Applications enabled by precise time & frequency services and their integration into existing networks

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VU VRIJE UNIVERSITEIT AMSTERDAM

GÉANT Time and Frequency Workshop

CERN

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Research carried out in collaboration with/with support from:

Quantum Delta the Netherlands
EURAMET
OPNT. TIME PROVISIONING
SURF
NWO
HORIZON 2020
TU Delft
VSL
CERN
kpn
Marc Weiss Consulting
FUGRO
UNIVERSITY OF AMSTERDAM

White Rabbit research in the Netherlands

Many groups active in WR worldwide

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 B.V. (spin-off company, 2014)

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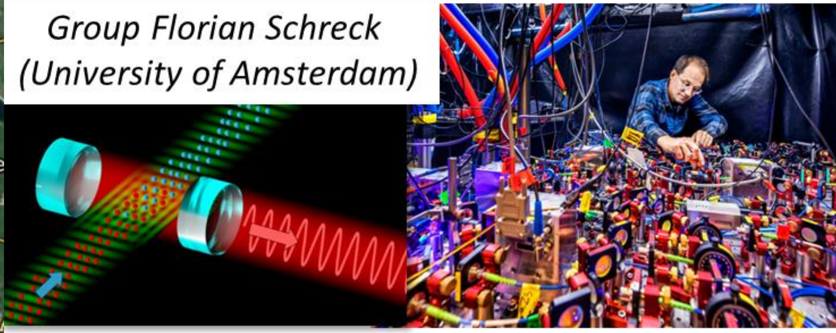
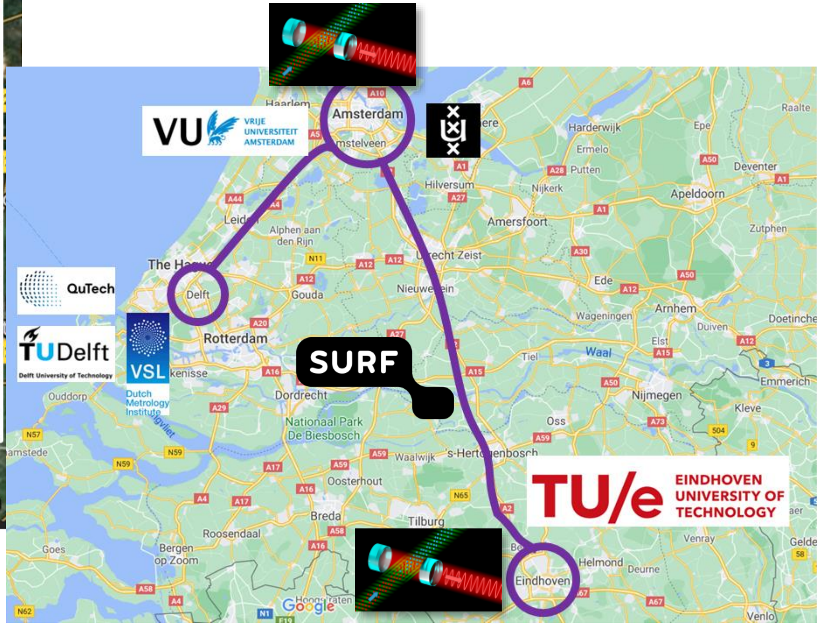
Local fiber-optic testbed (WR + ultrastable laser)

SURF

Quantum Delta the Netherlands

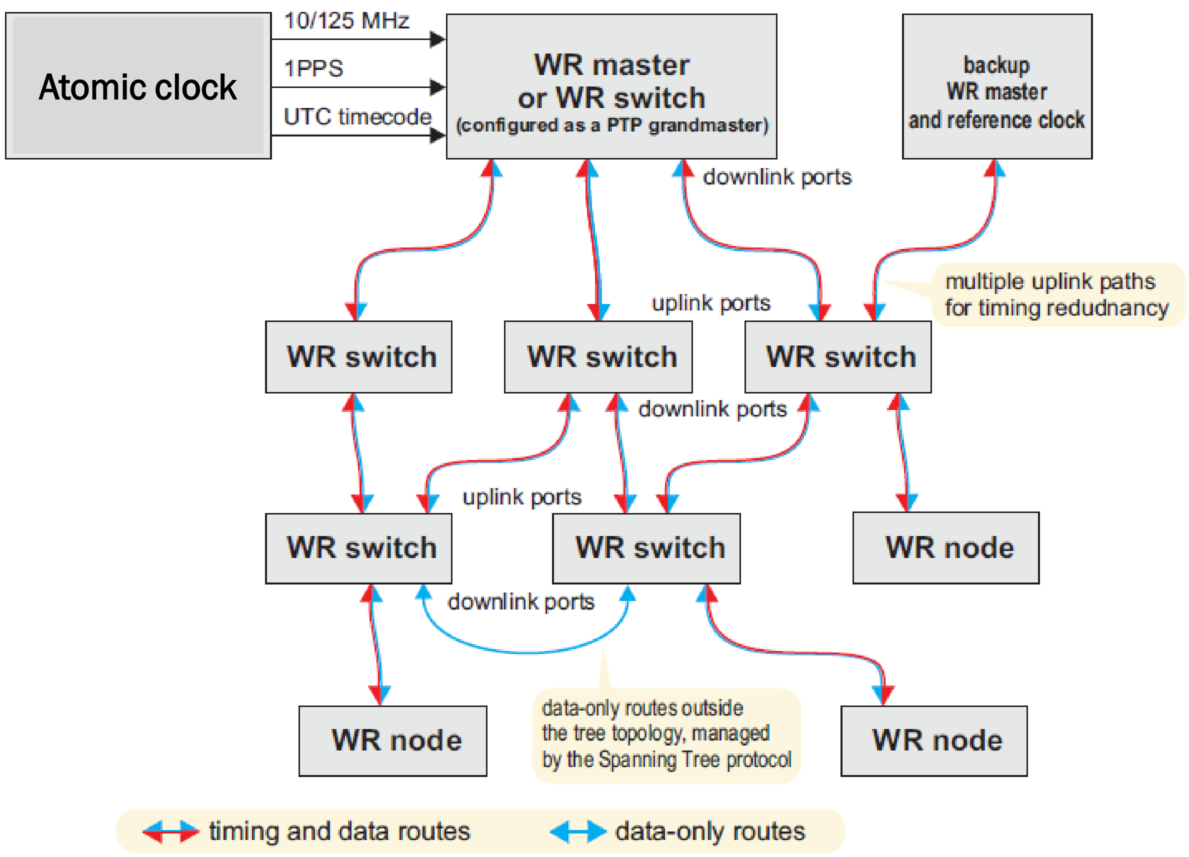
Group Florian Schreck (University of Amsterdam)





WR: subnanosecond network timing

'Timing' = node clocks display same time of day

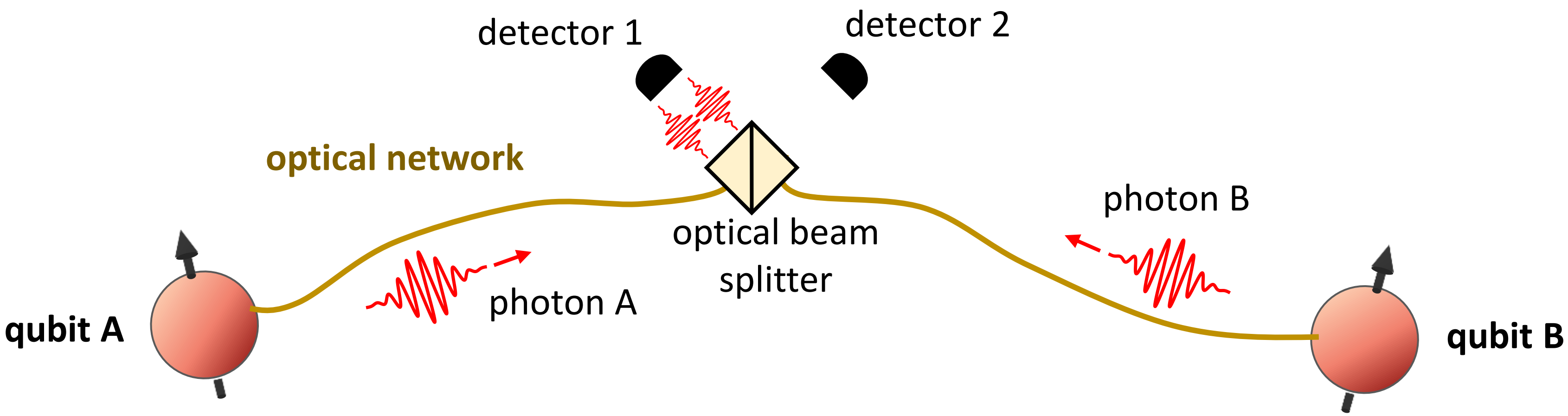


Graph: WR project website

- White Rabbit (see also talk Javier Serrano, CERN)
  - Other technologies exist (e.g. ELSTAB, Poland) with even better performance
- WR residual timing errors can be as small as 0.1 ns
- 0.1 ns timing happens to be the requirement for **two potentially ground-breaking new network technologies…**

