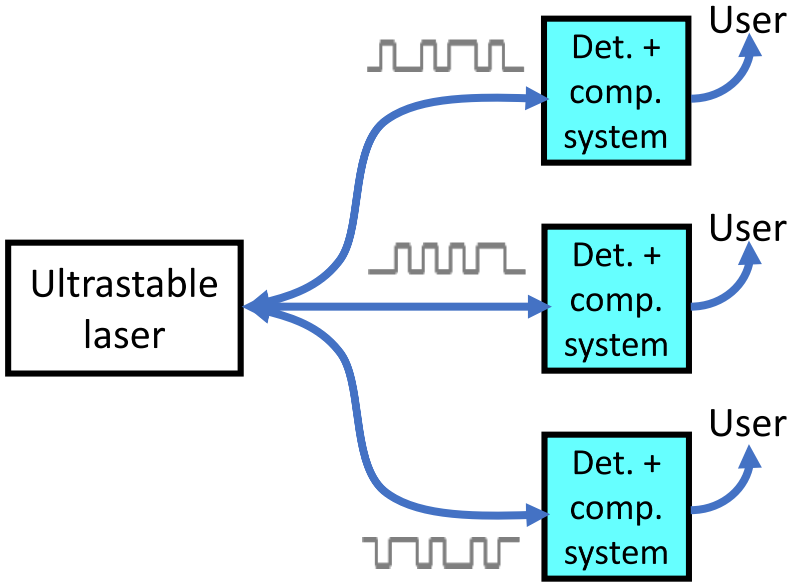


- Each user unit sends optical compensation signal towards ultrastable laser, where it is reflected back into the network (round-trip phase measurement)
  - User signal cross talk/interference
- Interference avoided by choosing different AOM frequency for each user
  - Carrier + bandwidth (~1 MHz) required for feedback
- Large networks:
  - Number of possible AOM channels limited by optical channel bandwidth
  - Each additional user requires reconsideration of the entire network

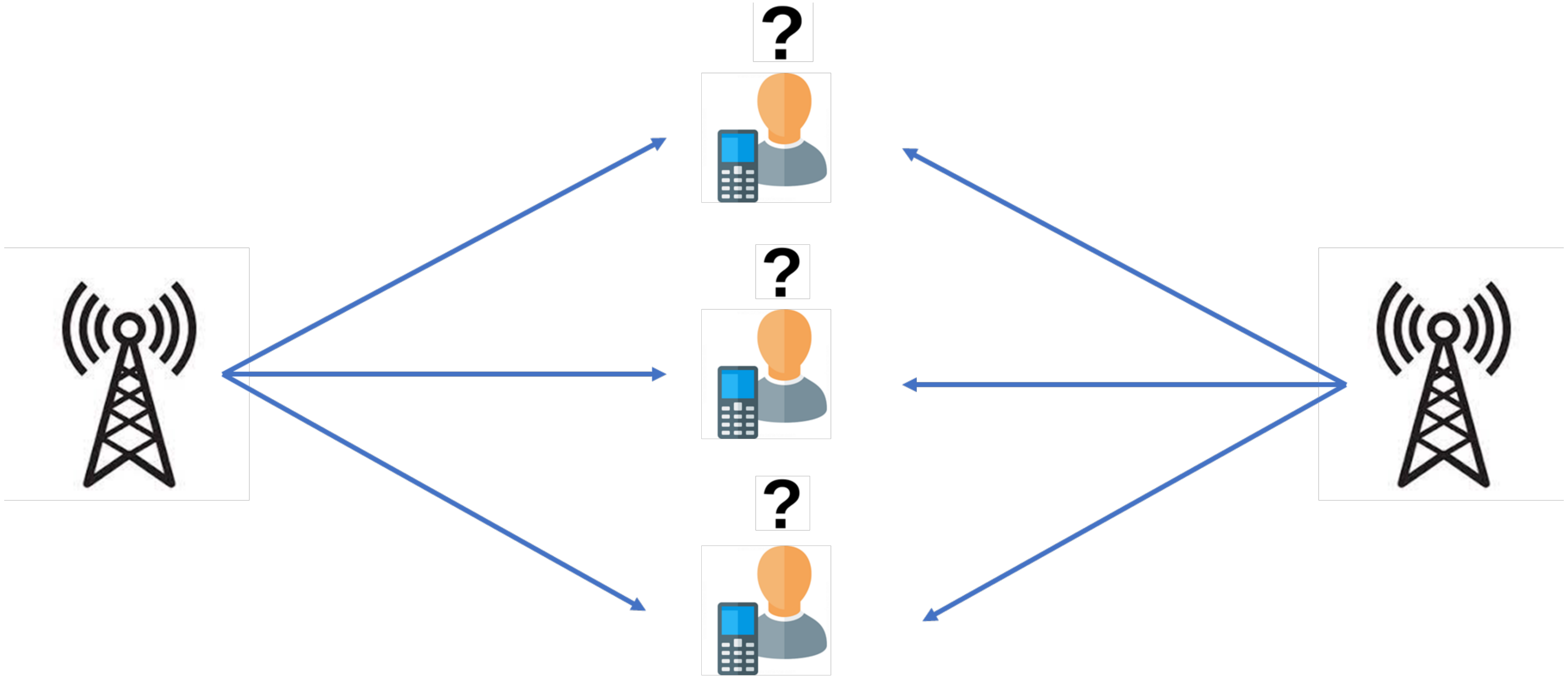
Our new approach: CDMA

- Idea: frequency hopping of AOM frequencies used for interferometric detection ('spreading')
  - Frequency hops are electronically removed from receiver round-trip signal ('despreading') ⇒ recover single rf tone for link stabilization electronics
- Code-Division Multiple Access: orthogonal pseudo-random frequency-hopping sequences (Gold codes)
  - Used e.g. in cellular networks, GPS, …

Rodrigo González Escudero (postdoc)

