Design of the Northwestern Link
Lille-Brussels-Amsterdam-Braunschweig
&
Potential Network Topologies for C-TFN

1st SIG-TFN meeting

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Jeroen Koelemeij, VU Amsterdam

(with input from many people within and outside SIG-TFN, and building on expertise of CLONETS, GÉANT, REFIMEVE, SURF, VSL, a.o.)

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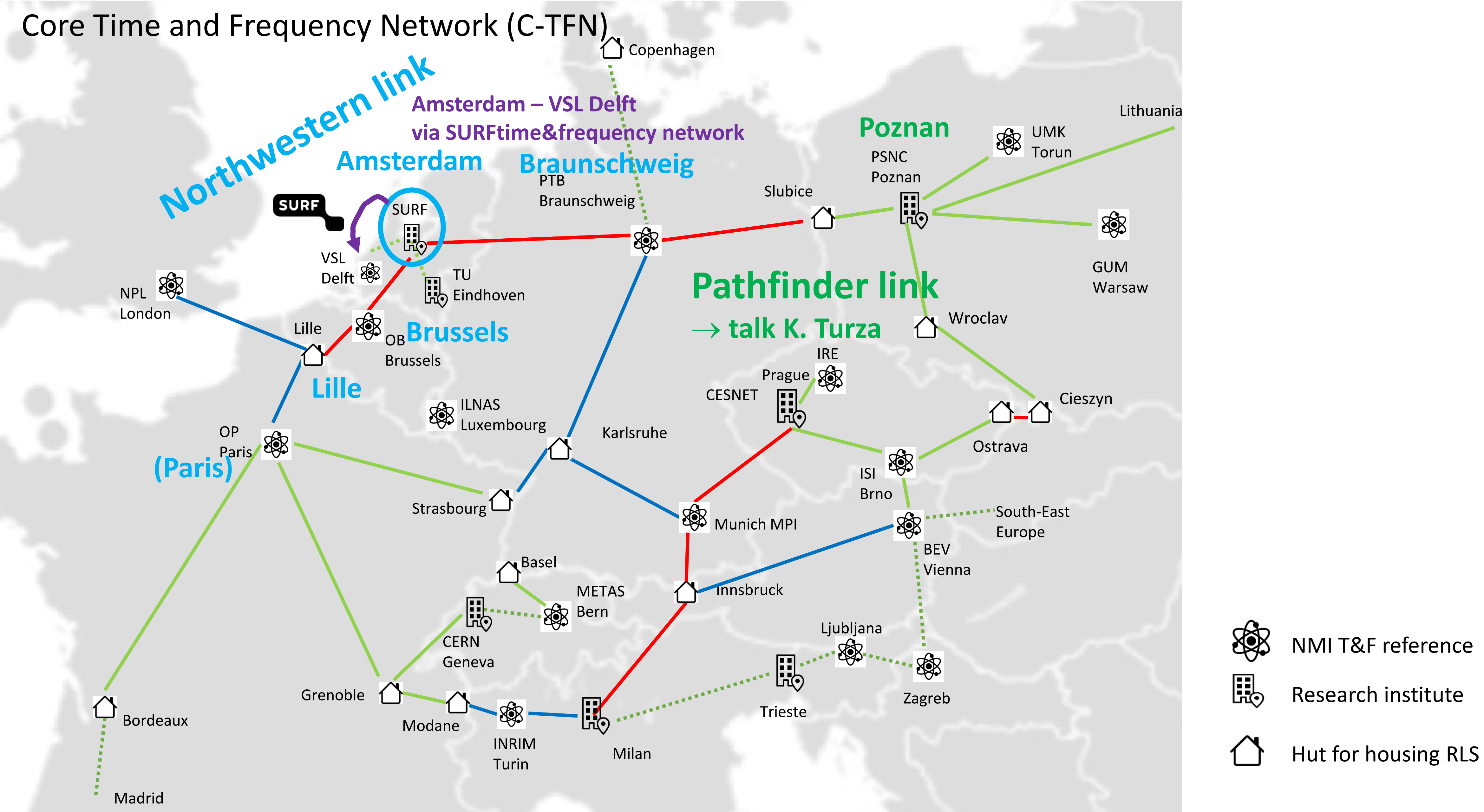
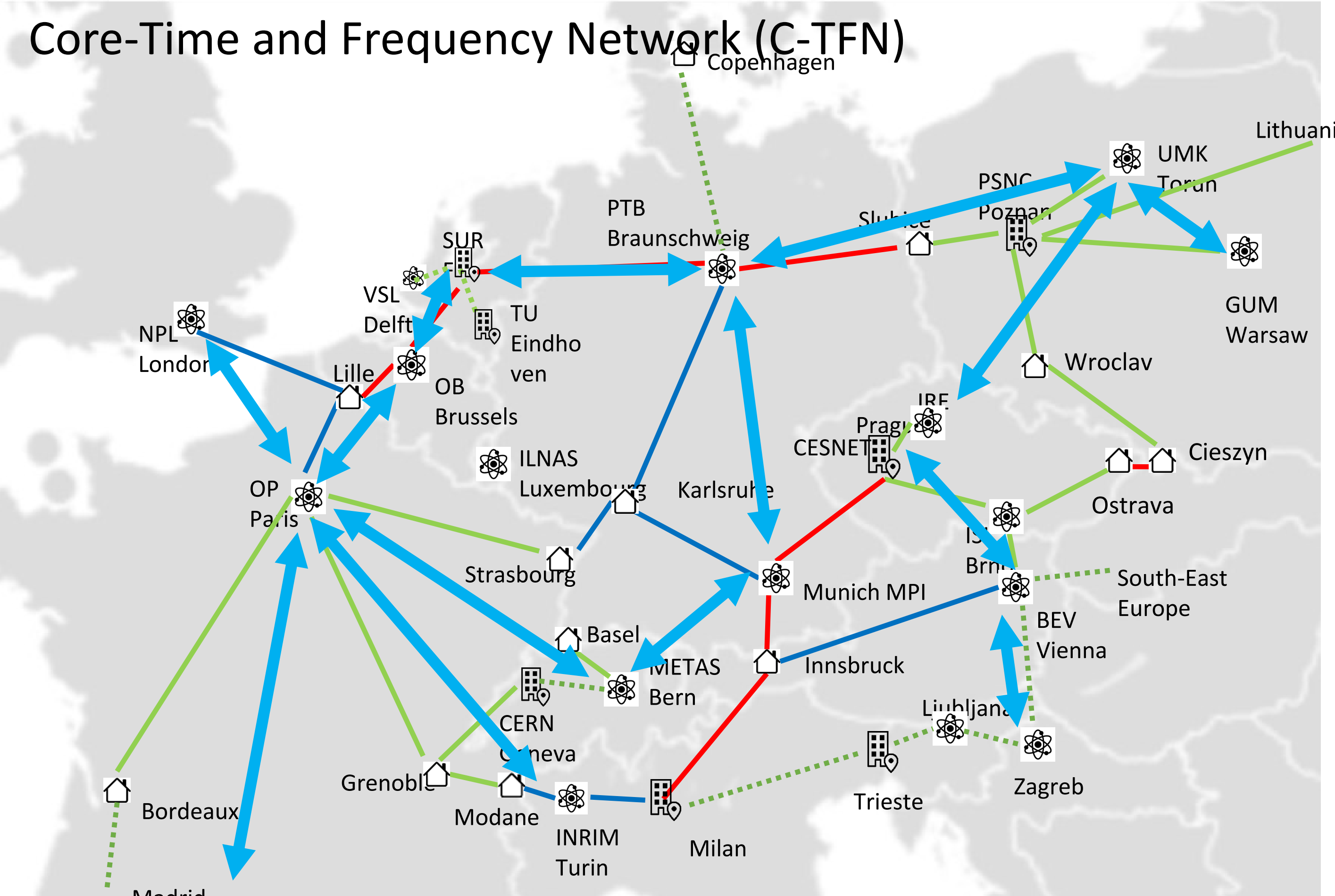
Contents

The northwestern link [network map taken from earlier slide by Guy Roberts/GÉANT]



Purpose of C-TFN

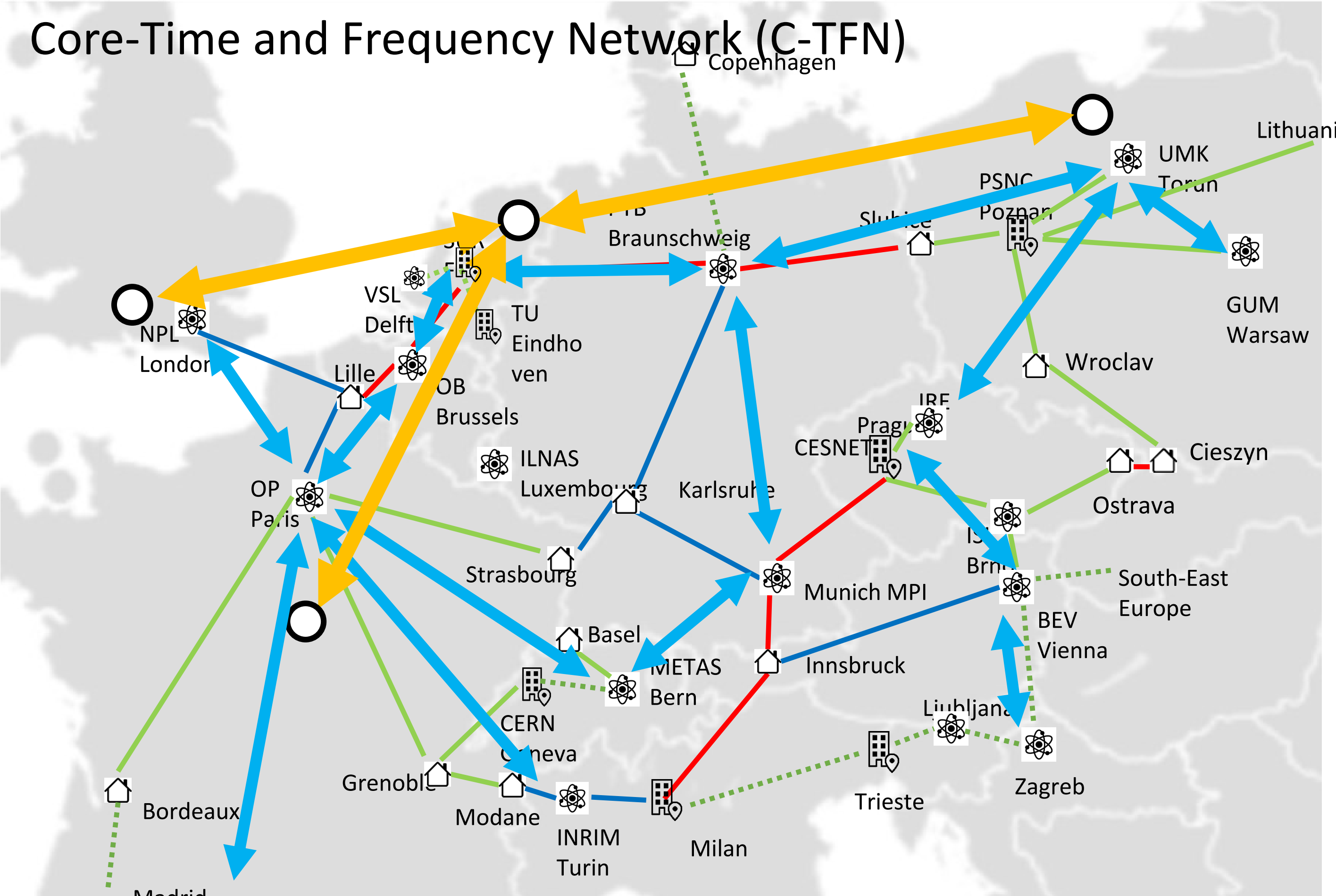
1. Time & frequency comparisons of distant atomic clocks/UTC(*k*) time scales via fiber-optic time & frequency links



1. Time & frequency comparisons for improved realization of TAI/UTC and SI second
2. Frequency comparisons of optical clocks (redefinition of the SI second)
3. Science cases that can be directly addressed with these measurements

Purpose of C-TFN

1. Time & frequency comparisons of distant atomic clocks/UTC(*k*) time scales via fiber-optic time & frequency links (C-TFN)
2. To enable time & frequency services to users/applications/scientific projects (cf. CLONETS D2.2) (TFN)