1. Quantum Internet

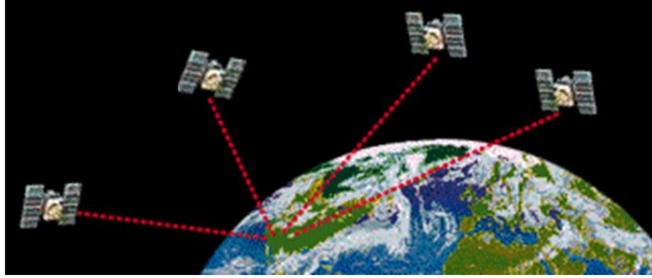
- Quantum networks:
  - Now: Quantum Key Distribution (QKD) – secure exchange of quantum information (**photons**)
  - Future: networks of entangled **qubits and photons** for distributed quantum information processing



- 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)

2. PNT systems beyond GNSS



GNSS: global navigation satellite systems

PNT: positioning, navigation and timing

- Electromagnetic wave at speed of light in vacuum: 1 ns ⇔ 0.3 m
  - c = 299 792 458 m/s
- Uncertainty GNSS receiver: 5-50 ns, or 1.5-15 m (or even worse)

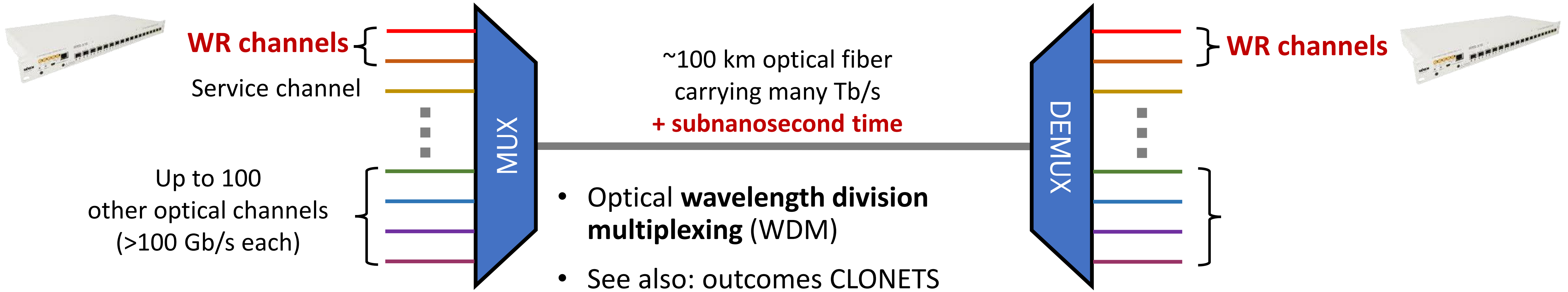
- Lane-level positioning of cars (decimeter-centimeter level) requires ~ 0.1 ns…
- Quantum Internet requires ~ 0.1 ns…

WR can help achieve this – but how?

Must use existing fiber-optic infrastructure, in parallel with telecom data

- **WR pro**: telecom equipment, facilitates acceptance by network operators
- **WR con**: bidirectional optical path needed, barrier to acceptance
  - Can be solved by **WDM** VSL, SURF, VU, VTT, CSC; Dierikx et al., *IEEE TUFFC* **63,** 945 (2016)

Optical wavelength division multiplexing (WDM)



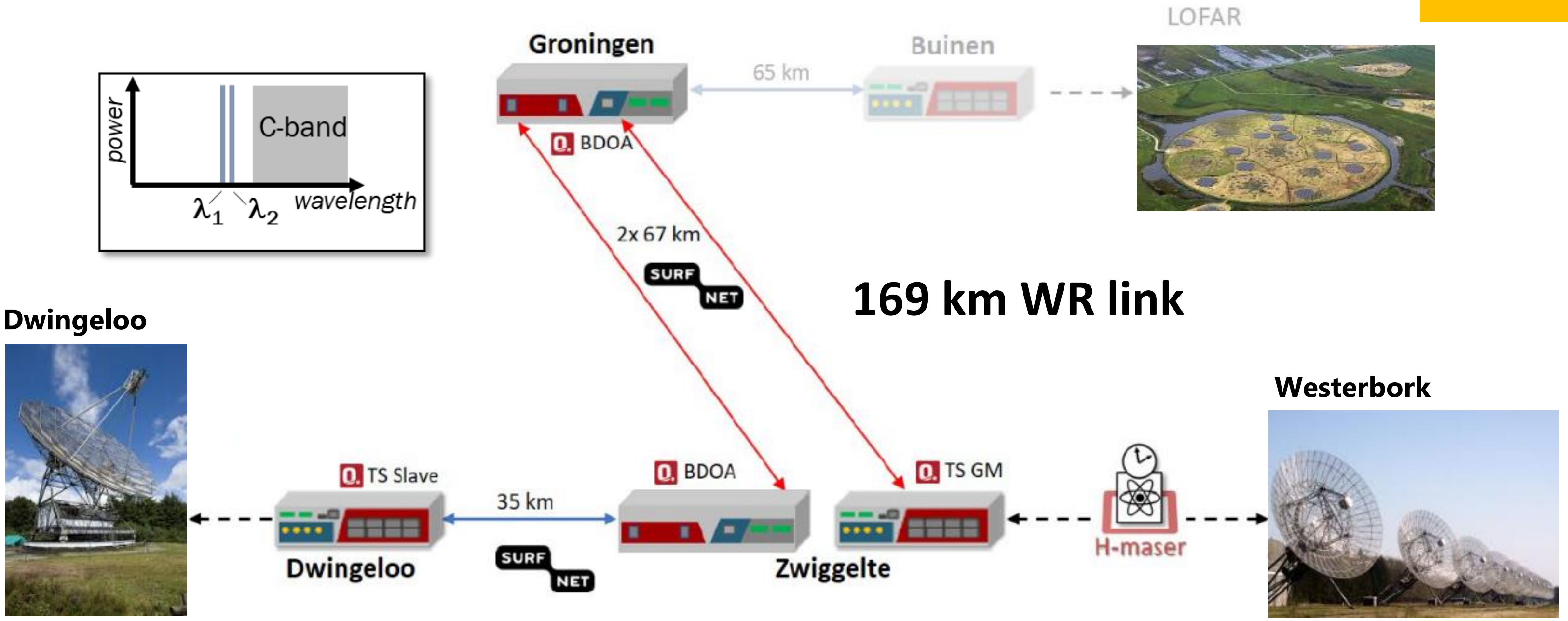
- Optical **wavelength division multiplexing** (WDM)
- See also: outcomes CLONETS project
  https://www.clonets.eu/clonets.html

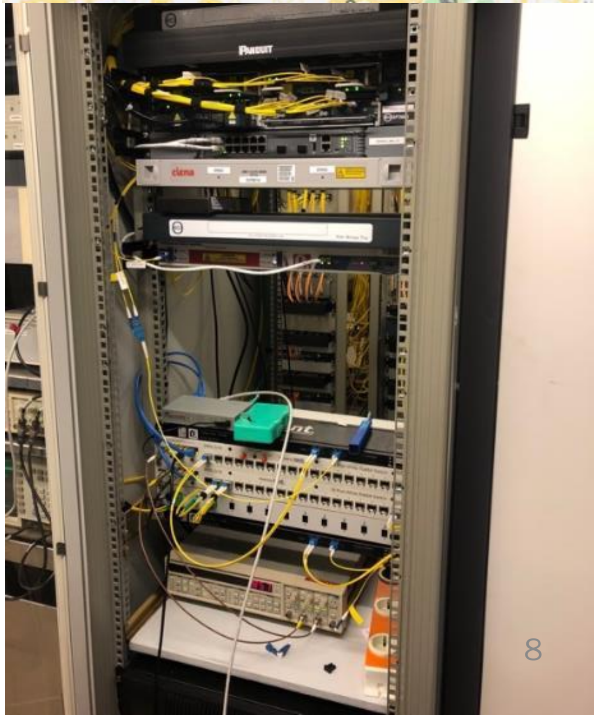
WR via WDM : E.F. Dierikx et al. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **63,** 945-952 (2016)
Earlier time transfer protocol via WDM: Lopez et al., *Appl. Phys. B* **110,** 3 (2013)

Example: SURFnet8

- WR time distribution over **live SURFnet8 production network** (2019)
- Purpose: synchronize Dwingeloo radio telescope to Westerbork telescope array
  - H2020 ASTERICS project – **VLBI demonstration using WR synchronization**
  - Similar: LOFAR radio telescope
- 2024: Nationwide time & frequency network rolled out by SURF

SURFtime&frequency





P. Boven, C. van Tour, R. Smets. Demonstration of VLBI synchronization via existing SURFnet/LOFAR network. ASTERICS GA Deliverable D5.14. https://www.asterics2020.eu/sites/default/files/documents/asterics-d5.14.pdf

WR and positioning – how?