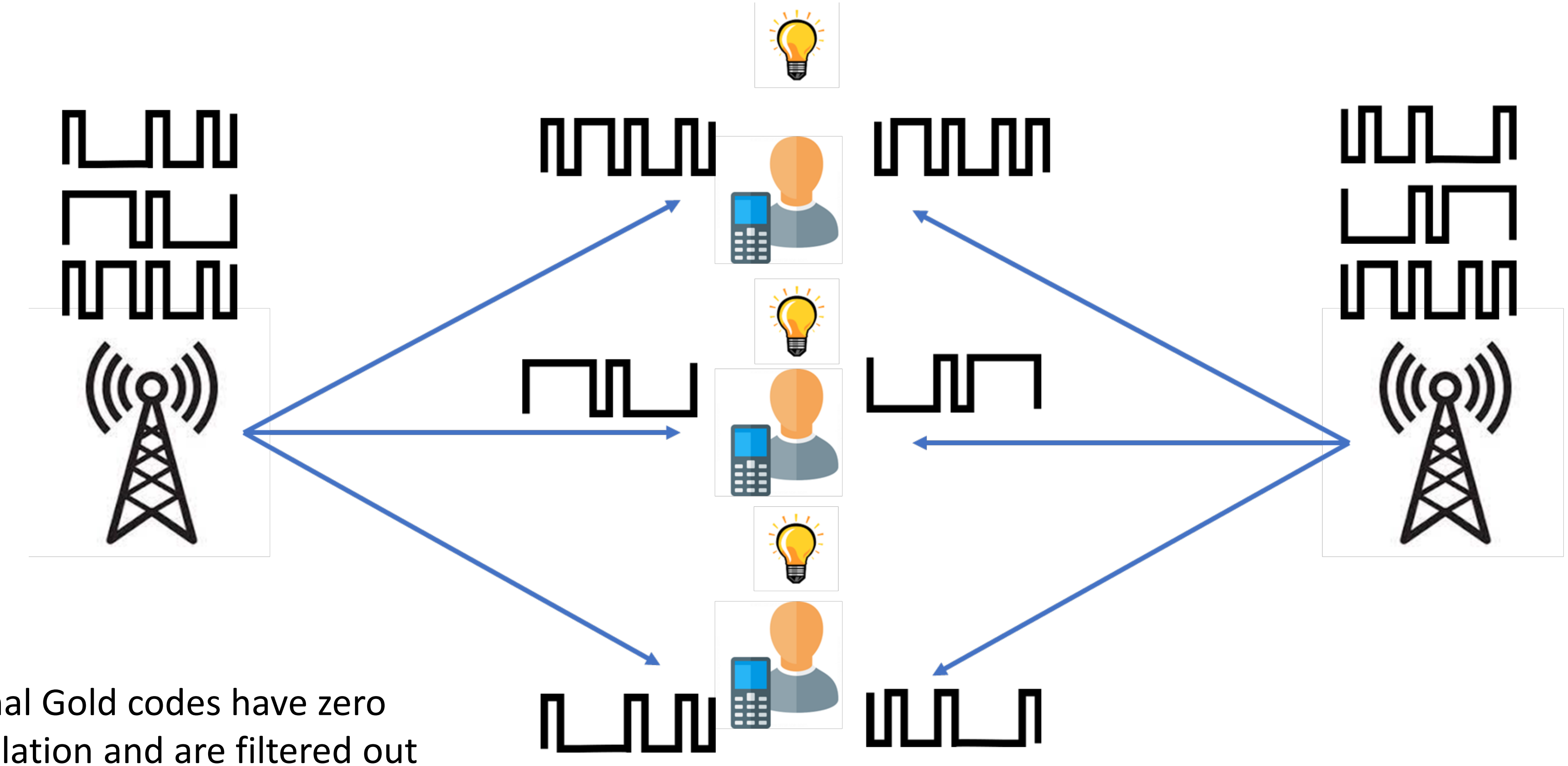


CDMA in cellular networks



“Communication networks,” in Introduction to Digital Communications, (Elsevier, 2016)

CDMA in cellular networks



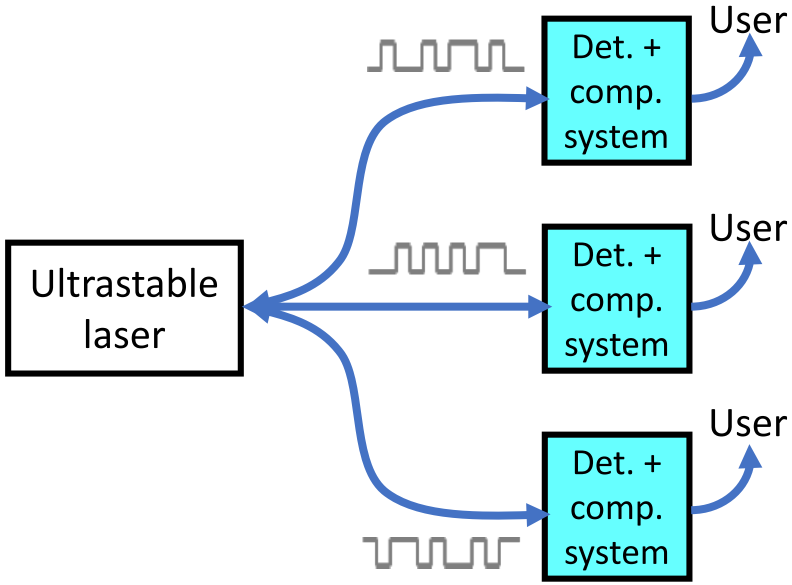
Orthogonal Gold codes have zero cross correlation and are filtered out (matched filter)

“Communication networks,” in Introduction to Digital Communications, (Elsevier, 2016)