Purpose of C-TFN

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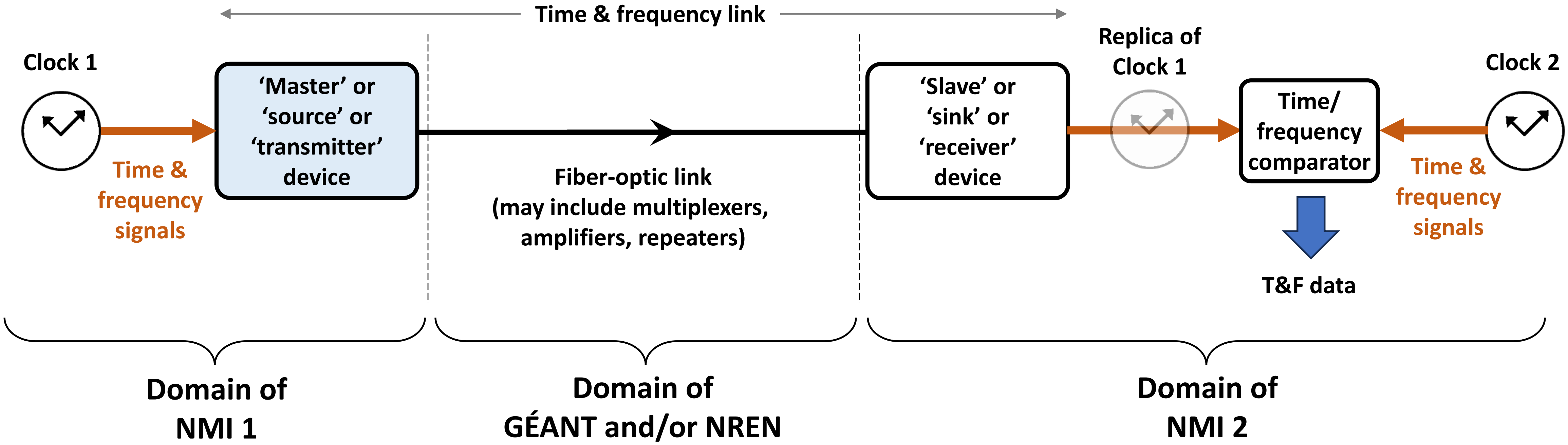
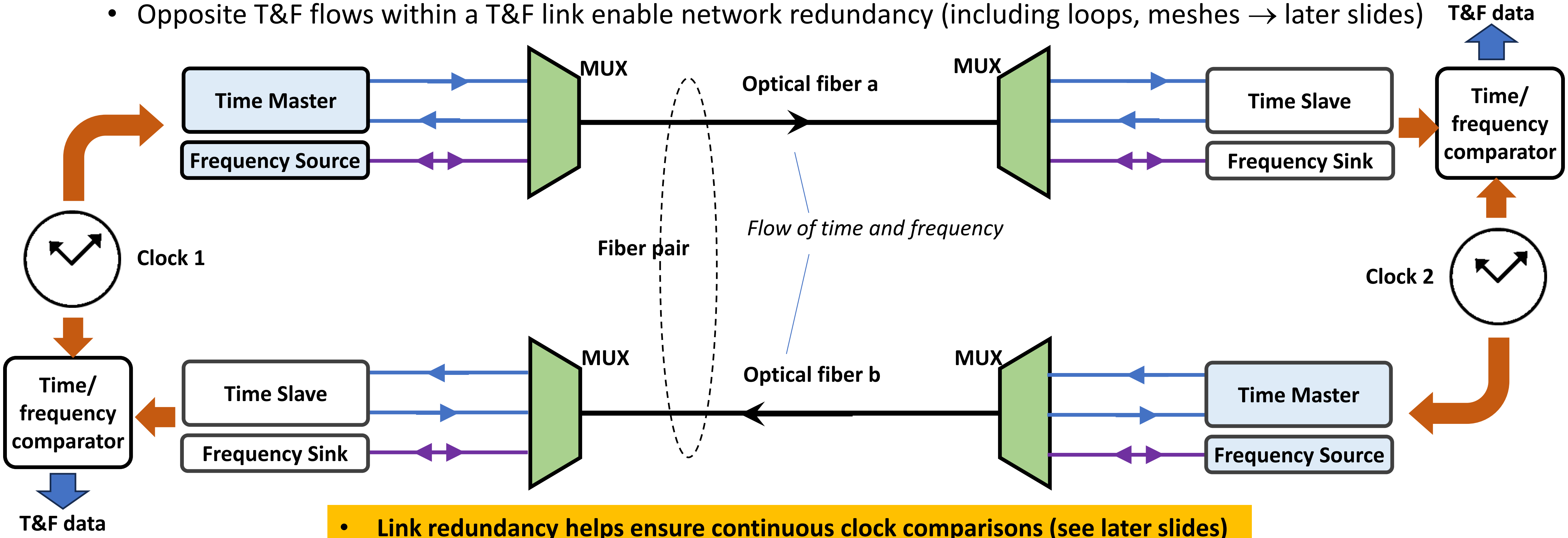


- T&F data is the main C-TFN product
- Maximize impact and utility by making T&F data available through a cloud application
- Several applications require that T&F data be uploaded and made available in quasi-real-time

Directionality: optical waves versus time/frequency

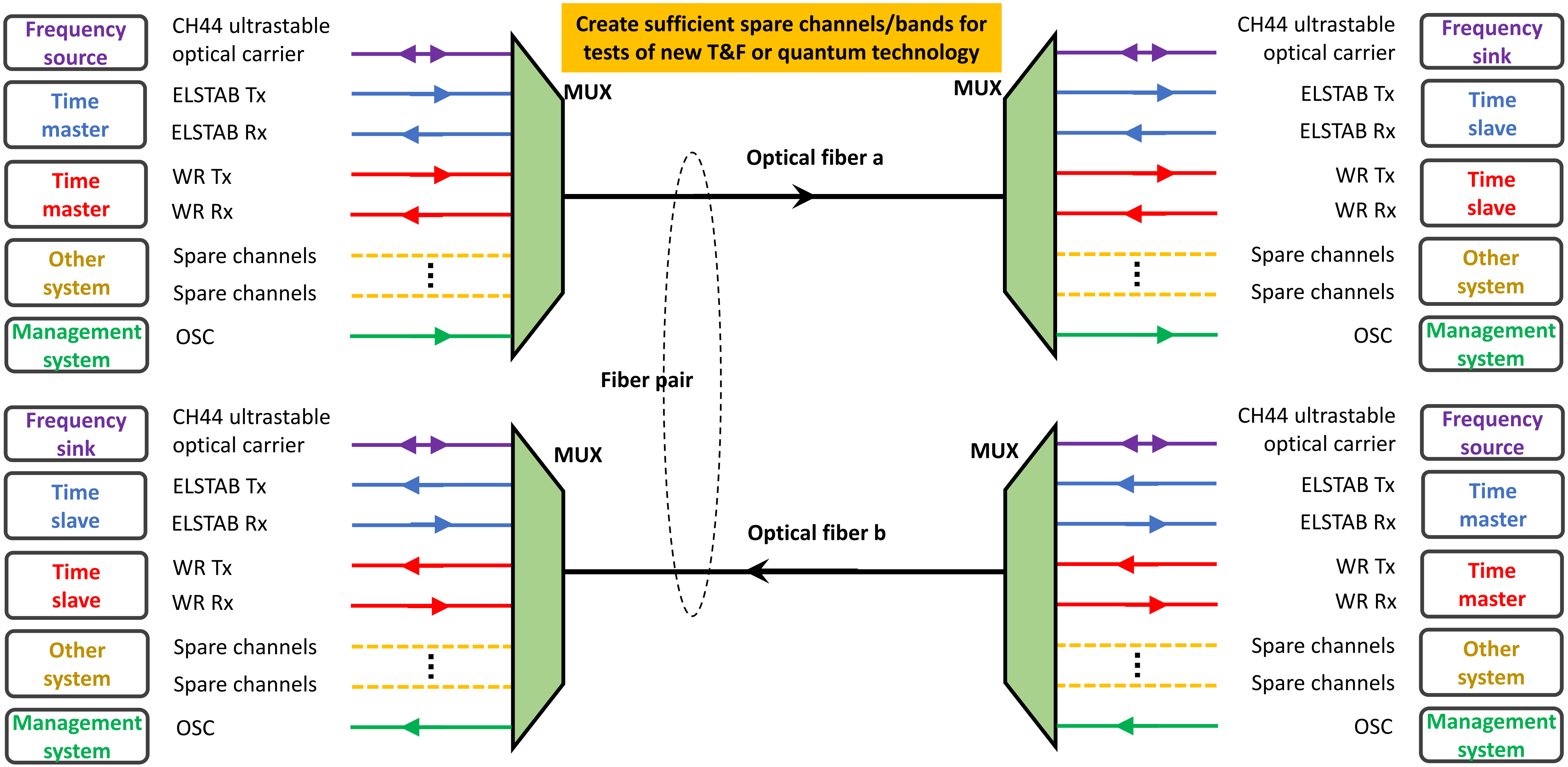
- All T&F technology considered for C-TFN requires **bidirectional** transmission of optical waves over the same physical fiber (for optical delay stabilization)
- By contrast, T&F links are hierarchical, with a **unidirectional** flow of time and frequency
- Opposite T&F flows within a T&F link enable network redundancy (including loops, meshes → later slides)



- **Link redundancy helps ensure continuous clock comparisons (see later slides)**
- **Link redundancy offers symmetry: clock 1 has no precedence over clock 2**
- **Enables measurement and elimination of delay asymmetry (e.g. Sagnac)**

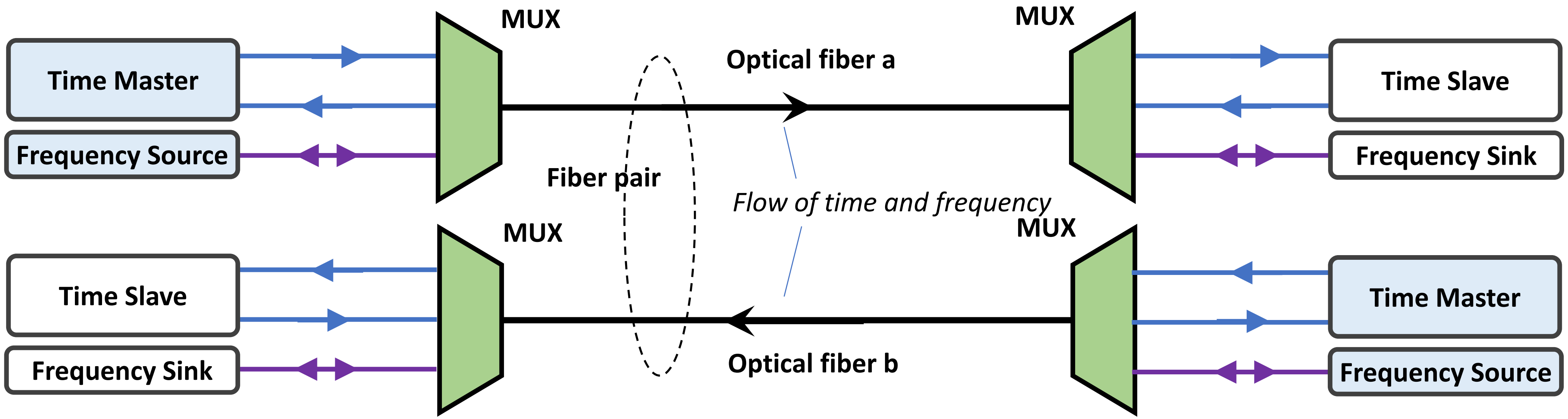
WDM wavelength plan for TF signals (lambdas TBD)

Clocks & comparators omitted for simplicity ***See also talks J.-O. Gaudron, J. Vojtech/V. Smotlacha, K. Turza, D. Calonico***



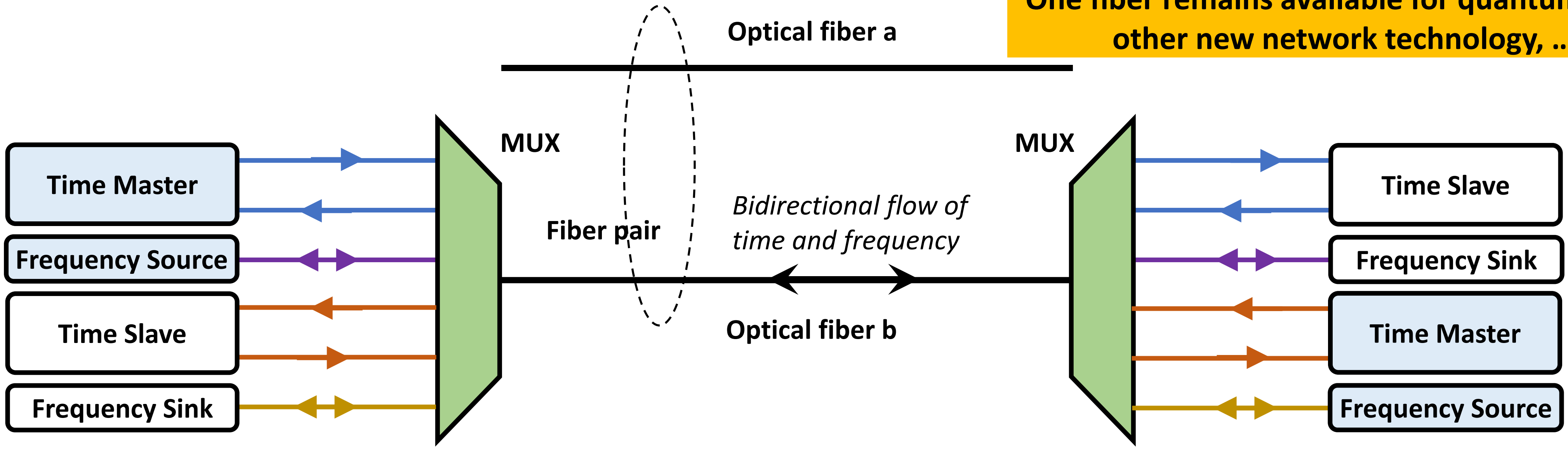
One or both fibers lit? See also talk K. Turza on Pathfinder results