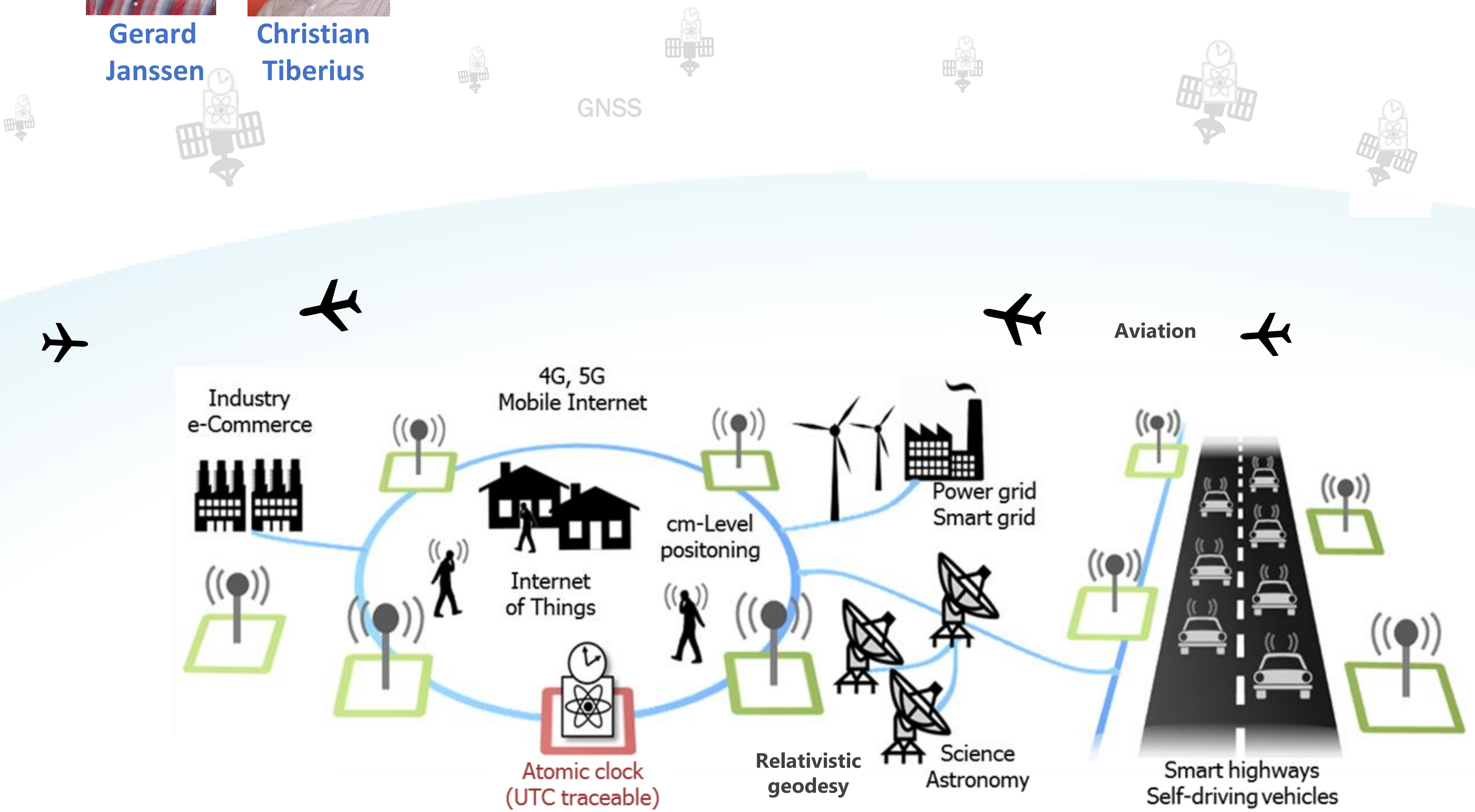
PNT through hybrid optical-wireless networks: ‘SuperGPS’ project

‘SuperGPS’ project

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

Gerard Janssen

Christian Tiberius



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

‘SuperGPS’ project

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

Gerard Janssen

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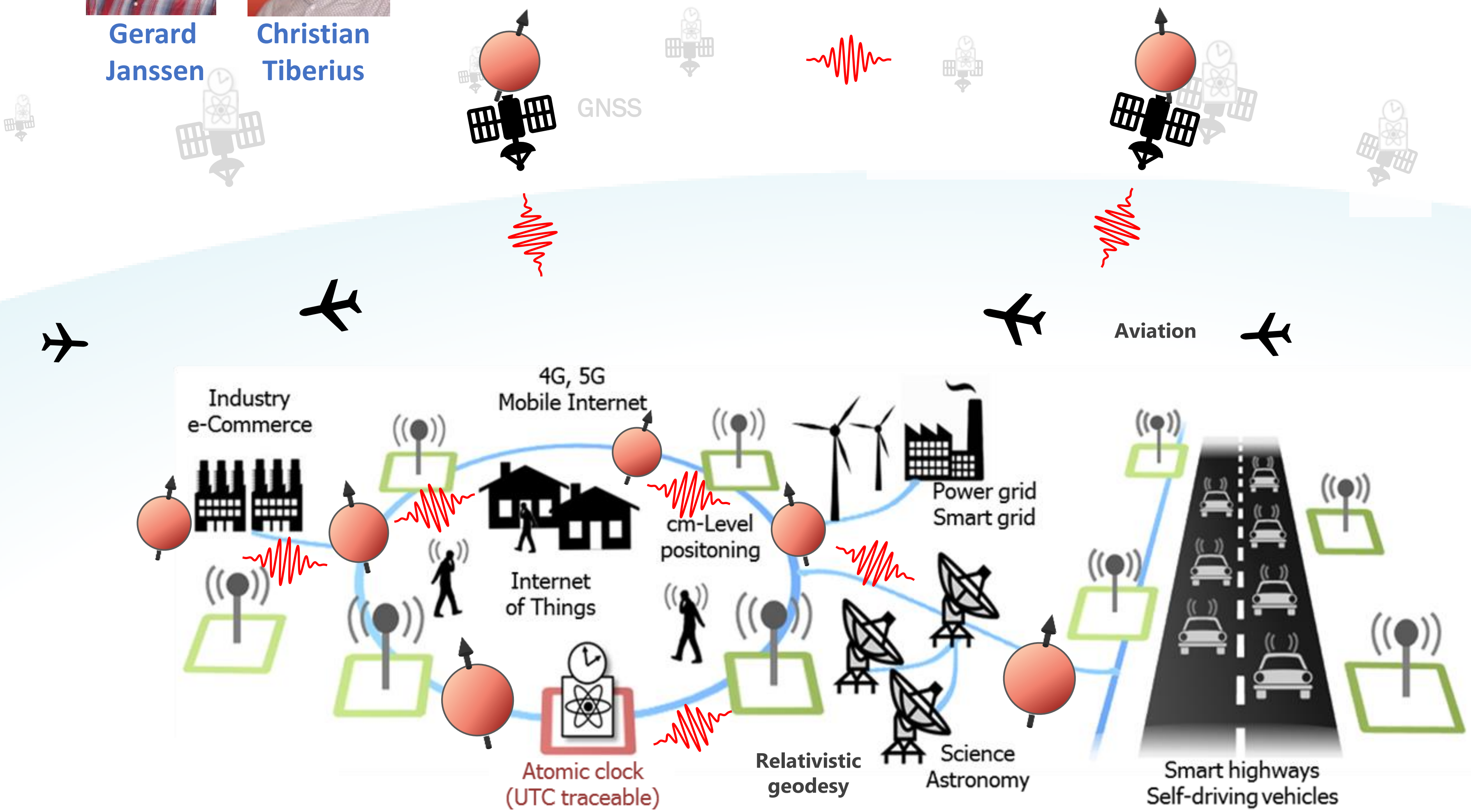
Back-up system for PNT through GNSS