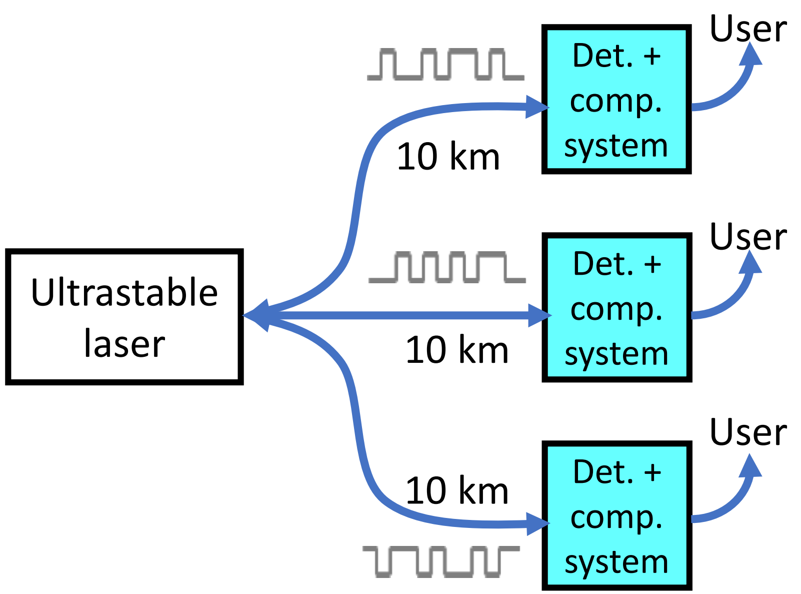
Our new approach: CDMA

- Idea: frequency hopping of AOM frequencies used for interferometric detection (‘spreading’)
  - Frequency hops are electronically removed from receiver round-trip signal (‘despreading’) ⇒ recover single rf tone for link stabilization electronics
- Code-Division Multiple Access: orthogonal pseudo-random frequency-hopping sequences (Gold codes)
  - Used e.g. in cellular networks, GPS, …
- Each user AOM operates at same nominal frequency (simplifies design), but different Gold code
  - Each receiver immune to cross talk due to round-trip compensation signals from other users
  - Each user: same hardware, unique Gold code can be assigned (in software) remotely: simplification of network operations

Rodrigo González Escudero (postdoc)



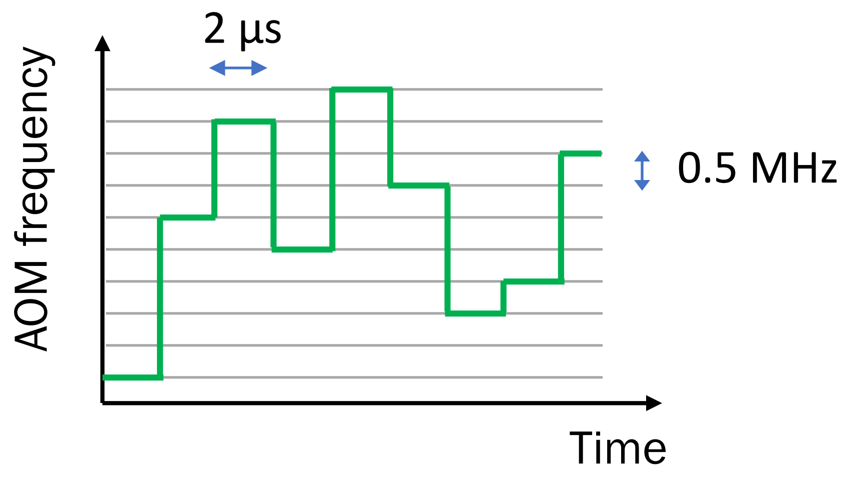
Does it work?



- Does the CDMA frequency hopping add noise?
- What is the impact of residual cross talk?
- How scalable is it really?

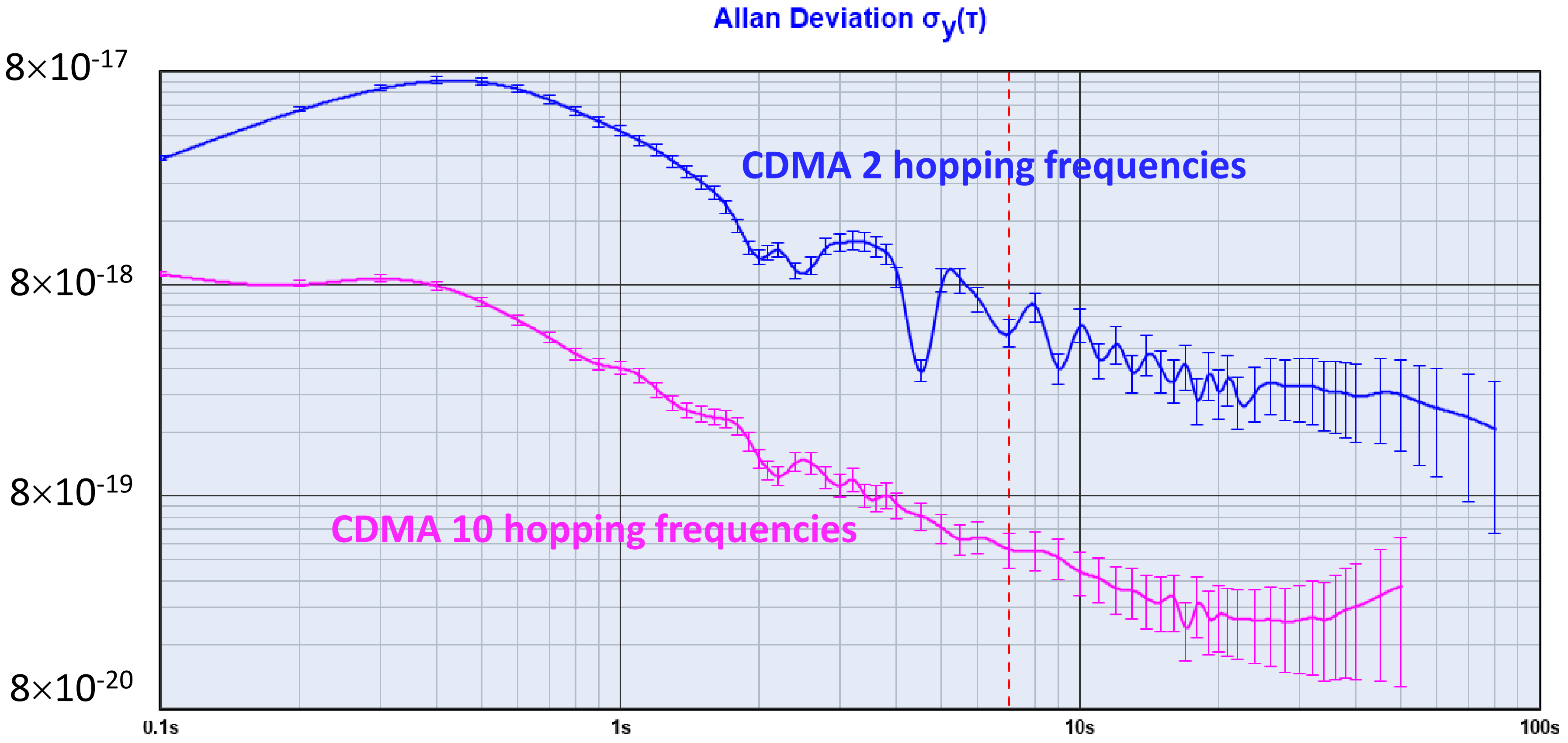
Preliminary results achieved for:

- 10 km spooled fiber links
- Frequency hopping:
  - 2 μs symbol duration
  - 10 frequency hopping levels
  - 0.5 MHz level spacing
  - Gold sequences length 50



Avenues for improvement

- Increase number of levels beyond 10
- Larger Gold codes (current code duration 5 symbols)



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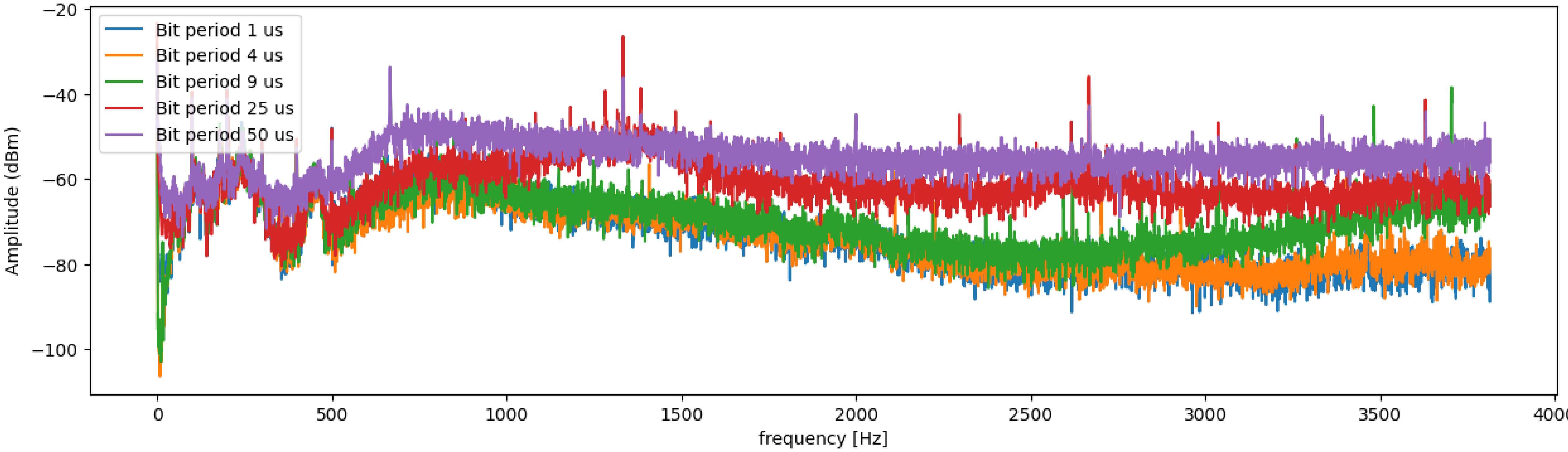
Avenues for improvement

Phase noise electrical beat-note signal after despreading

- Shorter symbols: reduced phase noise (previous data shown for 2 µs)



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White Rabbit research in the Netherlands

Many groups active in WR worldwide (*e.g.* Paris region: P.-E. Pottie *et al.*)

WR research in the Netherlands:

- Nikhef Amsterdam (WR hardware, KM3NeT neutrino telescope)
- VSL Delft [UTC(VSL)]
- SURF (NREN)
- JIVE Dwingeloo (VLBI radio astronomy)
- ASTRON (LOFAR radio telescope)
- **VU Amsterdam**
  $\Rightarrow$ OPNT bv (spin-off company, founded 2014) opnt. TIME PROVISIONING

- Also used in quantum key distribution/quantum communication networks
- Also used in radio astronomy (LOFAR, Very Long Baseline Interferometry, …)

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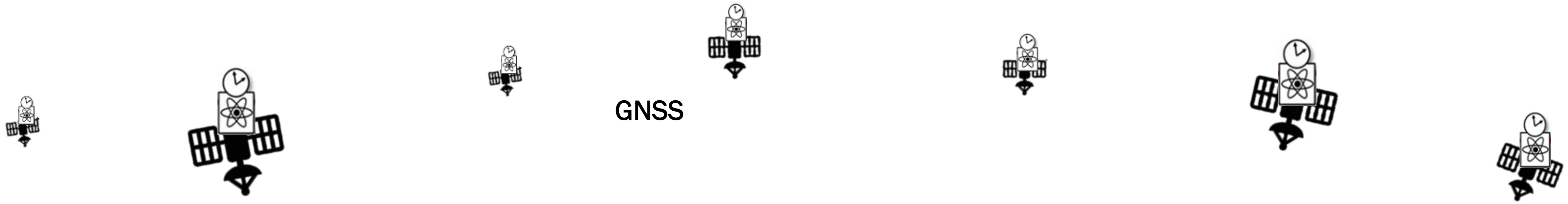
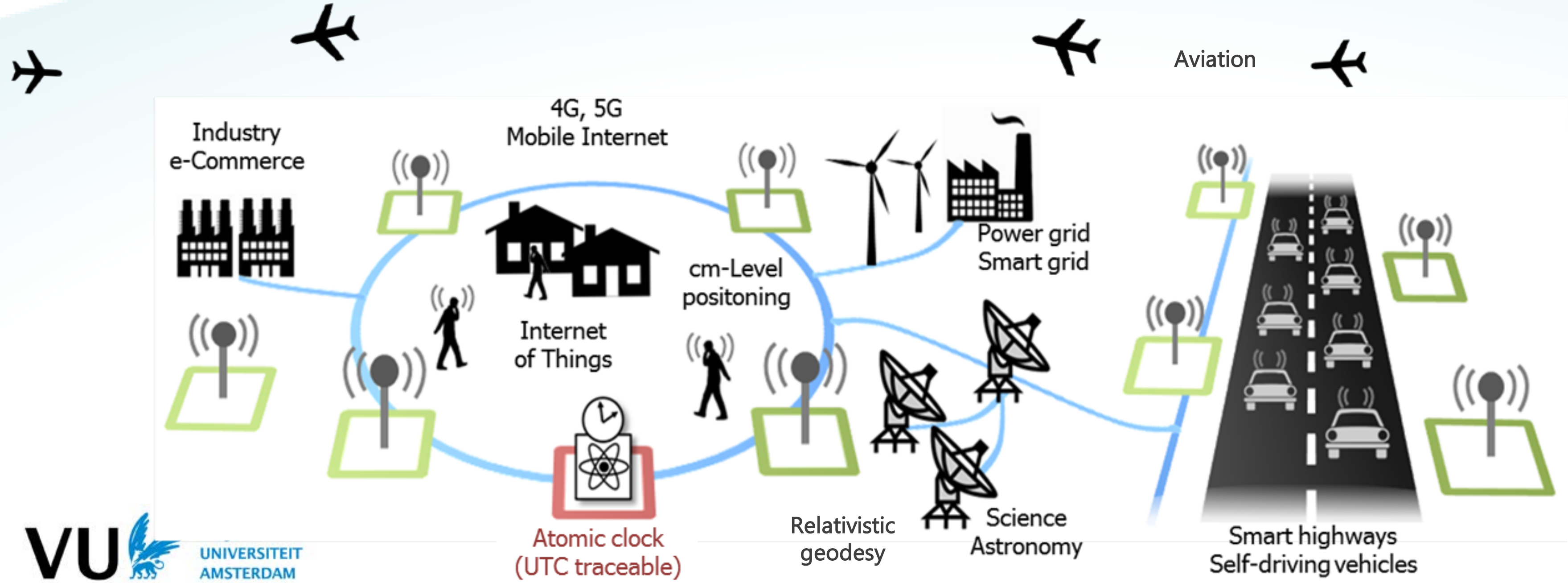
WR for positioning and navigation