Fiber-pair redundant links

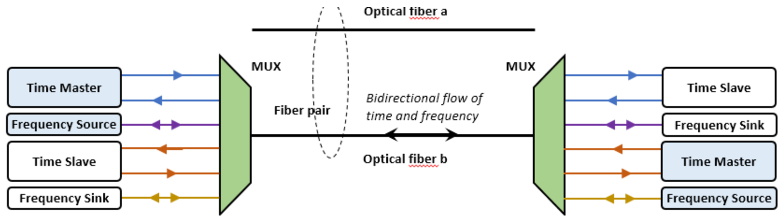


Single-fiber redundant links

One fiber remains available for quantum links, other new network technology, …

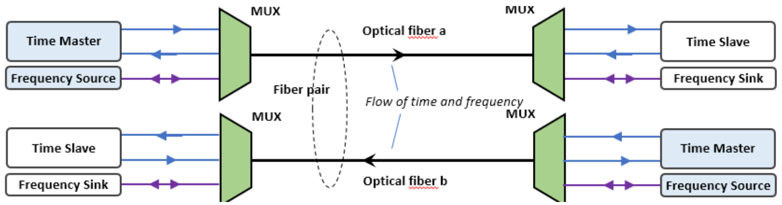


Considerations



Single fiber lit (bidirectional T&F flow)

- **Any improvements to be expected in the T&F performance itself?**
- Any challenges to be expected with Exail validation link, especially in case of non-redundant topology?
- T&F fiber could synchronize nodes of a quantum internet (entanglement of remote qubits)
- Such a quantum network needs time synchronization (<< qubit photon duration/10)
- Depending on the quantum platform used, the 'quantum fiber' needs be dark or barely lit*
- **How likely is it that a quantum technology (requiring dark or barely-lit fiber) needs to be deployed during the IRU term? What are the expected cost savings?**



Both fibers lit (opposite unidirectional T&F flows):

- Symmetry similar to DWDM data transmission systems
- Symmetrical network might be easier to design and manage from network operator PoV
- **Natural choice if one believes that future core networks will have regular DWDM data and T&F signals multiplexed over the same optical fibers**

* Stolk et al., PRX Quantum 3, 020359 (2022)
Burenkov et al., Opt. Express 31, 11431 (2023)

Wavelength considerations

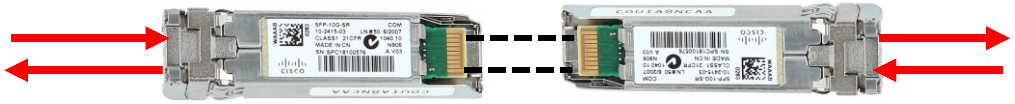
- Ultrastable optical frequency transfer
  - Ch 44 (1542.14 nm): de facto standard for ultrastable optical frequency transfer in Europe; widest choice in COTS equipment
- ELSTAB
  - Recent results NPL: ELSTAB compatible with both ultrastable optical carrier and White Rabbit (talk J.-O. Gaudron; see also results Pathfinder Link - talk K. Turza).
- WR (1.25 Gb/s OOK)
  - Can operate at any wavelength for which Gigabit Ethernet SFPs are available
  - Prefer 'wavelength-locked' DWDM SFPs over CWDM SFPs: DWDM SFPs have smaller wavelength drift $\Rightarrow$ less nonreciprocal delay variation due to chromatic dispersion (typically < 0.1 ns for a 100 km link [1])
  - DWDM SFPs with slightly tunable wavelength (via I2C) are commercially available (nice-to-have, could be useful for automated in-situ chromatic dispersion calibration)
- Before a wavelength plan is decided on, the **chromatic dispersion calibration procedures for time links must have been selected** (and tested, if procedure not part of current state of the art)
  - Chromatic dispersion delay asymmetry can be determined by varying wavelength over known amount (e.g. 0.08 nm) and measuring delay difference, or by swapping Tx and Rx wavelengths on both ends of a link
  - Suggestion PSNC: use external dispersion measurement device (<1% accuracy possible [2])

[1] C. van Tour and J.C.J. Koelemeij, ngVLA Memo #22 (2017) library.nrao.edu/public/memos/ngvla/NGVLA_22.pdf

[2] F. Devaux et al., *J. Lightwave Technol.* **11**, 1937–1940 (1993)

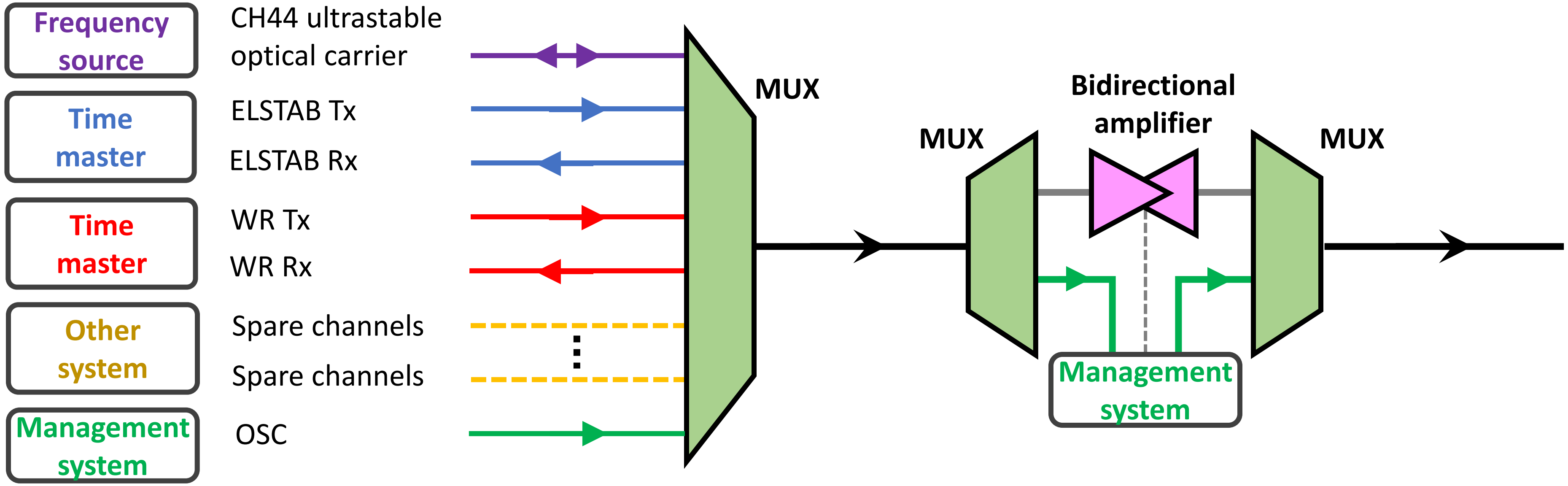
Amplifiers and repeaters

- Amplification: EDFAs for ultrastable optical frequency and ELSTAB
  - Separate or shared amplifiers? Await input from Pathfinder link, NPL, others…
  - Gain limited to ~20 dB (bidirectional operation)
- WR: insert a WR switch as a repeater (but: who owns that WR switch?)
- WR: OEO repeater (non-standard)
  - Cost-effective: SFP media converter + two SFPs
  - Gain ≈ Rx sensitivity ⇒ 35 dB possible
  - Performance in terms of added jitter as good as optical amplifier
  - Minor disadvantage: wavelength drift of DWDM SFPs in OEO ⇒ slight additional nonreciprocal delay variations due to chromatic dispersion



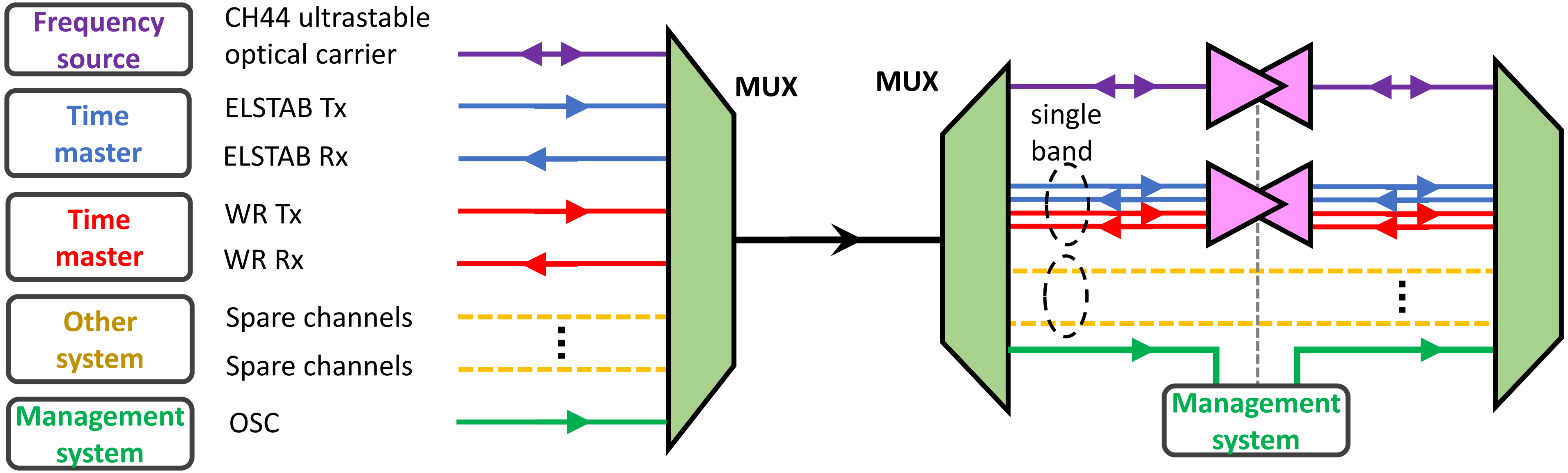
- WR alternative: EDFA (should work) or SOA (SOA: works, but non-standard?)
  - More expensive than OEO
  - SOA: bidirectional transmission of OOK signals can lead to cross talk via cross-gain modulation (XGM)
  - Using WDM filters and quasi-bidirectional amplifiers (two anti-parallel unidirectional amps) maximum amplifier gain (30-35 dB) attainable and XGM avoided (in case of SOAs)

Amplifier site design considerations



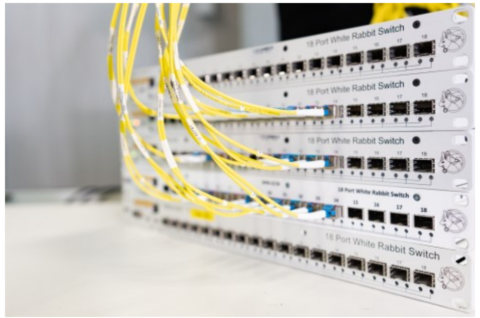
Preferred(?)

Feasible?



As opposed to…

White Rabbit and ELSTAB



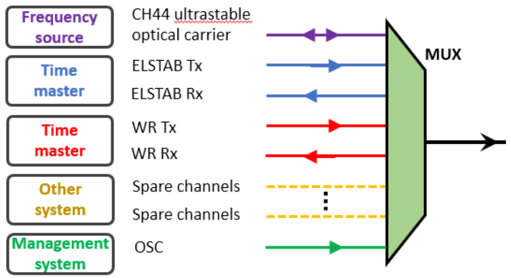
White Rabbit

- Affordable (most NMIs already use it) and scalable (18-port switch)
- Sub-nanosecond time uncertainty, frequency stability sufficient for Cs/Rb atomic clock comparisons
- WR not capable of comparing H-masers without loss of short-term stability
- WR Collaboration: very active and growing community, standardization ($\rightarrow$ see talk M. Lipinski)
- WR in C-TFN (arguably the premier TFN in the world): opportunity for Europe to consolidate its leading role in the WR business
- Gigabit Ethernet capability: means to transfer T&F data to cloud application

ELSTAB

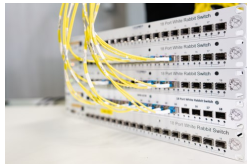
- High T&F stability and accuracy, sufficient to compare H-masers (must have!)
- Metrologically well established (developed for/by NMIs)
- System cost considerably higher than WR
- Performance may overshoot the needs of operators of cesium atomic clocks

Proposal: WR and ELSTAB (and possibly more)



Establish sufficient WDM channels and add/drop points to support ELSTAB and WR and future 'system X' so that:

- A WR-based time (+ data?) 'baseline network' with 100% coverage can be established
  - Low cost, affordable for any NMI
  - Establish at least one *uniform* and *ubiquitous* C-TFN – uniform network equipment, supervision system, calibration procedures, et cetera
  - WR is sufficient to reduce deviations UTC(*k*)-UTC by one order of magnitude (from nanoseconds to sub-nanosecond $\Rightarrow$ crosses barrier to what is needed for quantum, LOFAR, terrestrial PNT)
  - Benefit from (future) WR standardization and WR community efforts
  - Boost relevance of WR and Europe's prominence in the WR community and WR market