Could also support quantum networks and distributed quantum computing



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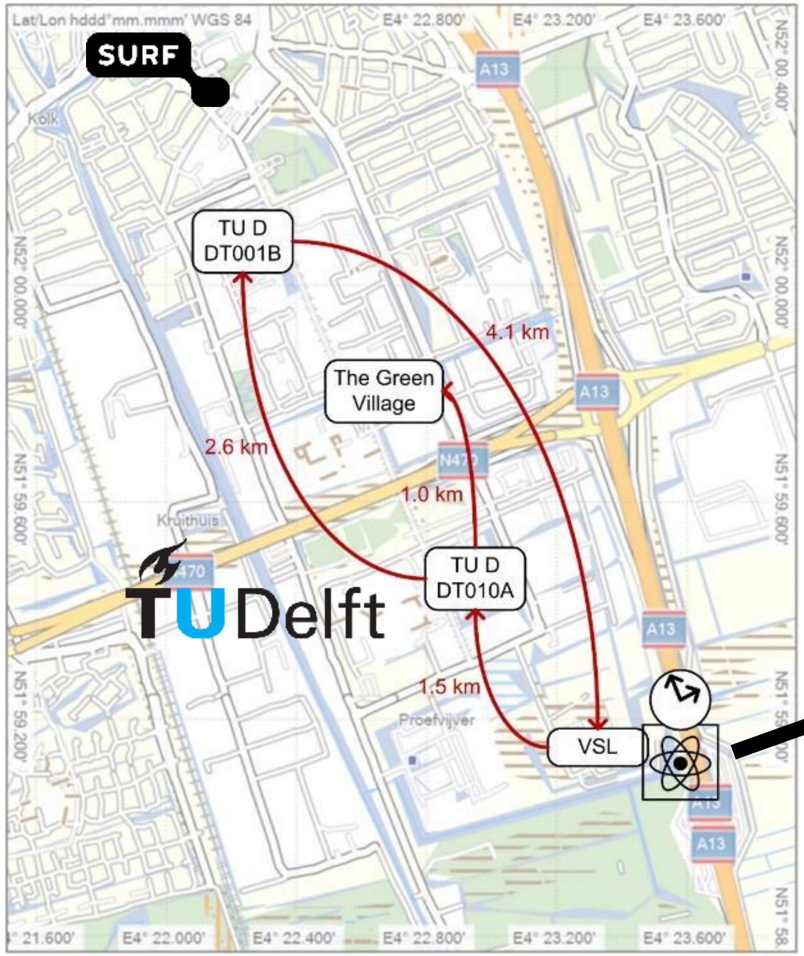
WR network VSL – TU Delft

Network map (Delft)



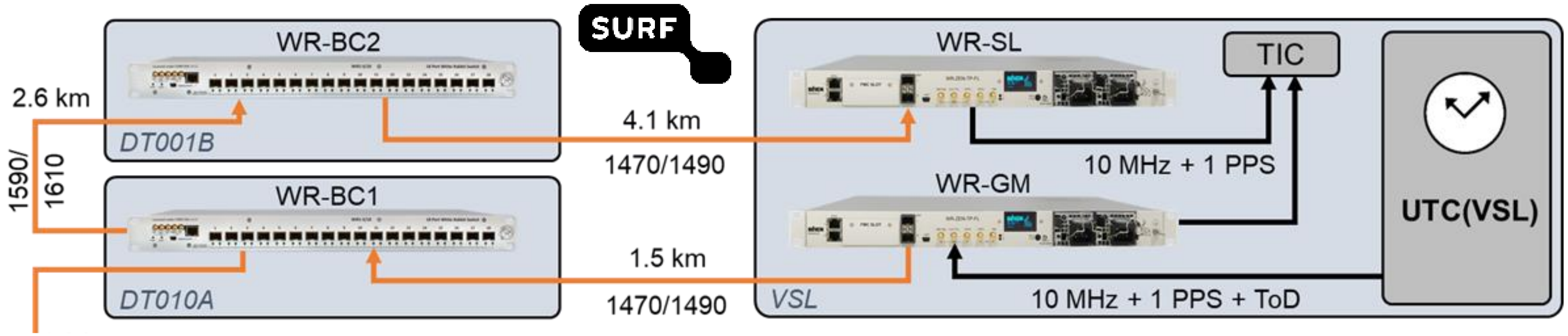
UTC(VSL)