'SuperGPS' project: a terrestrial networked positioning system





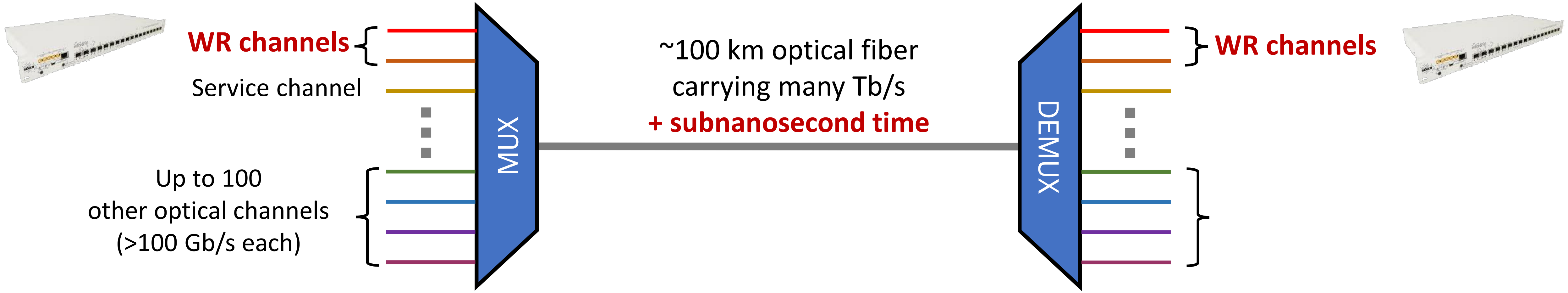
Christian Tiberius (TUD)

Gerard Janssen (TUD)

Network of the future:

+ Connectivity
+ Navigation
+ Time/frequency

Use existing fiber-optic telecom networks: WDM



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

- Optical **wavelength division multiplexing** (WDM)
- WDM: transmit data + WR signals without loss of capacity and timing uncertainty
- Is currently being rolled out (e.g. SURFnet8: data + WR timing over live network)*
- Time & frequency signals don’t require much spectrum
  - Less than 1% of total spectrum
  - Fiber-optic systems always have more than 1% of spectrum available

Positioning using smartphones…

GPS: positioning

Mobile network: map information, connection with cloud

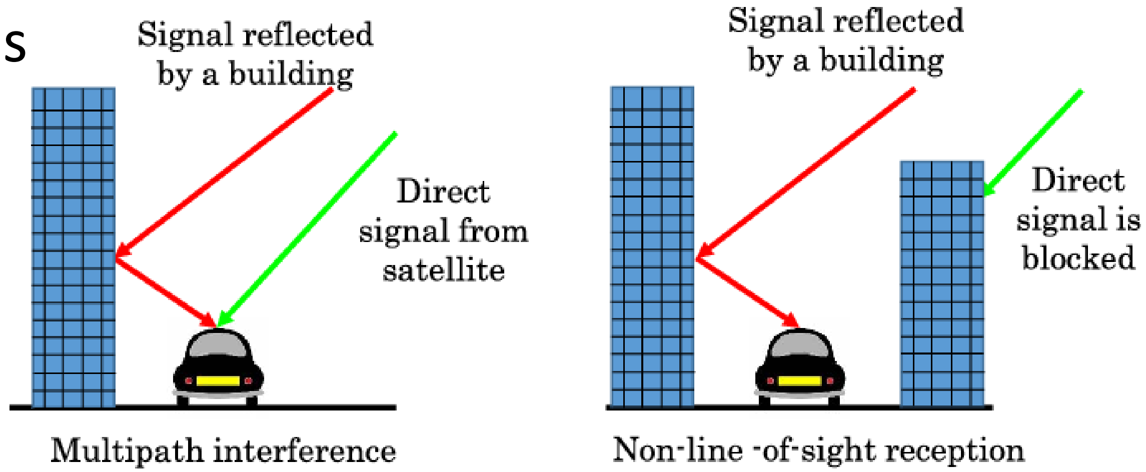
Positioning using smartphones…

GPS: positioning

Mobile network: map information, connection with cloud

Bottleneck 1 of GPS (or generally GNSS)

- GNSS in open field: uncertainty at the level of a few meter
  - Enhancements for cm precision exist, requiring additional reference receivers
- **Multipath**: reflected signals (buildings, objects) interfere with line-of-sight (LoS) signal
- Multipath errors: many meters in urban areas
- Prevents indoor use of GNSS



- Too bad for self-driving vehicles, drones, indoor positioning, …

Bottleneck 2 of GNSS

Bloomberg Businessweek

July 25, 2018, 11:00 AM GMT+2

The World Economy Runs on GPS. It Needs a Backup Plan

The small satellite network, which keeps global computer systems from freaking out, is shockingly vulnerable to all kinds of interference.