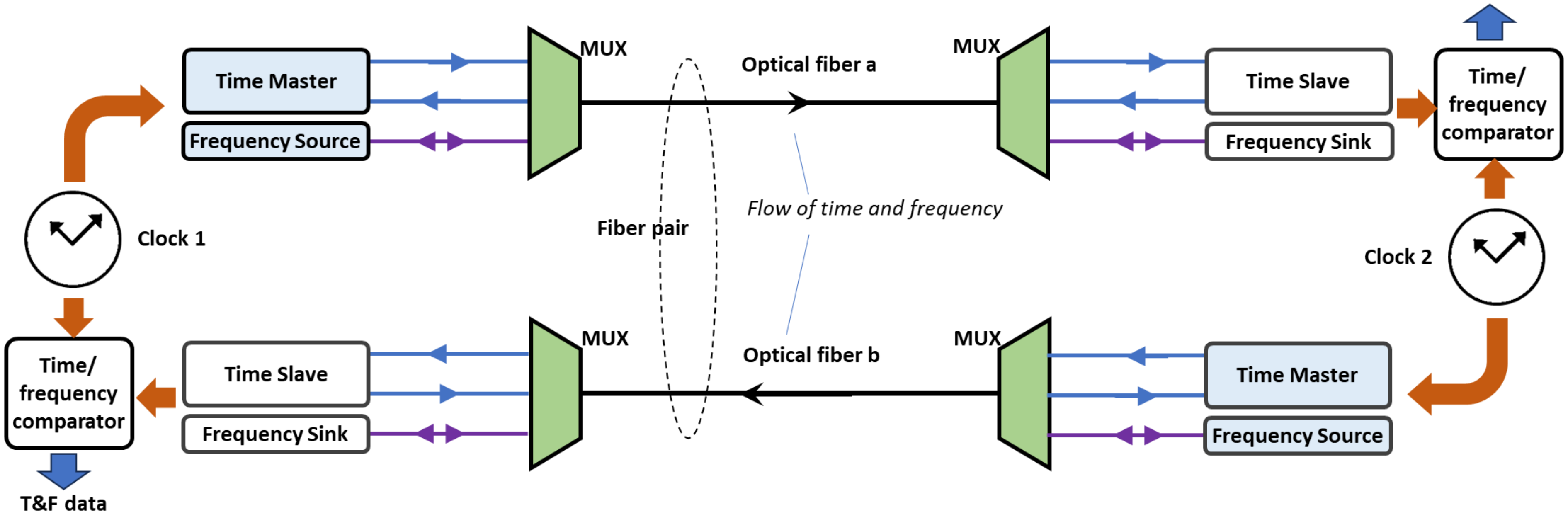


- **Any NMI can in addition choose for ELSTAB**
  - If higher frequency stability or higher time transfer accuracy is desired, e.g. for
    - NMIs operating H-masers
    - NMIs operating primary frequency standards
  - Now or at any time in the future
  - Uniformity is still possible and important, even if not all NMIs connected via ELSTAB

- NMIs can in parallel test other timing systems as they may become available in the future
  - Having multiple options $\Rightarrow$ reduced risk of vendor lock-in or critical dependence on single vendor

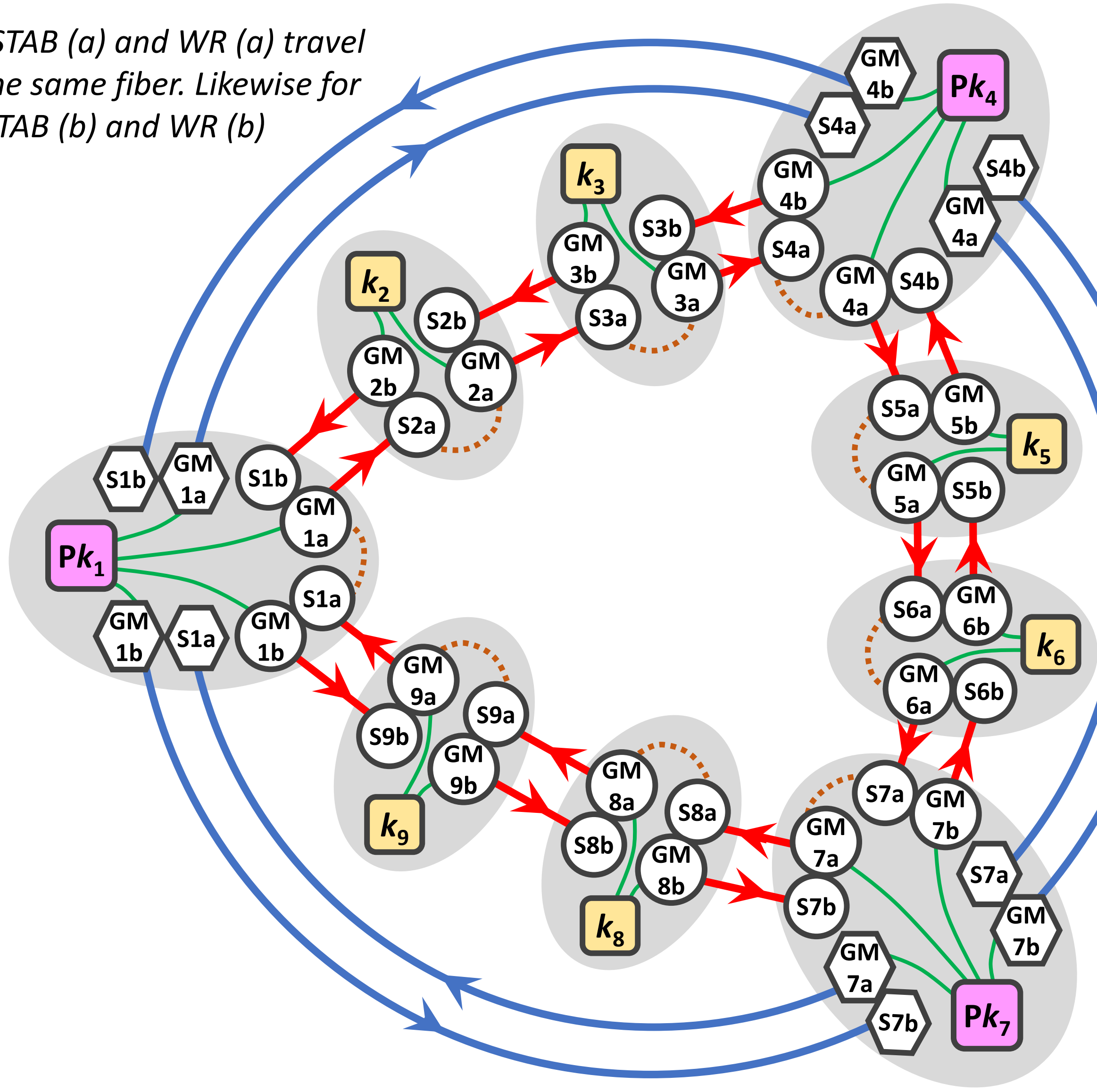
Resilience, continuity, and redundancy

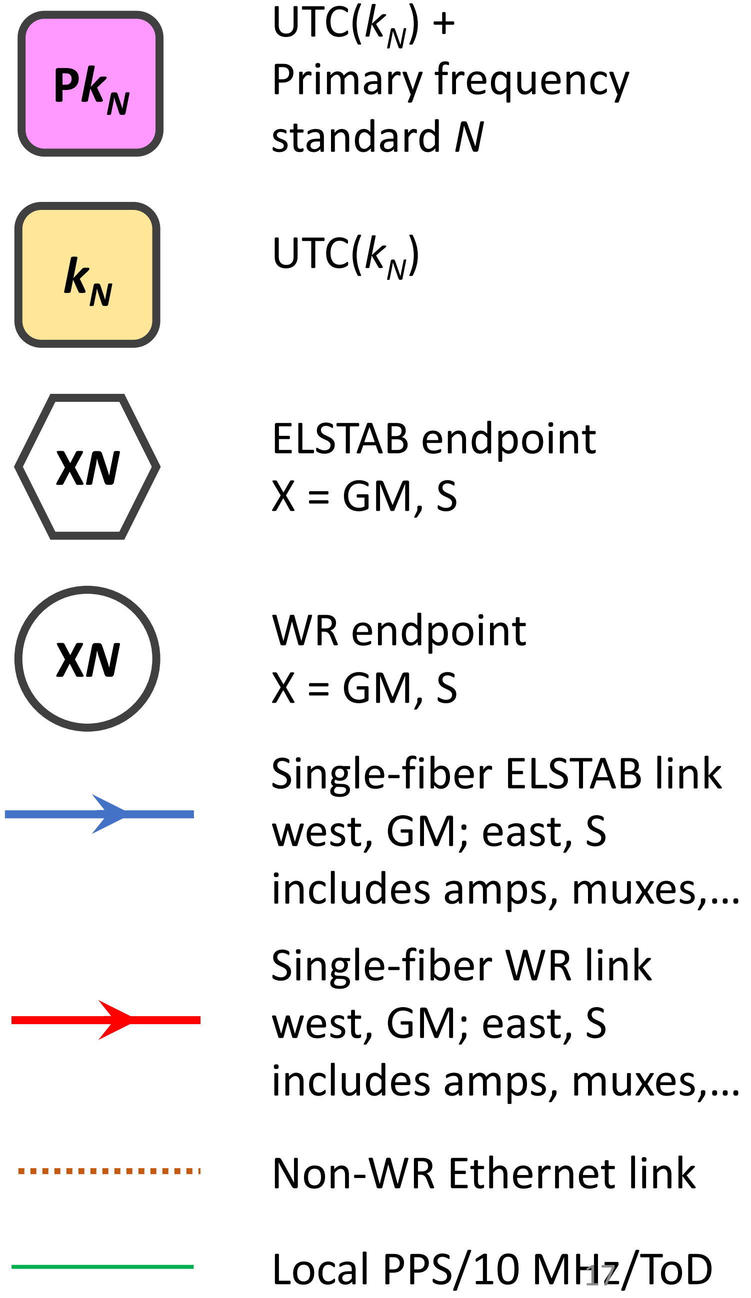
- Design philosophy: leverage network/path redundancy to guarantee continuity and resilience
  - Continuity and resilience limited by weakest link in the chain: let the T&F links be the strongest links in the chain
  - If T&F links fail-safe, then uptime of T&F service becomes (shared) responsibility of NMIs (as it should?)
- Span of control and responsibility of NMIs limited to their own domain (as much as possible)
  - Avoid (or minimize) prevalence of certain UTC(*k*) or frequency reference signals in the network



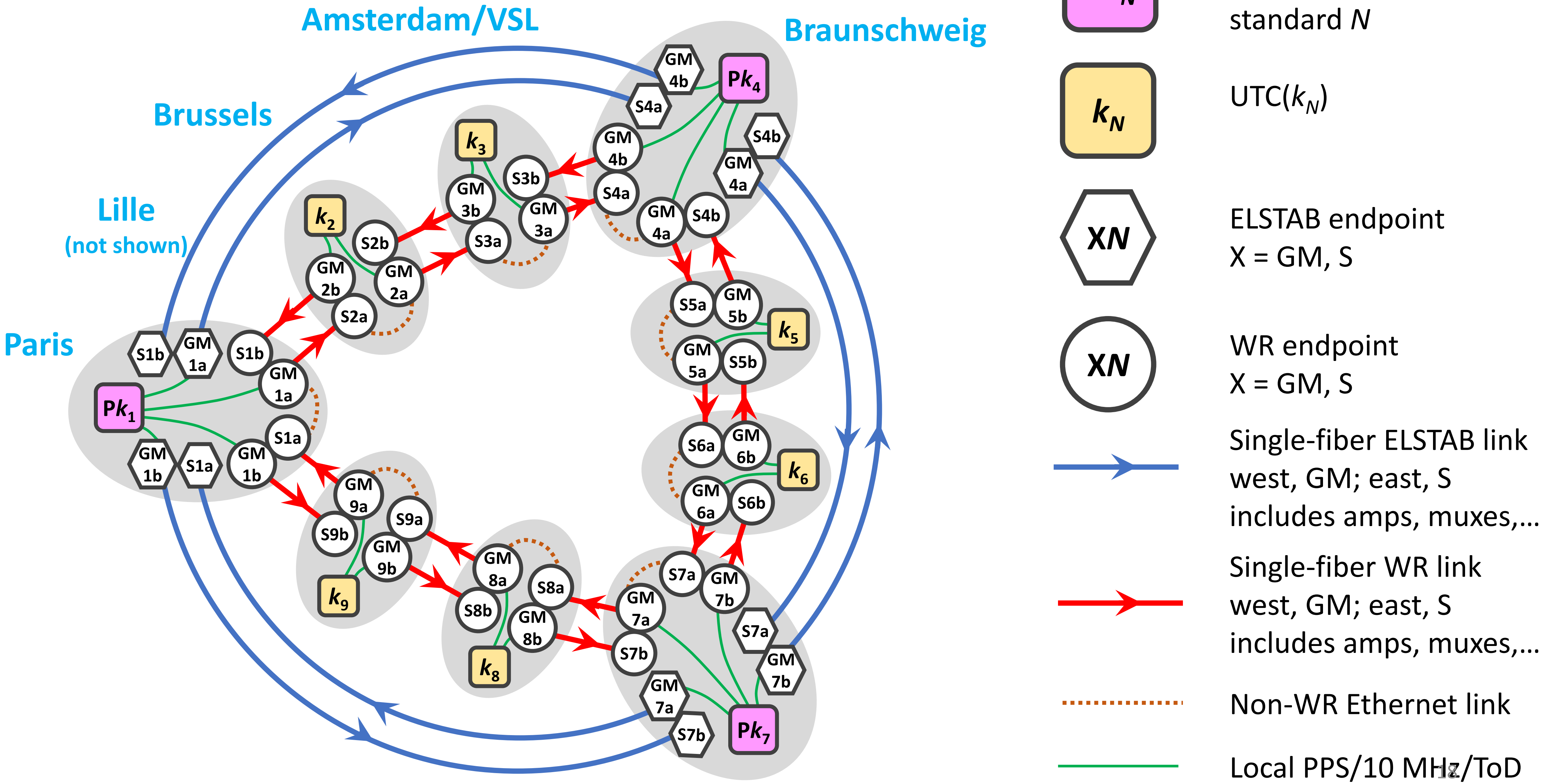
C-TFN time network topology

Signals ELSTAB (a) and WR (a) travel through the same fiber. Likewise for ELSTAB (b) and WR (b)