Erik Dierikx

Yan Xie

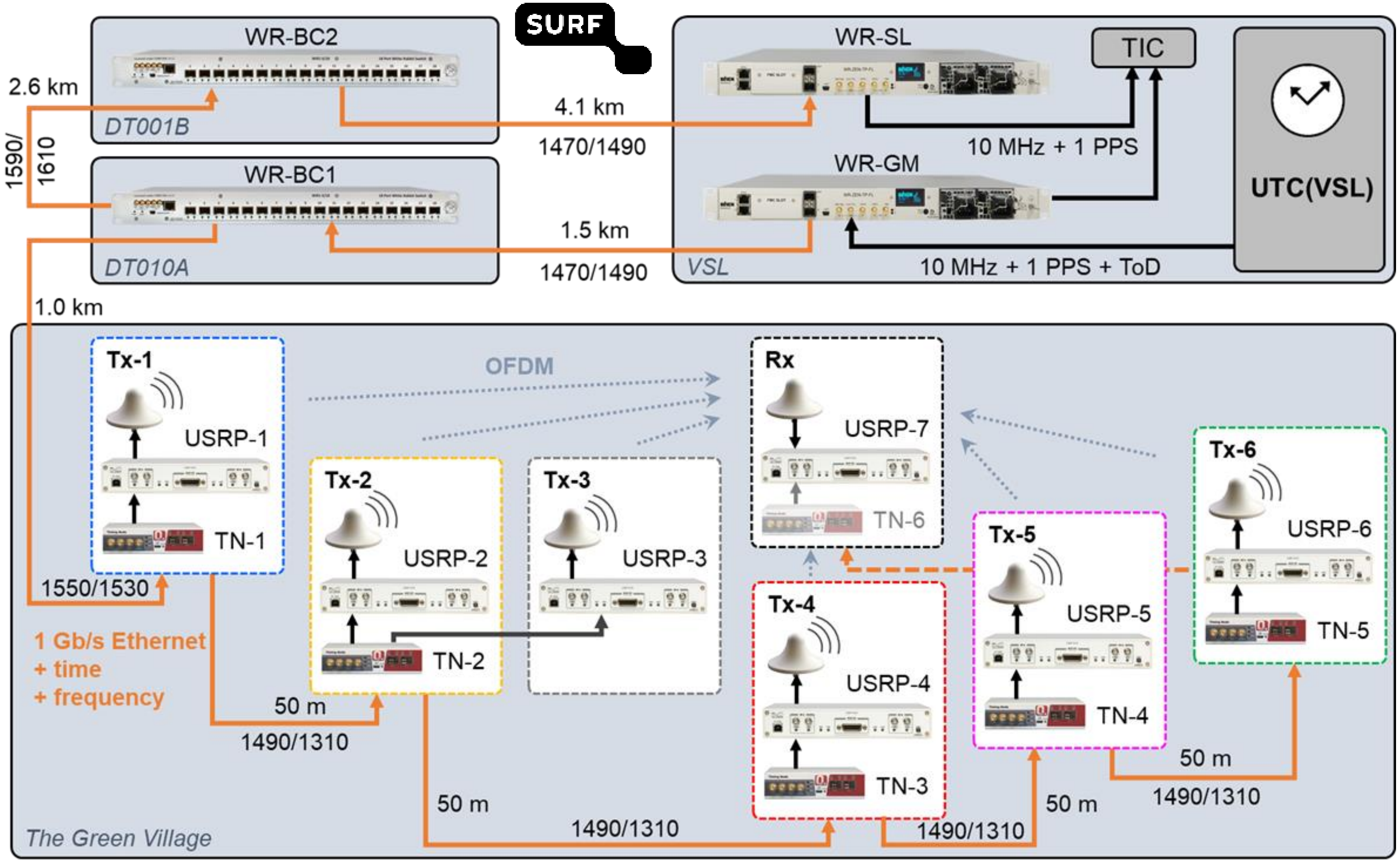
Hybrid optical-wireless network

- WR subnanosecond time distribution through optical fiber



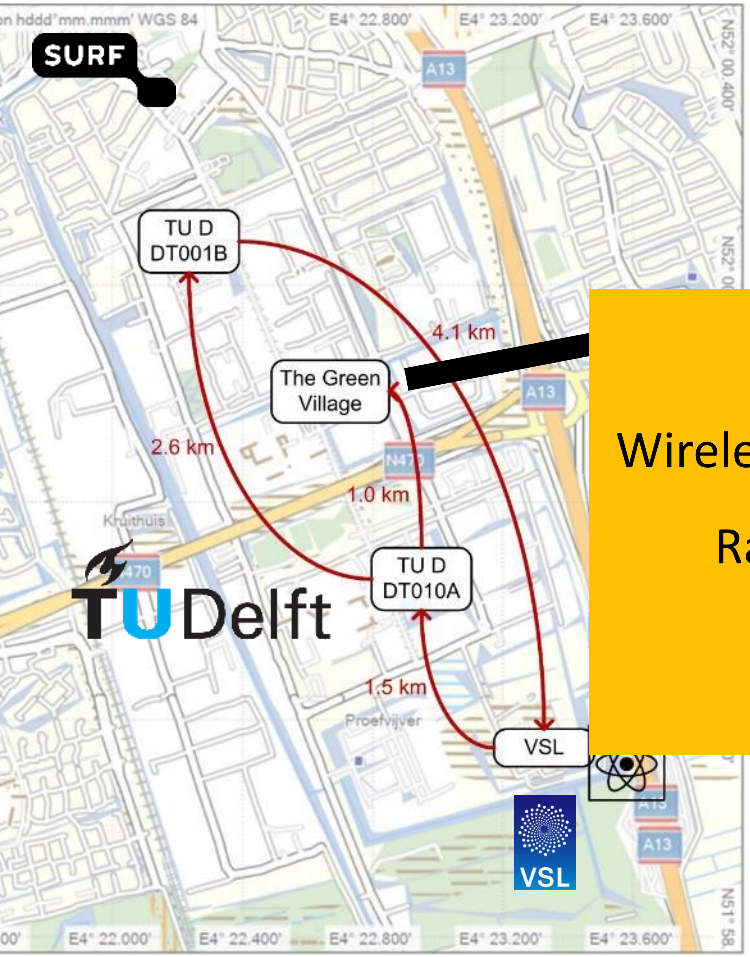
Hybrid optical-wireless network

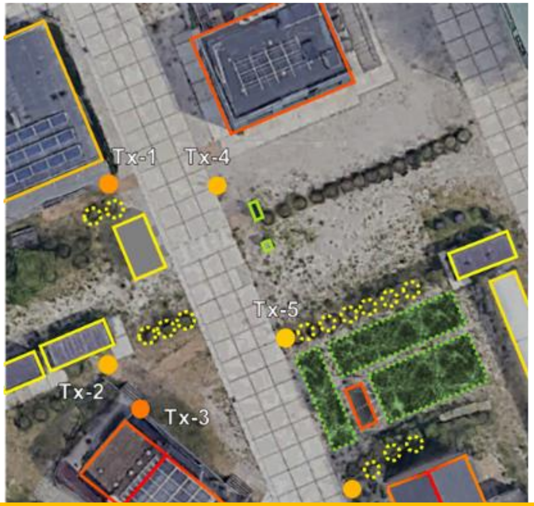
- WR subnanosecond time distribution through optical fiber **+ wireless PNT**



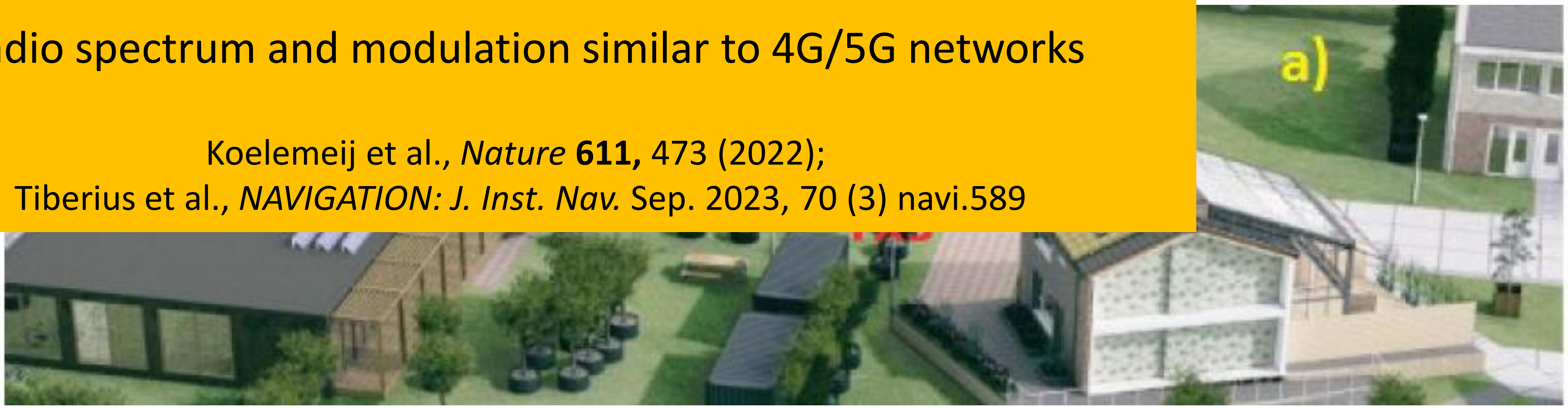
Field trial & performance

Network map (Delft)





The Green Village site @TU Delft, Sep 2020



Positioning with 10 cm uncertainty

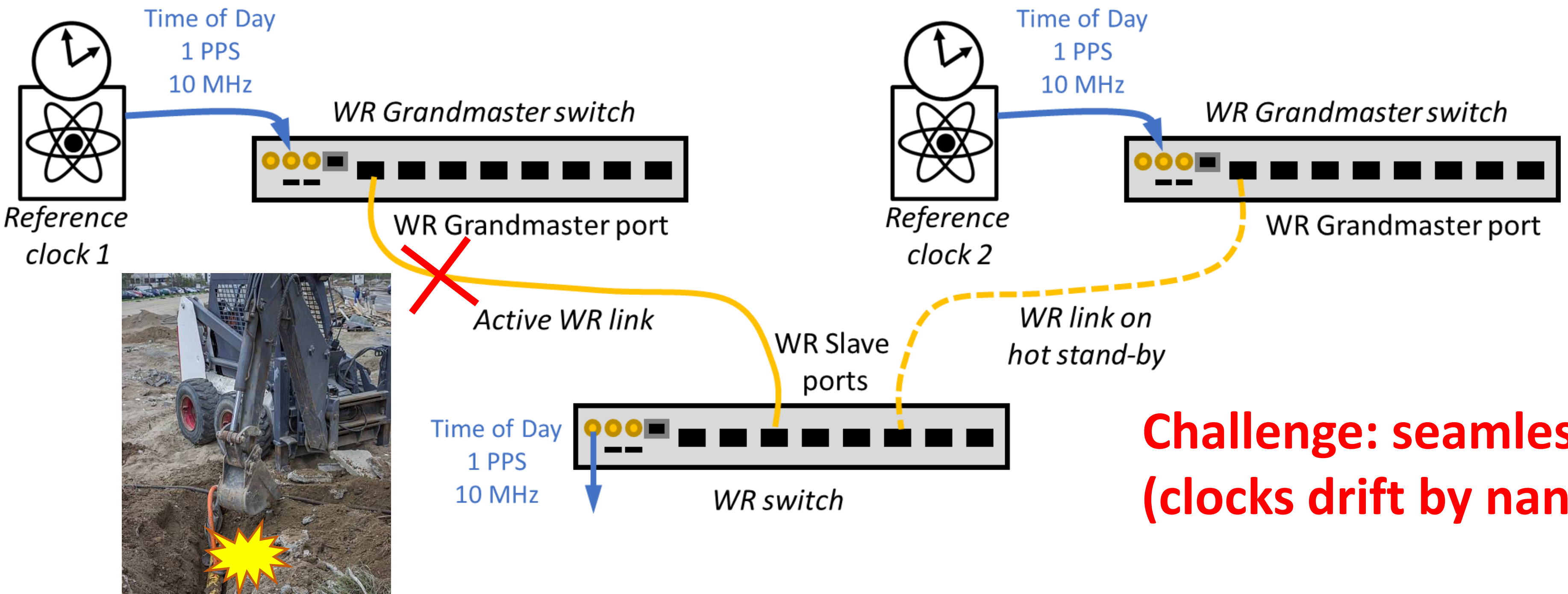
Wireless network time distribution with subnanosecond uncertainty

Radio spectrum and modulation similar to 4G/5G networks

Koelemeij et al., *Nature* **611,** 473 (2022);
Tiberius et al., *NAVIGATION: J. Inst. Nav.* Sep. 2023, 70 (3) navi.589

Redundancy and fail-over

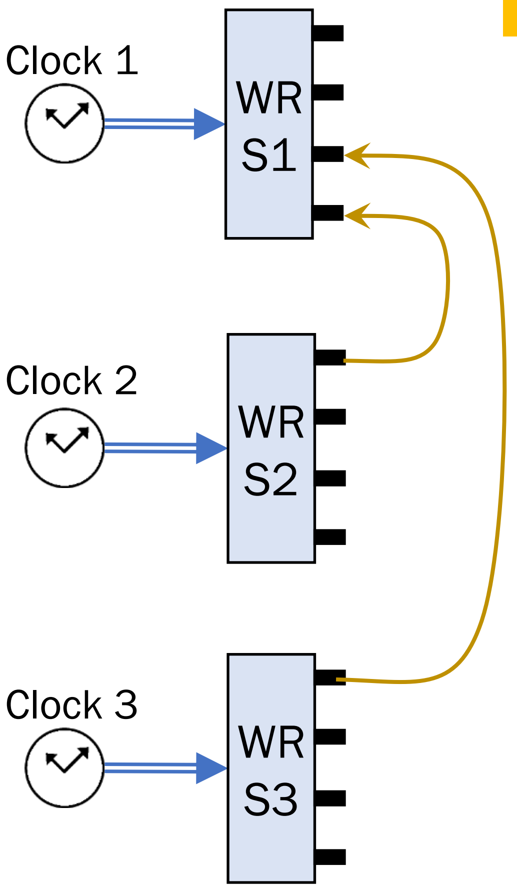
- GNSS backup & quantum networks: **security and reliability are of the essence**, and so must be timing accuracy, availability and integrity
- BUT: WR designed for single reference clock: single point of failure
- Need for redundant clocks and paths + fail-over mechanisms