SuperGPS: designed to provide an independent positioning and timing system with reduced sensitivity to multipath

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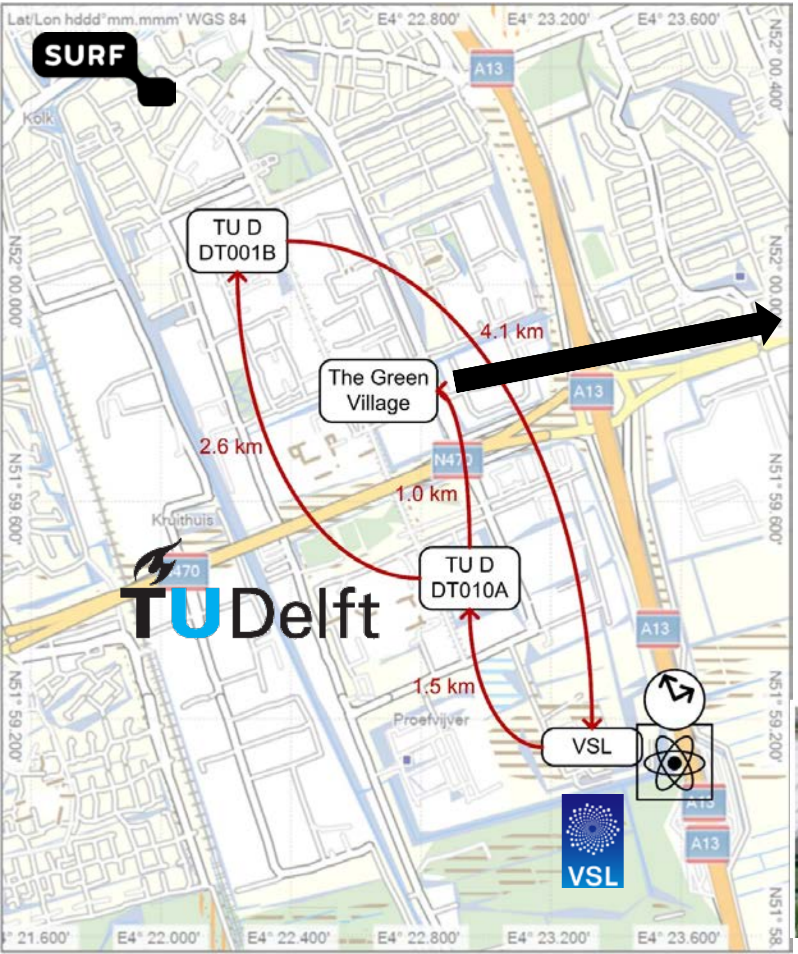
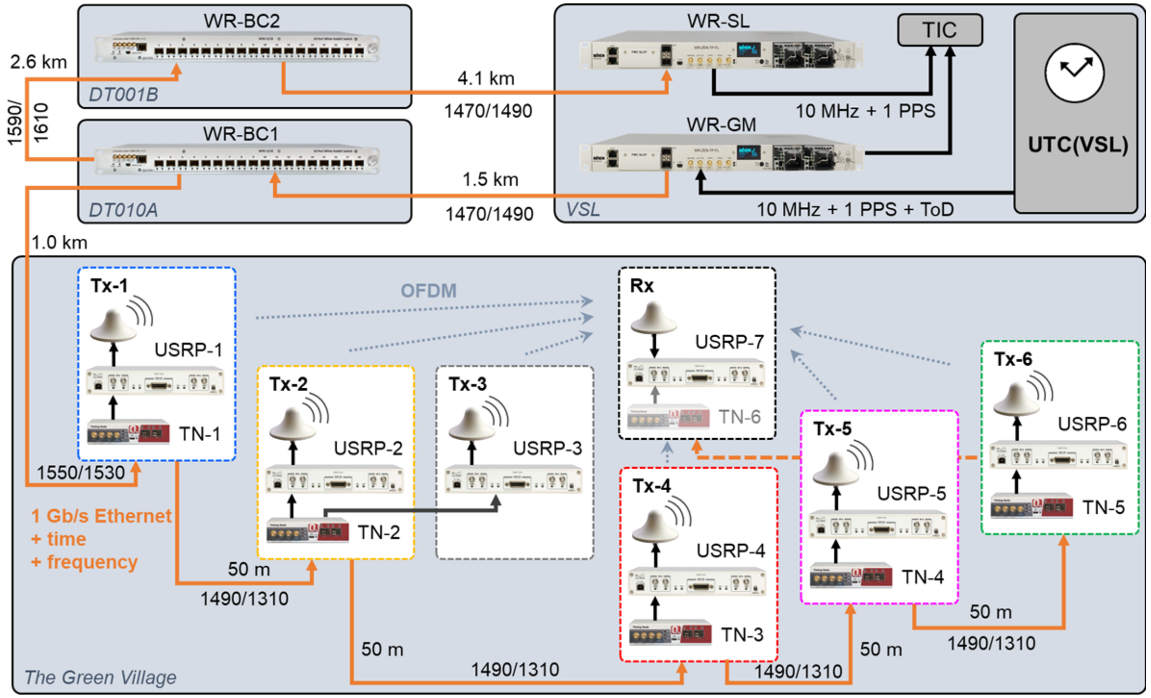
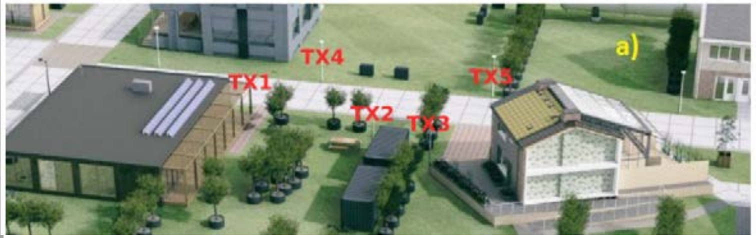
First SuperGPS trial at “The Green Village”
(TU Delft, Sep 2020)

- WR fiber-optic time distribution with 0.2 ns uncertainty (0.2 ns ⇔ 6 cm at speed of light)







Dealing with multipath

- Capability to resolve LoS from multipath signals depends on radio bandwidth
  - Think of pulses: large BW, short pulse, better time resolution
- But radio spectrum is extremely scarce