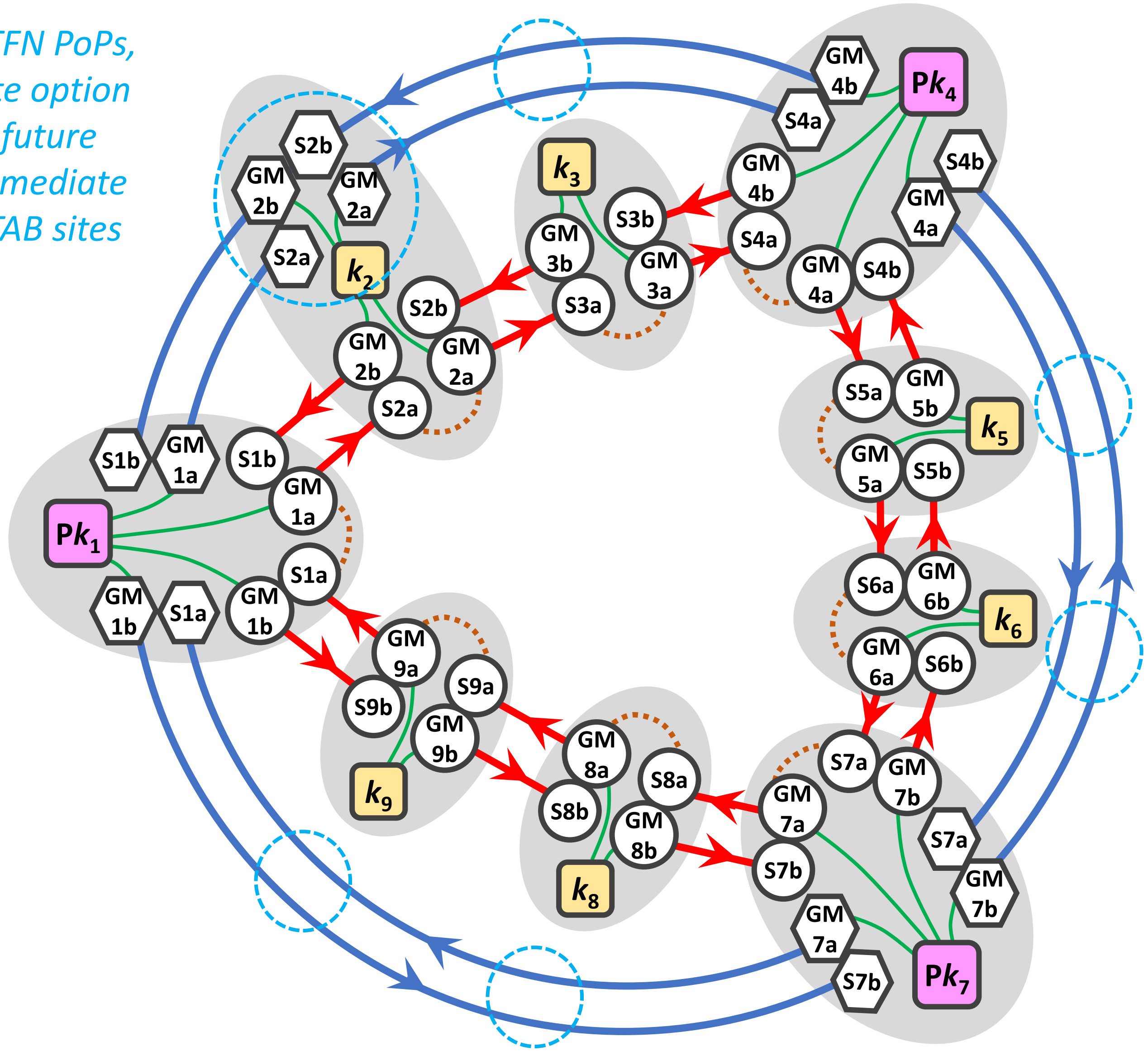


C-TFN time network topology



C-TFN time network topology

At C-TFN PoPs, create option for future intermediate ELSTAB sites



Pk$_N$ — UTC(k_N) + Primary frequency standard N

k_N — UTC(k_N)

XN — ELSTAB endpoint X = GM, S

XN — WR endpoint X = GM, S

Single-fiber ELSTAB link west, GM; east, S includes amps, muxes,…

Single-fiber WR link west, GM; east, S includes amps, muxes,…

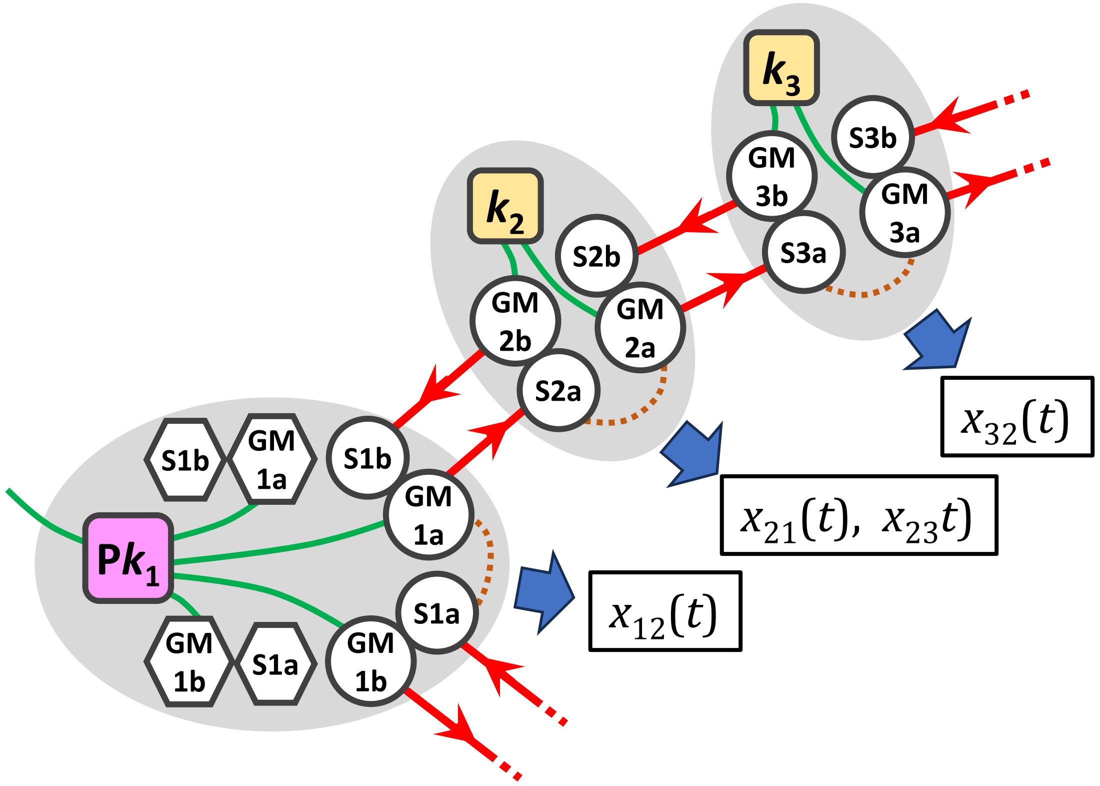
Non-WR Ethernet link

Local PPS/10 MHz/ToD

Time network considerations

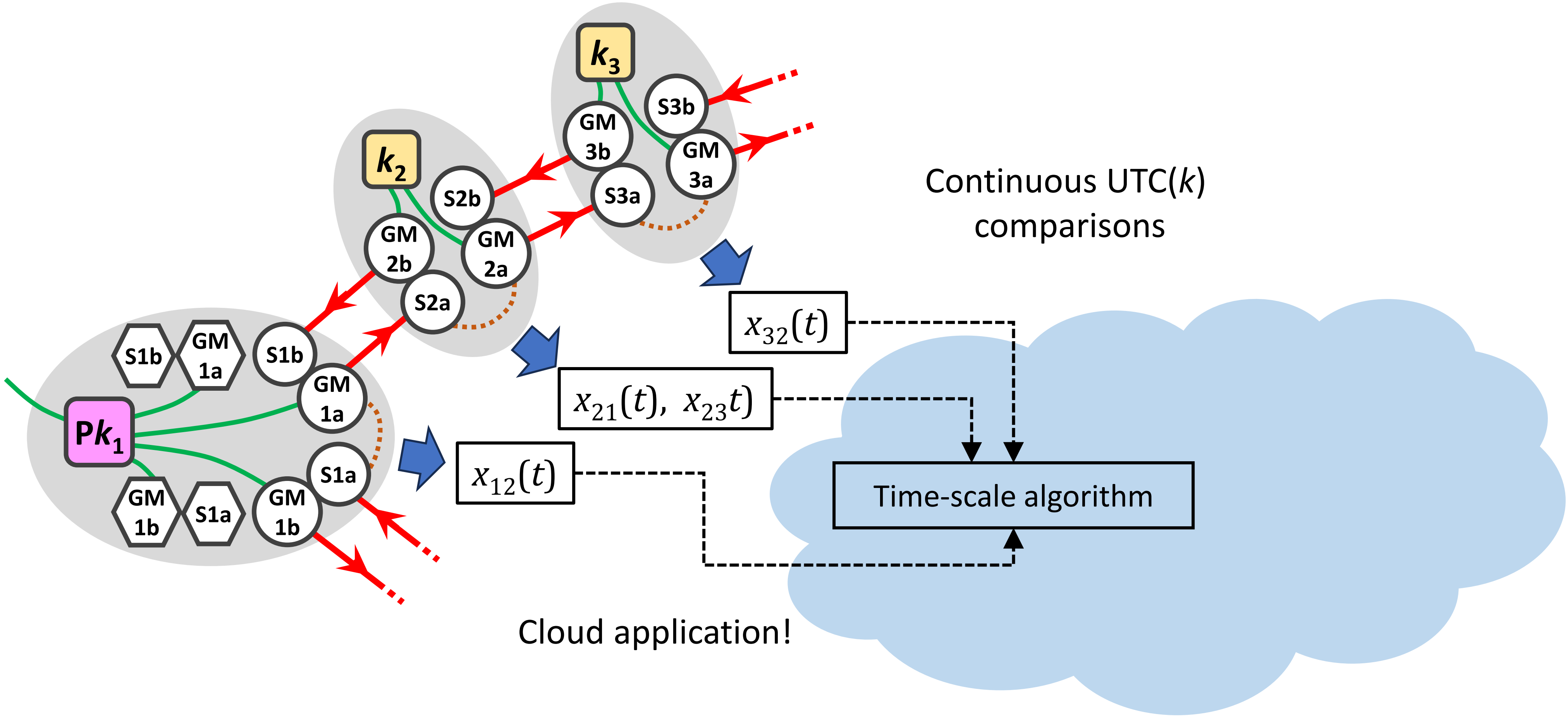
1. Purpose: strictly for comparisons, i.e. there is no physical ‘grandmaster network time’
   1. Only distinction made is between UTC(*k*) sites with and without primary frequency standards
   2. Any ubiquitous time scale is virtual (cf. paper time scale), with physical realizations generated only locally by designated laboratories
2. Sites with primary frequency standards directly compared via high-stability, high-accuracy ELSTAB system
   1. High stability and accuracy for an optimal connection between TAI and SI second (future: ultrastable optical frequency links and SI second based on optical clocks)
   2. ELSTAB sites form high-accuracy pivot points to assess ‘end-to-end’ (or rather pivot-to-pivot) accuracy and stability of WR links (and other TF transfer methods, including satellite)
3. Redundant fiber pairs with opposite ELSTAB time flows:
   1. If connected to at least two neighbors under nominal conditions, at least one connection to neighbor remains available in case of a fiber break
   2. Two-way monitoring of link performance & determination of ‘east-west’ Sagnac delay (practically zero enclosed area)
4. Nearest-neighbor comparisons via WR
5. Redundant fiber pairs with opposite WR time flows:
   1. Redundancy: a given UTC(*k*) site will be connected to at least one neighbor in case of fiber break, and to at least two neighbors
   2. Two-way monitoring of link performance & determination of delay asymmetry (e.g. Sagnac delay)
6. Segmented GM-S WR links may be networked together via local non-WR Ethernet links