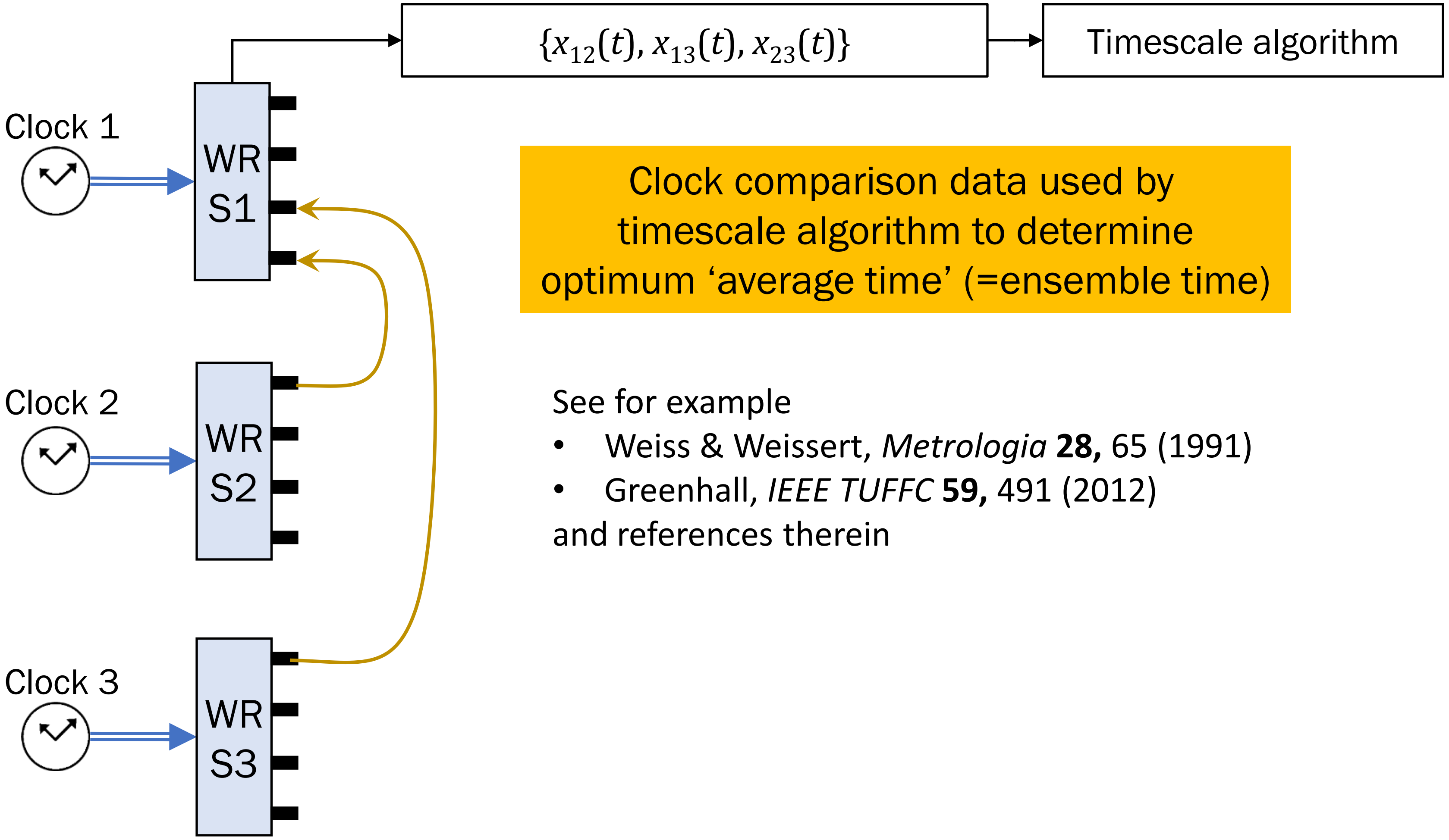
Challenge: seamless fail-over (clocks drift by nanoseconds)

Network timescale based on a clock ensemble

WR switch measures time differences between all three clocks:
$\{ x_{12}(t), x_{13}(t), x_{23}(t) \}$



Network timescale based on a clock ensemble



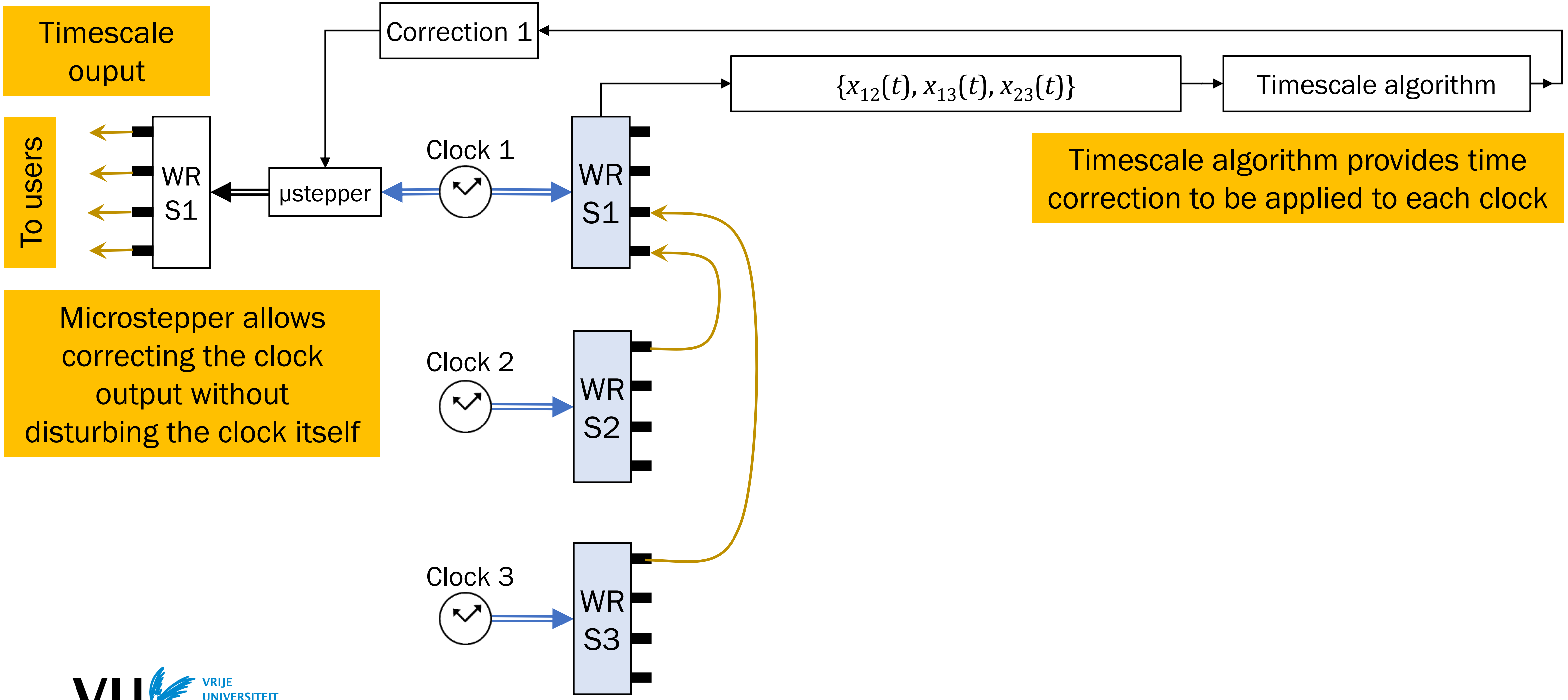
Clock comparison data used by timescale algorithm to determine optimum 'average time' (=ensemble time)