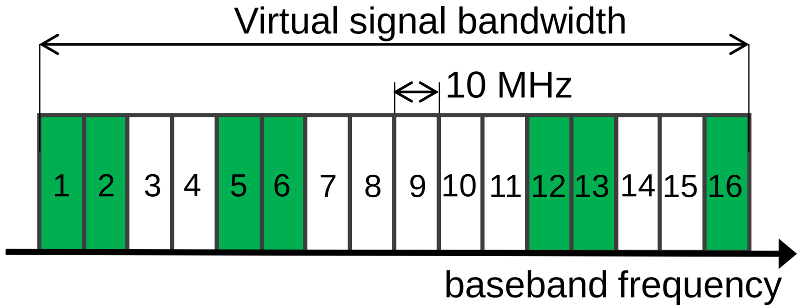
NOS NIEUWS • 14-12-2012, 18:28

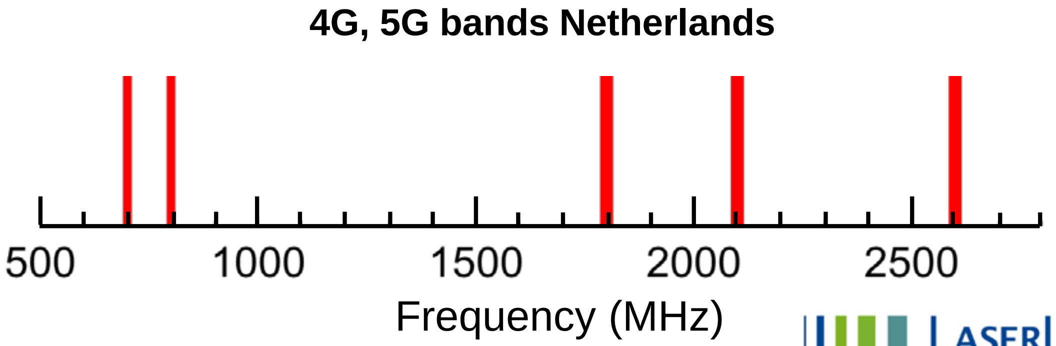
Veiling 4G-frequenties levert 3,8 miljard op

Het kabinet heeft 3,8 miljard euro opgehaald met de veiling van frequenties voor de volgende generatie van het mobiele internet. Het kabinet rekende in ieder geval op 470 miljoen. Naast de drie telefoonbedrijven die nu al mobiel internet aanbieden komt er een nieuwe concurrent bij: Tele2.

Achieving large BW in scarce spectrum

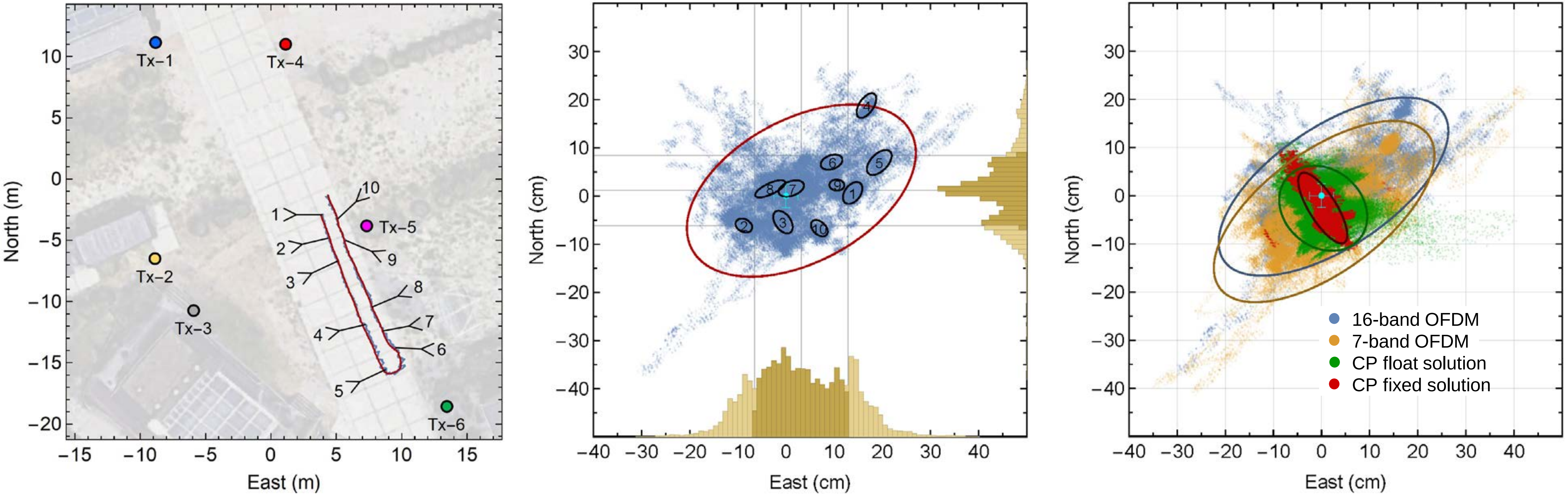
- Trial at TUD: license from Agentschap Telecom, 200 MHz around 3.96 GHz
- Use sparse bands (70 MHz out of 160 MHz)
  - Dun, H., Tiberius, C. C. J. M., Diouf, C. & Janssen, G. J. M. Design of sparse multiband signal for precise positioning with joint low-complexity time delay and carrier phase estimation. *IEEE Trans. Veh. Technol.* **70,** 3552-3567(2021).
- Virtual BW of 160 MHz
- PNT signals claim only a marginal part of the capacity (few %, could be less)
- License spectra of mobile network operators look similar (but dispersed over larger range)!
- Use same radio modulation format as 4G, 5G





Positioning results

Koelemeij et al. *Nature* **611,** 473 (2022)



~10 cm uncertainty – much better than GPS under comparable conditions!