Network time scale based on a clock ensemble



Continuous UTC(k) comparisons

Network time scale based on a clock ensemble



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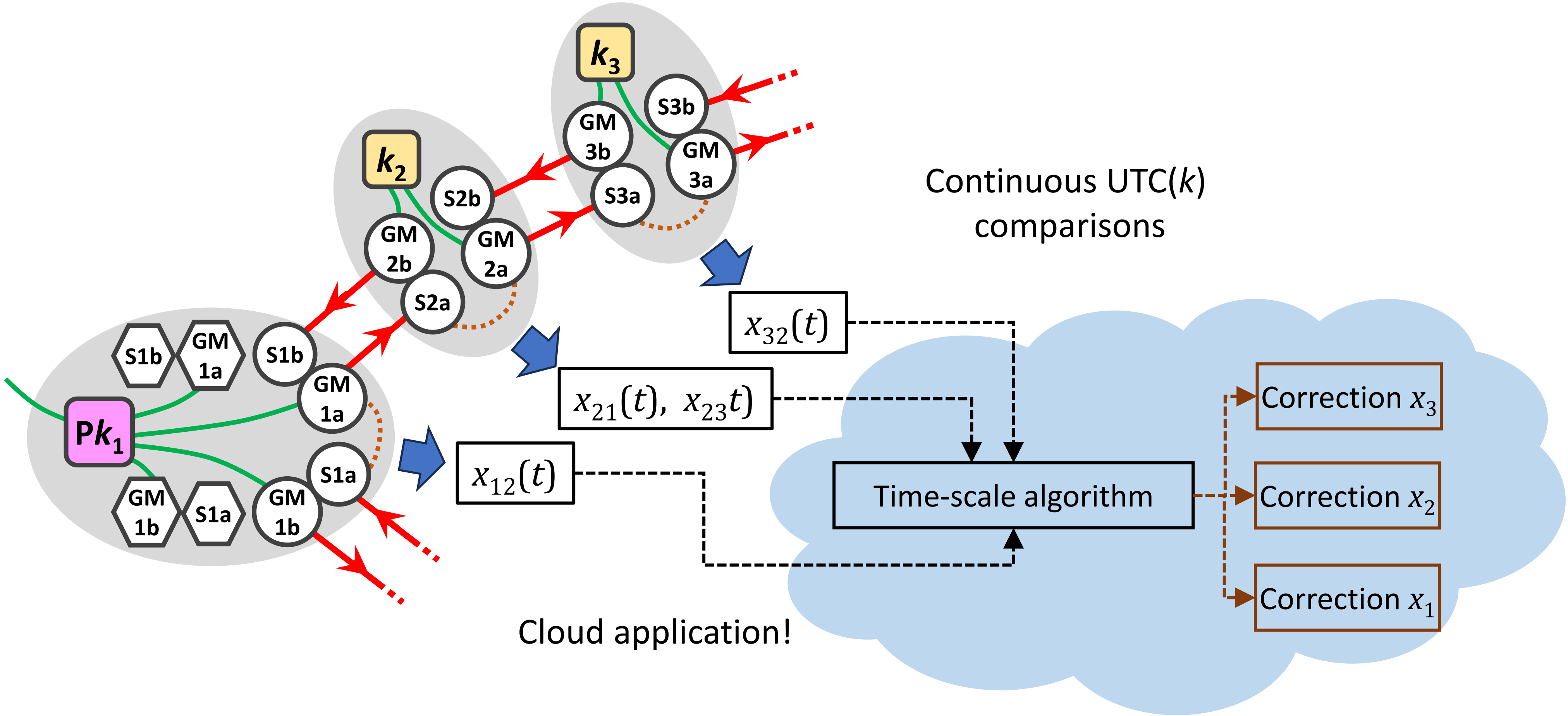

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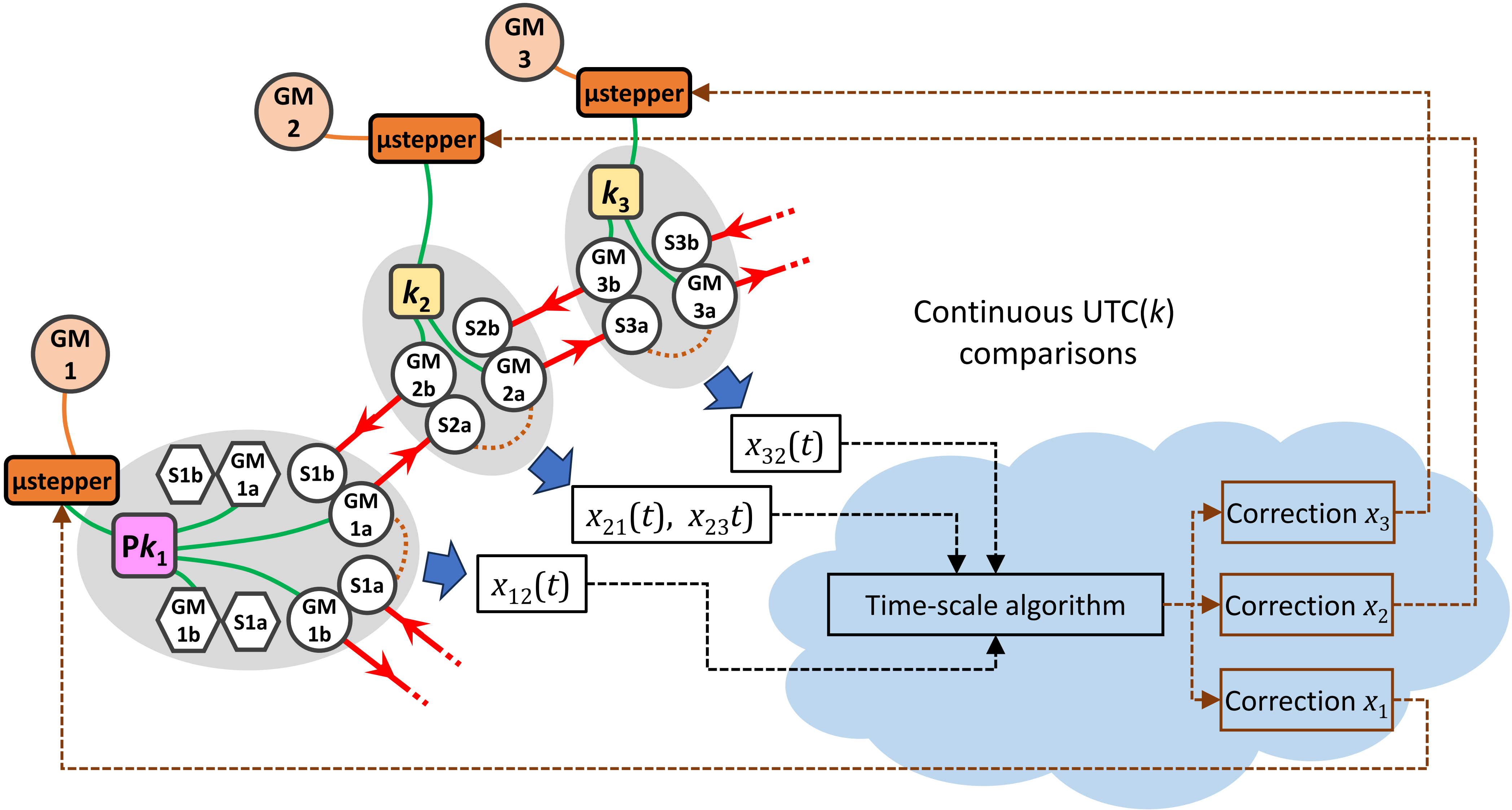
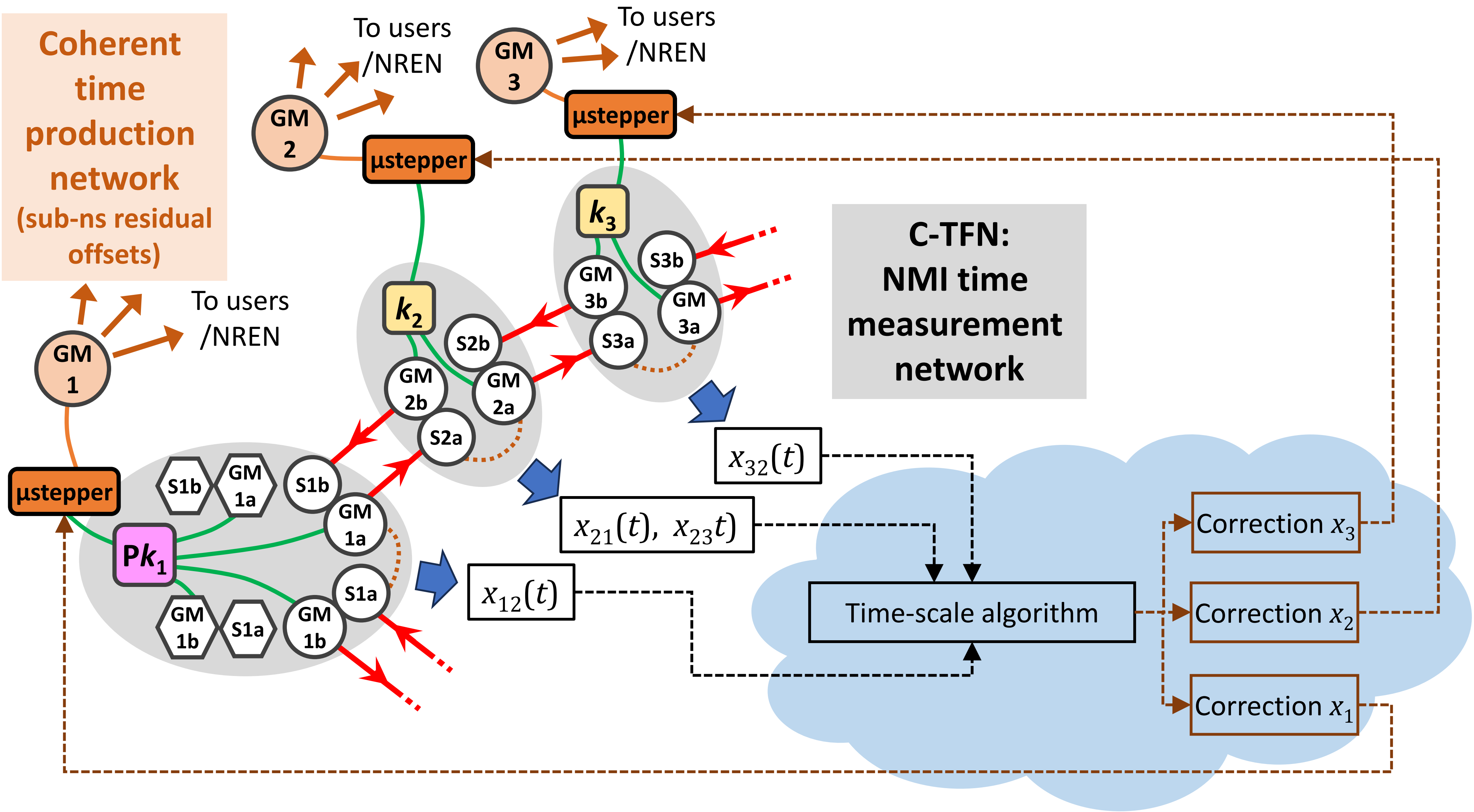