See for example

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

and references therein

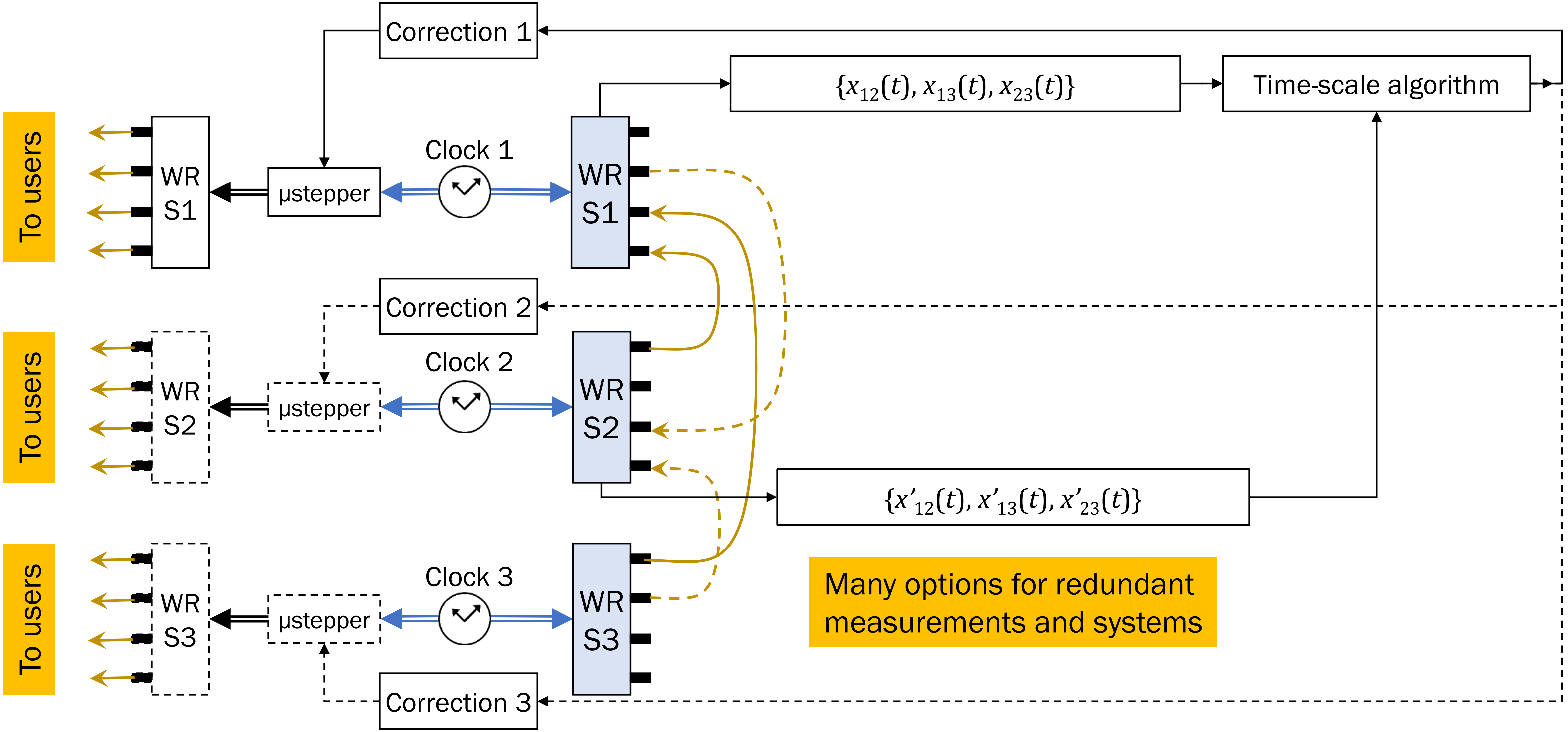
Network timescale based on a clock ensemble



Timescale algorithm provides time correction to be applied to each clock

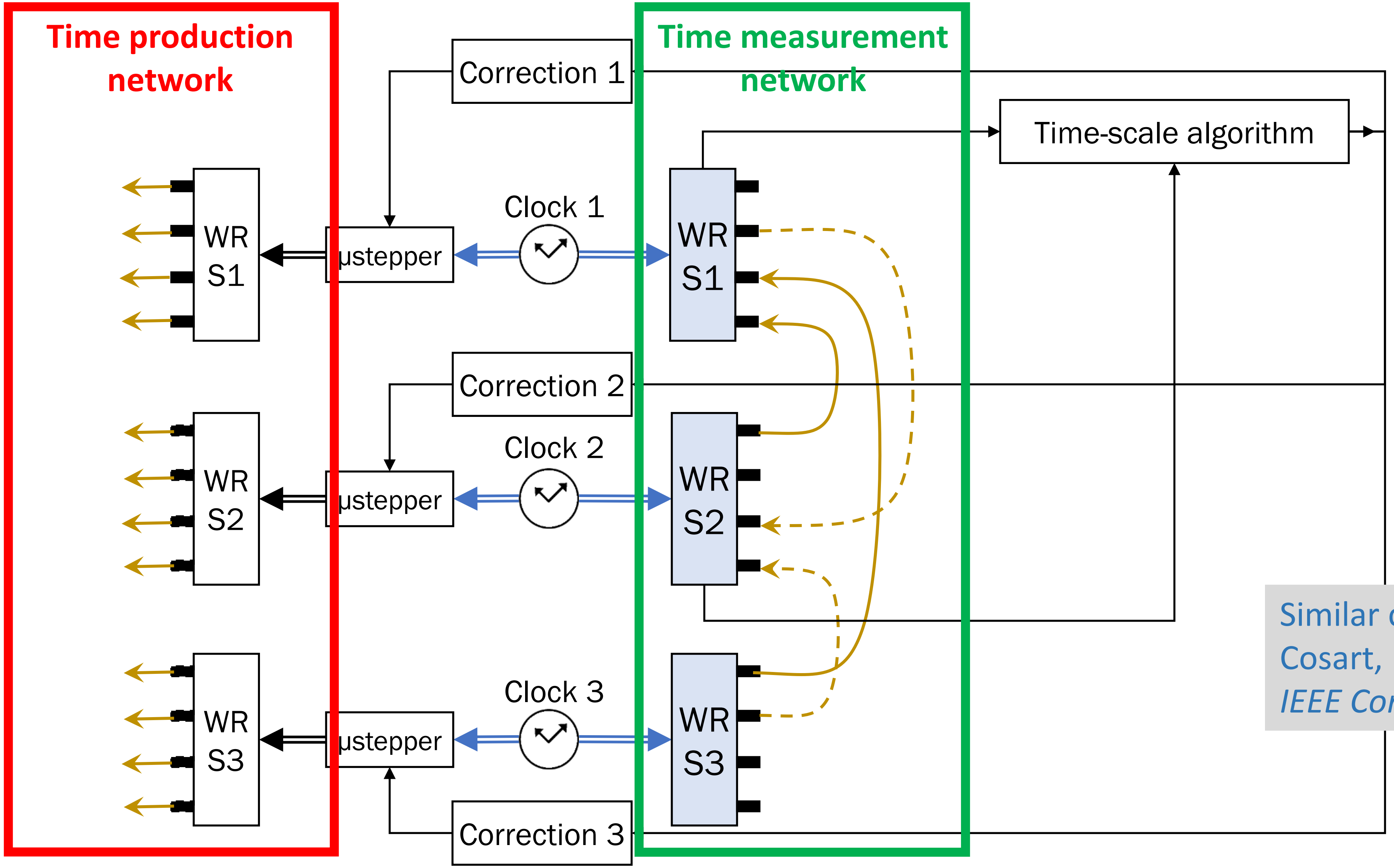
Microstepper allows correcting the clock output without disturbing the clock itself

Extensions for increased redundancy



Many options for redundant measurements and systems

Time measurement and time production networks



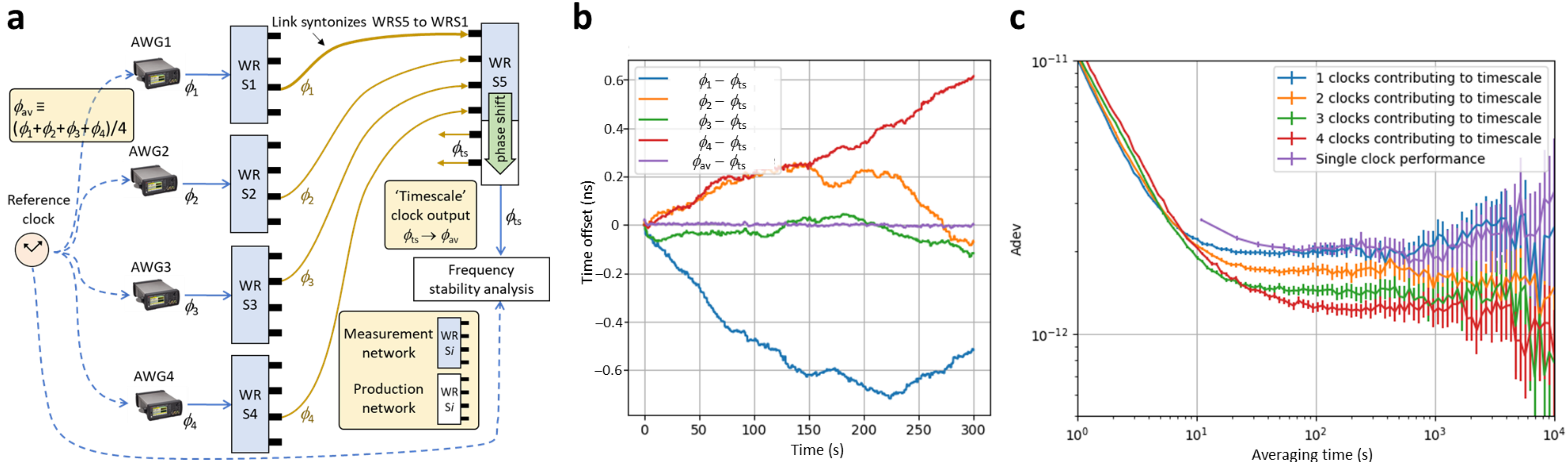
Similar concept proposed by Cosart, Imlau, Zampetti *IEEE Comms. Mag.* April 2023, p.28