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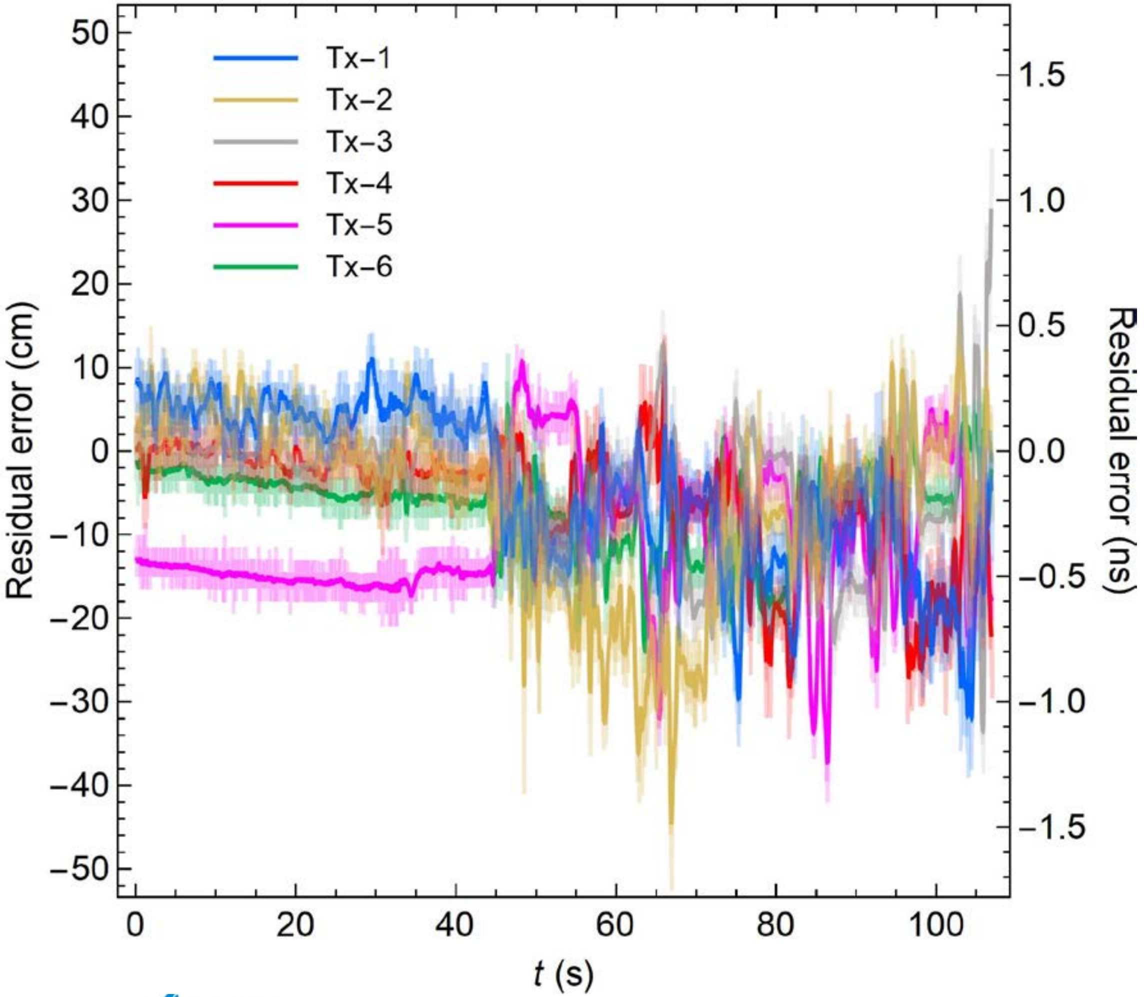
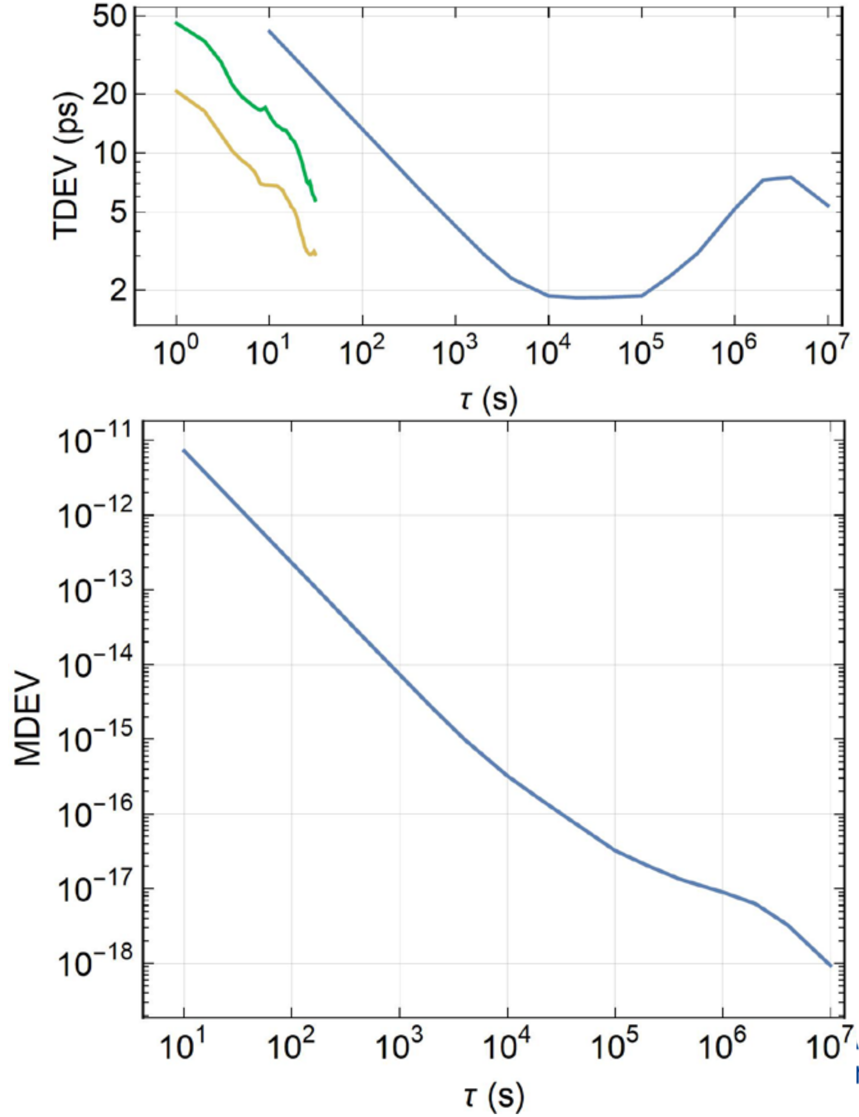
Subnanosecond wireless time transfer

Koelemeij et al. *Nature* **611,** 473 (2022)

Rx residual time/range errors



Roundtrip VSL – TUD – VSL (8.2 km)



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