Network time scale based on a clock ensemble



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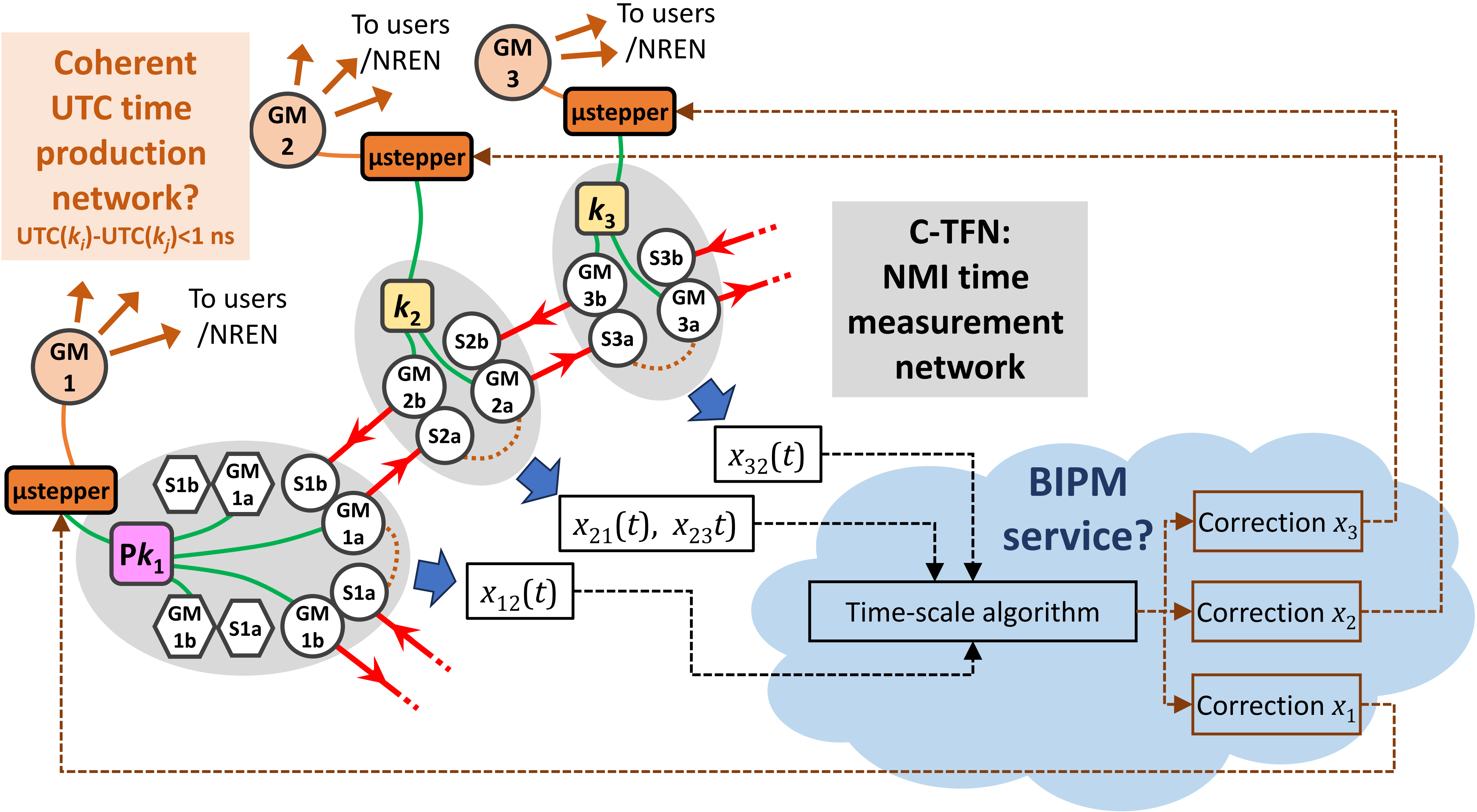
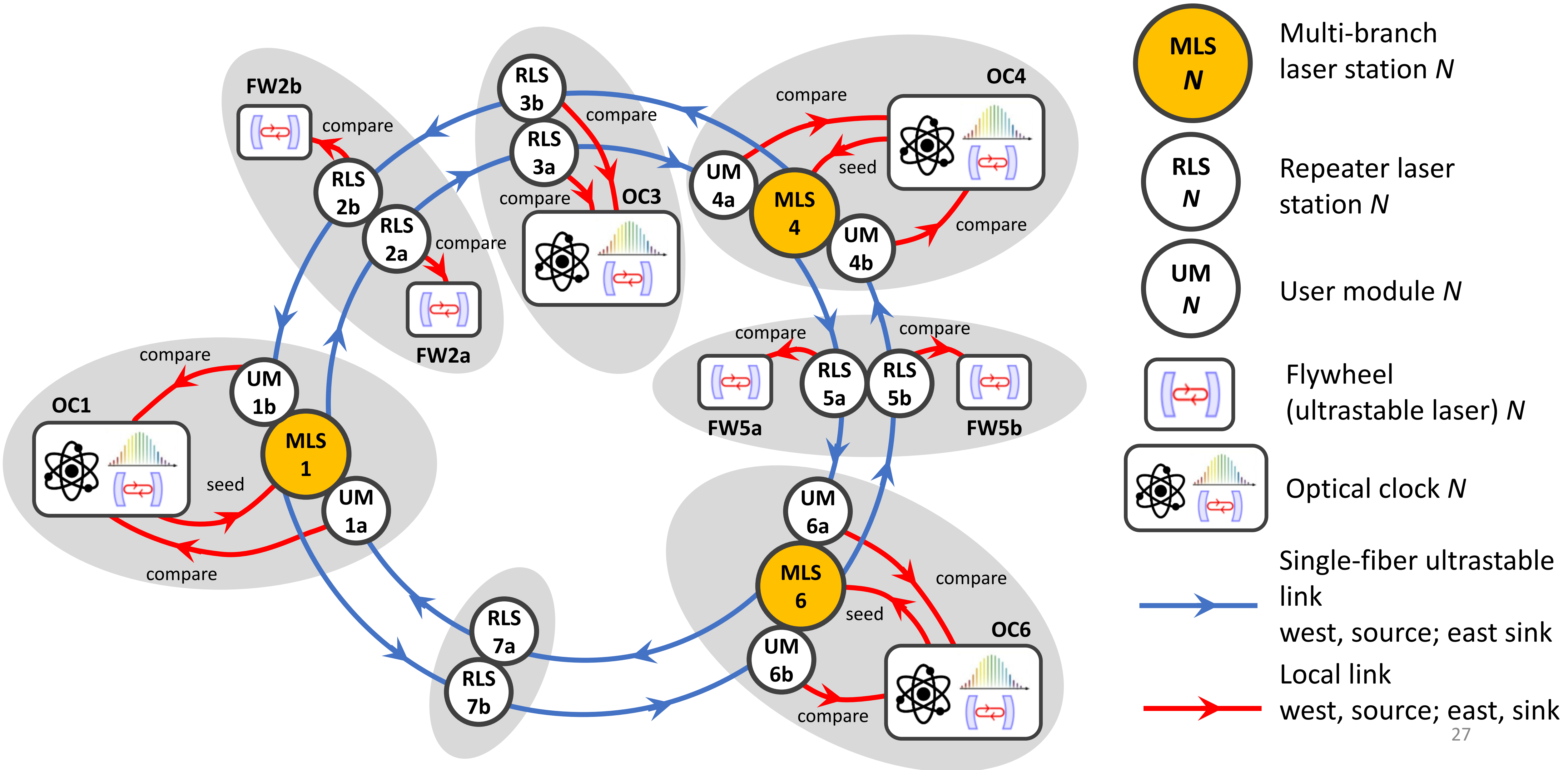


Optical frequency network topology

assumption: Exail equipment



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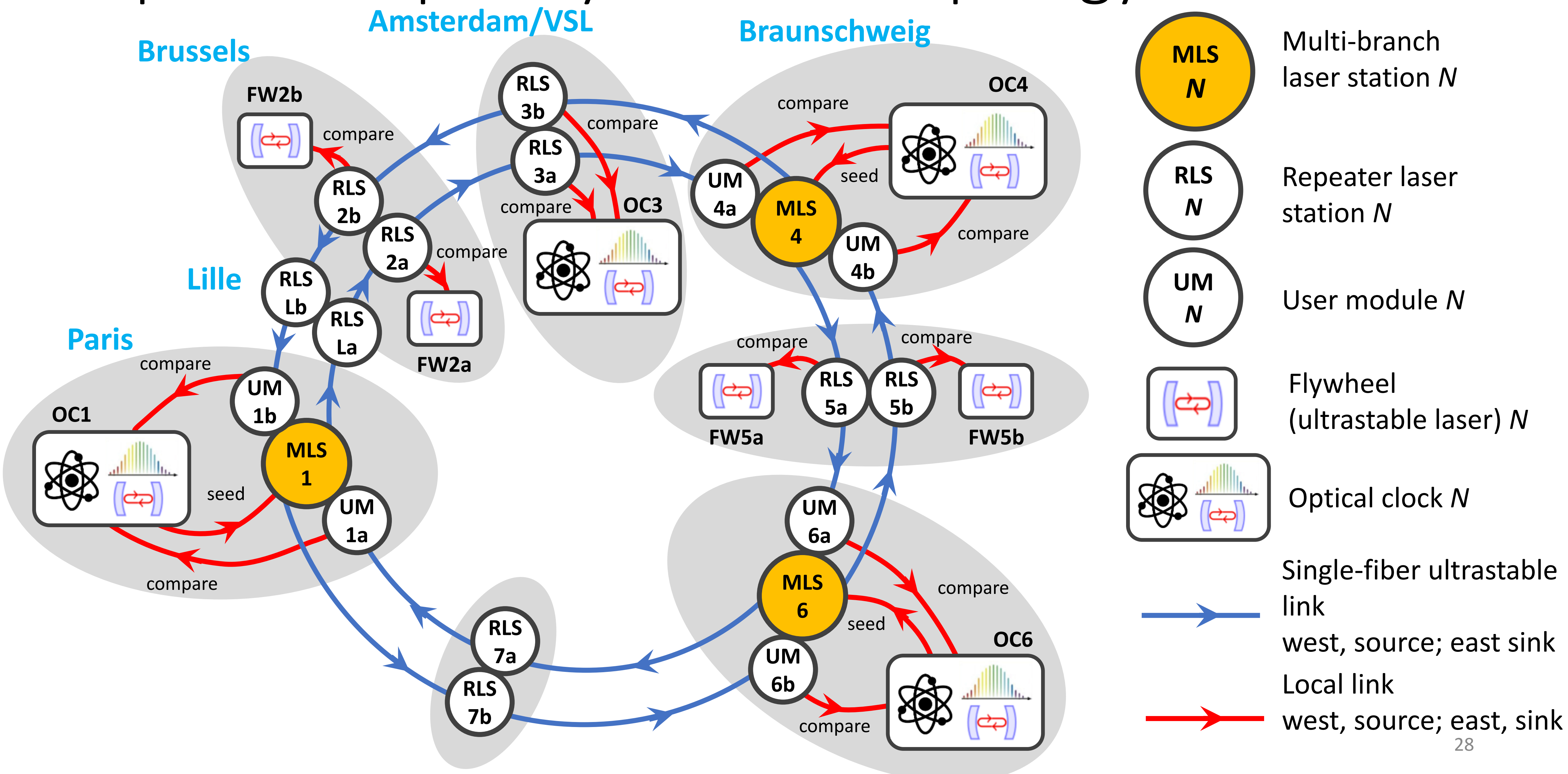
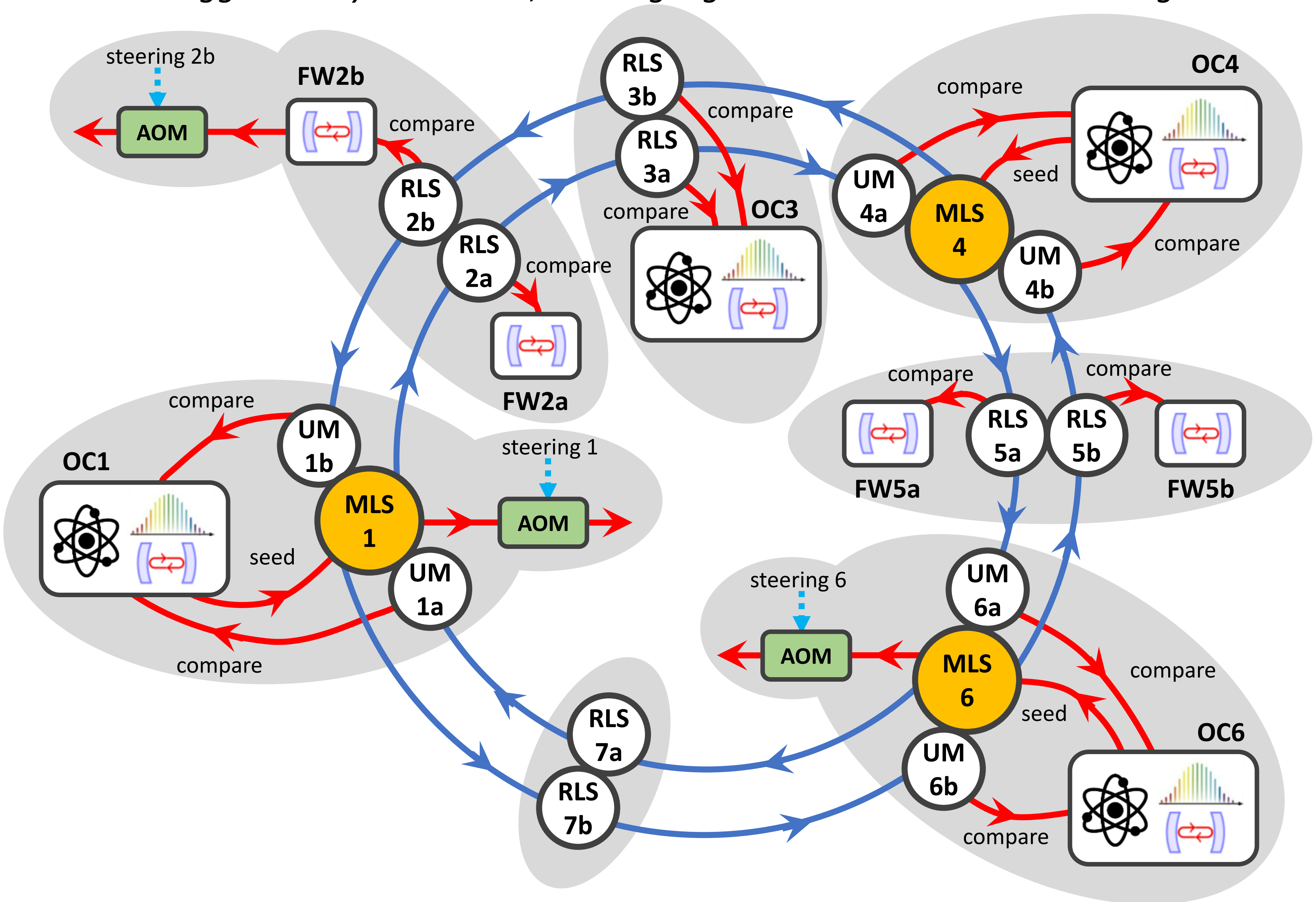
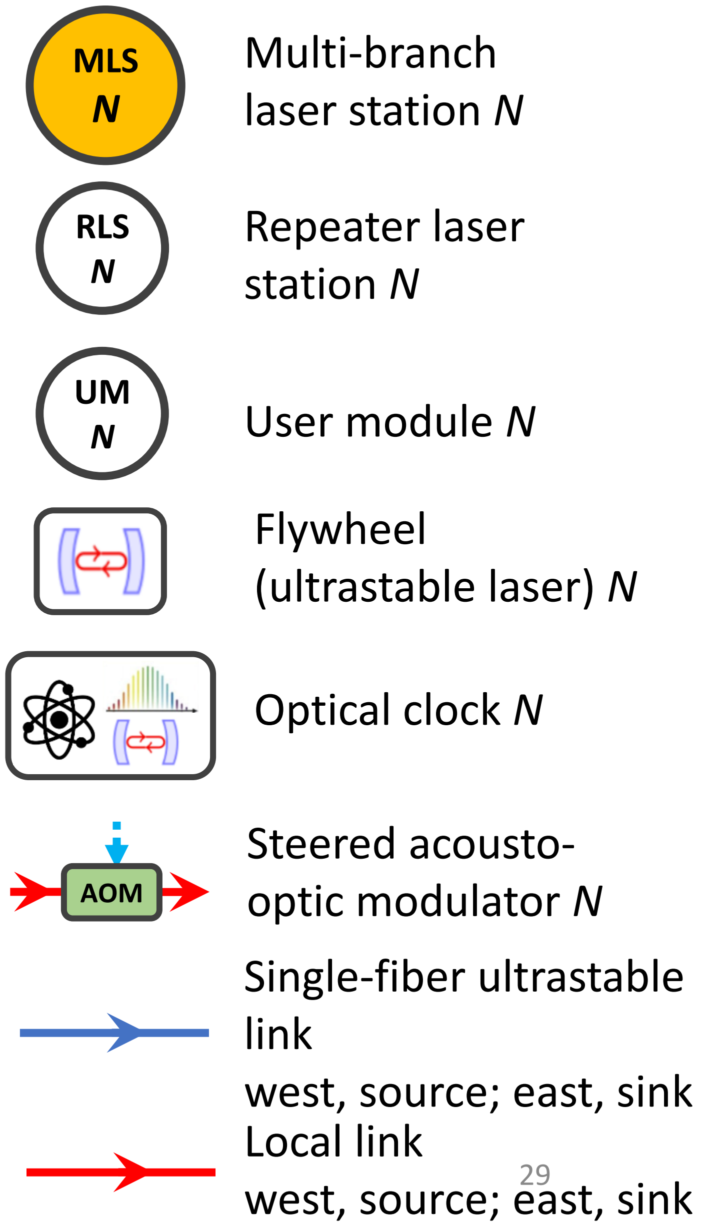