Proof-of-principle clock ensemble



Rodrigo González Escudero
Marc Weiss
Sougandh Kannoth Mavila

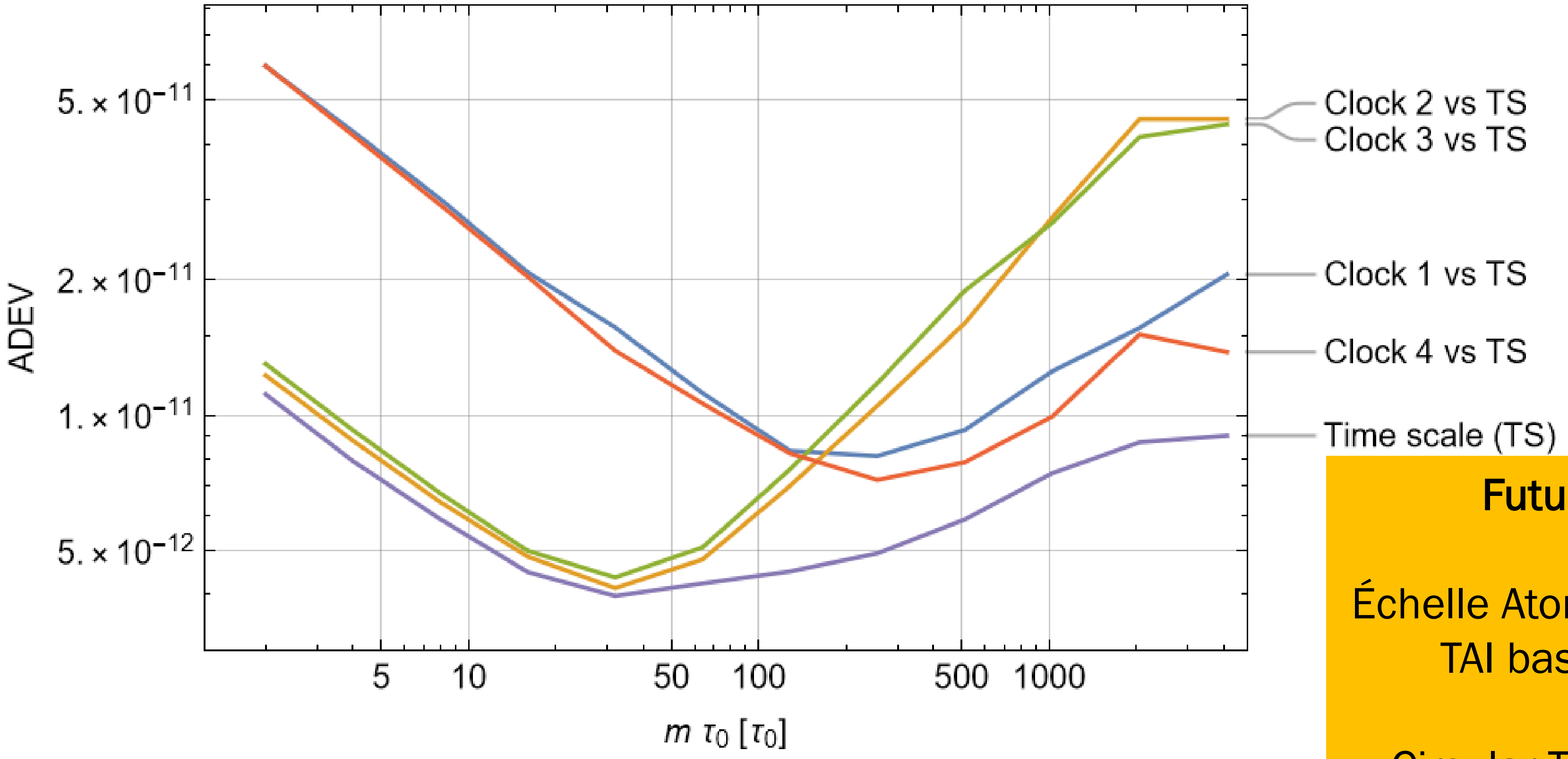
- Measurement network monitors four ‘clocks’
- Algorithm: simple mean of clock times ⇒ improves stability of production network time



The power of clock ensemble algorithms

- Multiple clocks offers not only redundancy, but also more stable network time!

Simulation (to be tested in a WR network with real atomic clocks soon):



Future UTC(?)

Échelle Atomique Libre and TAI based on WR?

Circular T every second (instead of daily/weekly)?

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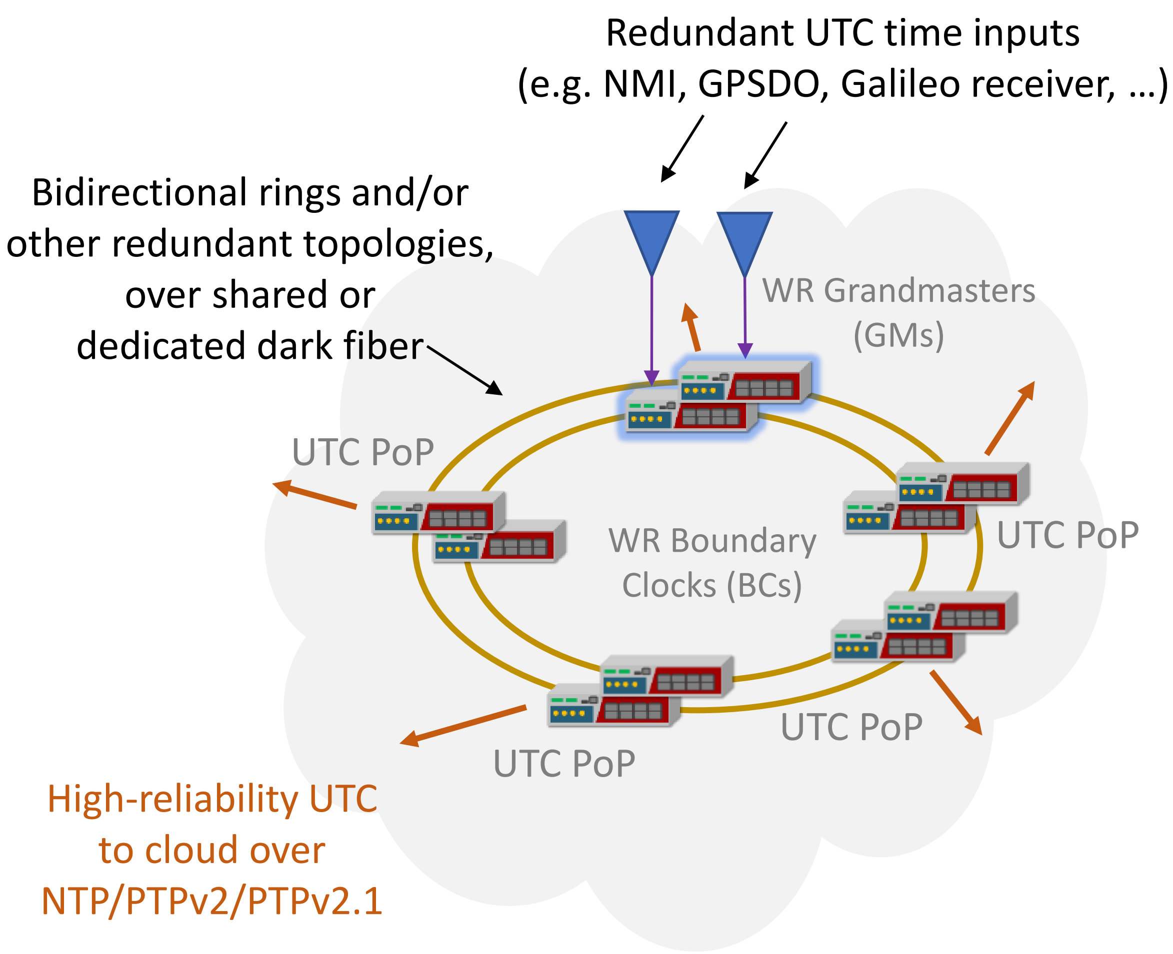
Layered network & organic growth

- Start with backbone network
- Deploy WR only there where necessary
- WR gear can also provide time through other protocols (NTP, PTP)
  - Energy grids, mobile networks, data centers, financials, …
- WDM: add ultrastable laser wave
- Reserve 2×4 channels per fiber pair
  - Fiber 1: 2× WR, 2× WR calibration
  - Fiber 2: 2× WR, 2× ultrastable laser
  - 25 GHz spacing?



See also: Krehlik et al., *IEEE TUFFC* **64,** 1884 (2017), and:
CLONETS Deliverables, https://www.clonets.eu/clonets.html

Thank you!

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