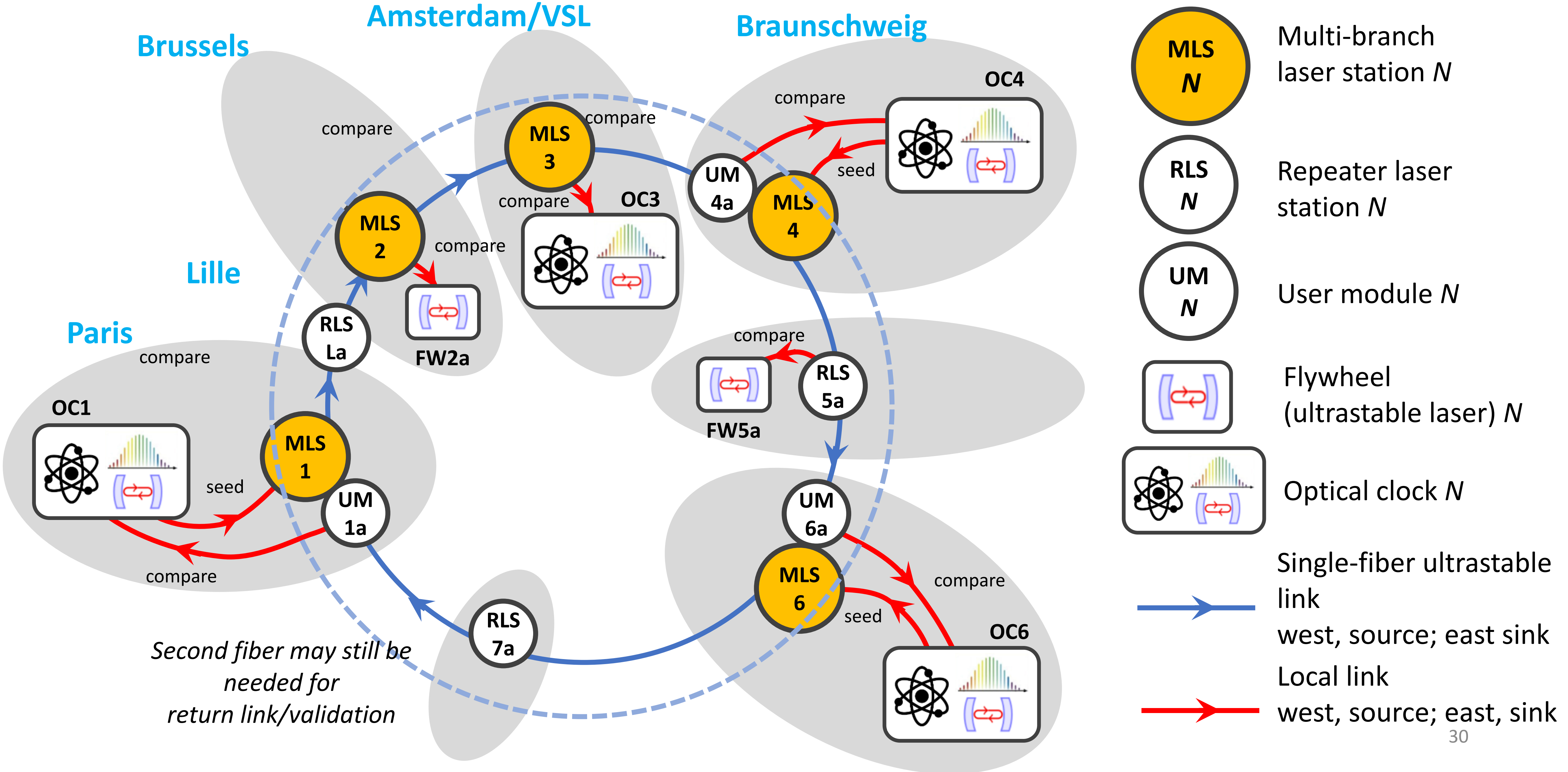
Optical frequency network topology w/ steering

Suggestion by P.-E. Pottie; steering algorithm similar to time scale algorithm





Optical frequency network topology w/o redundancy



Frequency network considerations

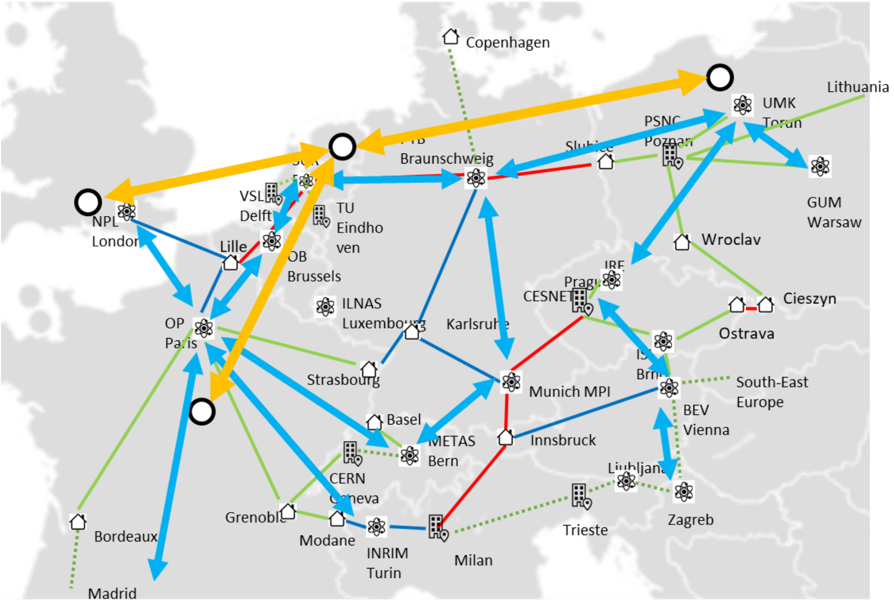
1. Purpose: strictly for comparisons, i.e. there is no ubiquitous ‘reference frequency’
    1. Distinction between sites with optical atomic clock (OC) with or without MLS, and flywheel ultrastable laser
    2. Should meet requirements for comparisons for redefinition of SI second
    3. Any ubiquitous reference frequency would virtual (cf. paper time scale), with physical realizations generated only locally by designated laboratories
    4. Concept of virtual or ‘paper’ reference frequency does not yet exist, but would technically be feasible
2. Redundant fiber pairs with opposite frequency flows:
    1. Needed at all during first phase of C-TFN?
    2. If connected to at least two OCs under nominal conditions, at least one connection to OC available in case of fiber break
    3. To-way monitoring of link performance
    4. Practically zero enclosed area, so practically no Sagnac frequency noise (except for negligible(??) nonreciprocal noise due to east-west relative delay asymmetry of order 10^{-6})
3. If closed loop, Sagnac phase could be determined by differencing cumulative phases in clockwise and counter-clockwise directions
4. Without AOM steering: flywheel sites could use post-correction data to maintain traceability to SI second of neighboring OC
5. With AOM steering:
    1. Frequency-lock to neighboring MLS (and effectively copy SI second realization from typically a different nation in real time)
    2. Or use AOM for steering to virtual reference frequency/virtual SI second
6. OC sites can also use AOM steering to produce virtual SI second

Transparent virtual T&F links for applications

- Network design with emphasis on sovereignty and national responsibility of NMIs
  - Realization of TAI/UTC and of the SI second
  - Traceability of TAI to SI second
- Network designed for clock comparisons, not for a ‘European time dissemination’ network

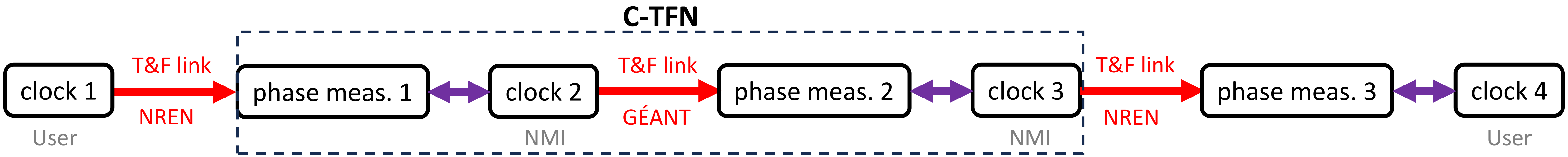
But what if an application requires a cross-border time link to non-NMI locations?

- Example: radio astronomy stations (LOFAR, VLBI)

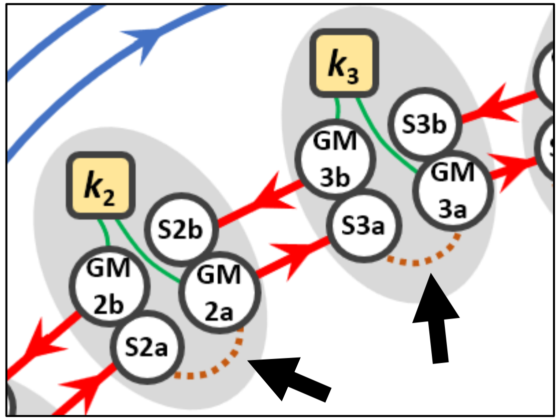


Transparent virtual end-to-end T&F links

- Ideally, C-TFN should enable ‘transparent’ links, either physically or virtually, enabling direct phase/time comparisons between clocks located in different member states

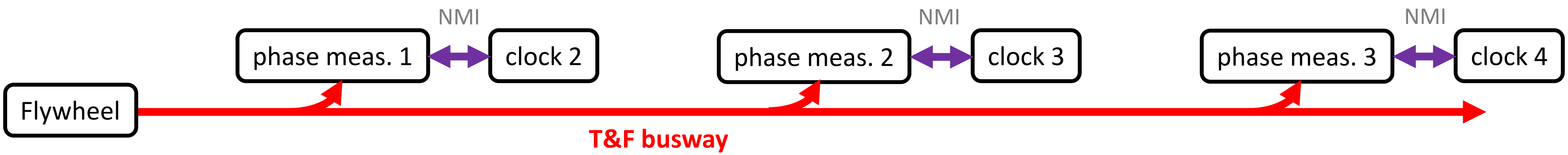


- Virtual link: total phase difference = ∑ measured phase differences
- Implies the need for phase comparisons at any location where a segment of C-TFN terminates, and a new segment starts
- Implies **need for quasi-real-time cloud application for T&F data**
- In WR, such phase comparisons can be made with picosecond resolution via the **inactive WR links**:



Additional 'T&F busway'? cf. 'Eavesdropping' method G. Grosche/PTB

- Idea: transmit a flywheel signal to all locations in the network ('T&F busway')



- One (or a few) institute(s) would be responsible for the flywheel, but strongly relaxed requirements on uptime and traceability to UTC or SI second (only stability required)
- NMIs compare their clocks locally against busway signal. Hypothetical(!) future example scenario:
  - NMI reports to BIPM the difference $x_{\text{NMI}} - x_{\text{busway}}$
  - BIPM computes and publishes x_{busway} – UTC
- Avoid accumulation of phase measurement noise in virtual links
- Could operate in parallel with dedicated, segmented 'nearest neighbor' network
  - No critical dependence on T&F busway
  - Stability improvement?
  - Busway could also be fed into NRENs or other networks for non-critical applications

C-TFN → C-PNT ?


European Commission

An Assessment of the Future EU Complementary Position Navigation Time (C-PNT) Ecosystem

Public Edition
Release 1.0 (March 2024)

Bonenberg, L., Motella, B., Paonni, M., Fortuny Guasch, J.

→ See also talk by L. Bonenberg

System of systems scenario: A market-driven system of systems approach, with the EC responsible for regulations. This scenario uses a mix of PNT infrastructures, leading to a resilient and continuous PNT provision.

> Within the proposed "**system of systems**", the non-GNSS components would be best referred to as **Complementary (Continuous) PNT (C-PNT)**, given their objective to provide resilience, extend PNT to specific environments that cannot be served by GNSS, and act as limited spatial and temporal backup supporting existing infrastructure.

C-TFN could conceivably form a T&F backbone for C-PNT services

Credits

- GÉANT SIG-TFN project lead
- Dutch SIG-TFN team:
  - Sander Klemann, Paul Klop (SURF)
  - Erik Dierikx (VSL)
- Very helpful discussions with:
  - SIG-TFN members
  - Florian Schreck, Klaasjan van Druten, Sumit Sarkar (University of Amsterdam)
  - Rodrigo Gonzalez Escudero, Sougandh Kannoth Mavila (VU Amsterdam)
  - Marc Weiss (former NIST, independent consultant)
  - WR Collaboration & community members
  - Exail Bordeaux team
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Thank you!

j.c.j.koelemeij@vu.nl