30-03-2023

Deliverable D2.1
Technical Design Report

Deliverable D2.3

Contractual Date:	01-10-2020
Actual Date:	03-08-2022
Grant Agreement No.:	951886
Work Package	WP2
Task Item:	Task 2.1
Nature of Milestone:	R (Report)
Dissemination Level:	PU (Public)
Lead Partner:	PTB
Document ID:	CLONETS-M30-008

Authors:	P-E. Pottie (OBSPM), P. Krehlik (AGH), Ł. Śliwczyński (AGH), T. Liebisch (PTB), H. Schnatz (PTB)

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 951886 (CLONETS-DS).

Abstract

This document summarises a technical design for an international core fibre network for providing high-performance time and frequency signals to diverse stakeholders at defined core sites, in order to satisfy the identified needs of the science community.

Table of Contents

Table of Figures

Table of Tables

Executive Summary

This document sets out a first version of a Time-and-Frequency (T&F) architecture for a European network to support the high-level science cases (SC) analysed and defined in WP1.

To do this, WP2 has:

- **Developed a first vision of an architecture** that considers the users of SCs and related PoPs (with WP1).
- **Defined four types of services to be provided by the network**, including Relative Frequency, Relative Timing, Absolute Frequency, and Absolute Timing.
- **Identified necessary functionalities as building blocks for the hardware of the network:** For each hardware block, an estimation was prepared for their TRL level and their "best performance level" and methods, tools, and procedures for monitoring, supervision and maintenance proposed.
- **Derived a generalised topological structure** for the technical design of an European core network (ECN).
- **Discussed and developed an engineering model for the hardware building blocks** identified to facilitate time and frequency measurements at the highest level and allow transfers from one national implementation to another without loss of performance, thus assuring interoperability at a European level.
- **Proposed a ring infrastructure** consisting of several regional links including the identification of existing infrastructure and missing links.
- **Identified existing national implementations and fibre infrastructure** available from GÉANT or NRENs, **as well as missing connectivity** between PoPs and user sites.

This deliverable is based on input from WP1 and provides input for task D2.2 as well as WP3.

1 Introduction

The objectives of WP2 are to:

- Define an architecture that supports T&F services at the highest, most advanced level of stability and accuracy, without interdependencies between either providers or users, to allow parallel use by different scientific communities and multiple users at the same time.
- Design an engineering model as well as a deployment strategy that assures interoperability of already existing implementations at the European level and possible future extensions.
- Create a Data Management Plan to ensure that all envisioned users profit from a common data platform in an appropriate way.

To address these objectives, the WP has been divided into several tasks and subtasks.

All partners except TUM and UB have contributed to the tasks. The WP is led by PTB, the responsible task leaders are CNRS for Task 2.1, AGH for Task 2.2, and PTB for Task 2.3.

In the context of this report, we address only the activities of Task 2.1, which deliver input for Task 2.2.

Work package number	WP2										**Lead beneficiary**					**PTB**		
Work package title	Technical Design																	
Participant number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Short name of participant	GÉANT	PSNC	PTB	CNRS	INRIM	CESNET	Menlo	ISI	UGR	7Sol	TUM	U Bonn	PIKTIME	AGH	UP13	RENATER	UCL	MUQUANS
Person months per participant:	5	12	8	18	8	4,8	5	1	8	8	0	0	1,5	6	2	2	3	8
Start month	M3											**End month**				M24		

Table 1: Overview of the contributing partners to Work Package 2.

1.1 Description of Work

This report comprises the work on **Task 2.1: Drafting architecture of the system** (led by CNRS) and its subtasks:

- Subtask 2.1.1: Drafting technical designs, for a time and frequency reference system at the technical level
- Subtask 2.1.2: Definition of core sites

1.2 Relation to other Tasks

Work Package 1 has analysed high-level scientific cases which meet the characteristics of time-and-frequency (T&F) use-cases that would greatly benefit from access to a T&F reference system via a research infrastructure, assessed the needs of the respective science cases and general user requirements, and identified user locations.

Furthermore, WP1 defined four types of T&F-Services to be provided by the proposed fibre network, which would serve as a research infrastructure to meet the specific needs of the scientific community.

Based on the findings of WP1, Task 2.1 has developed an engineering system with a functional analysis and a Work Breakdown Structure (WBS). Based on this WBS, we focused on the technical realisation of a T&F reference system as a research infrastructure, which fulfils the requirements derived from WP1.

Covering all related technical aspects, the system architecture developed in WP2 considers hardware and conceptual factors and cooperation with national networks, as well as the processing and analysis of data provided by the system.

The system design developed in this Task (2.1) feeds the design of the engineering model assuring interoperability of already existing national T&F implementations at the European level and possible future extensions wherever possible, as well as deployment strategy (**Task 2.2)**.

2 Drafting Technical Designs (Subtask 2.1.1)

The goal of this subtask is to design an architecture at the technical level for a time and frequency reference system based on an optical fibre network. The aspiration of CLONETS-DS is that this network should extend across Europe and serve as a European Research Infrastructure, thus hereinafter we refer to this network architecture as the European Core Network (ECN).

The function of the network is to provide users with reference time and frequency signals. It can be represented as shown in the diagram in Figure 1.

Signal sources are related to time and frequency standards. Signal sources fed into fibres are propagated over a fibre network. Phase perturbations and propagation delays are compensated. Reference signals are delivered to users.

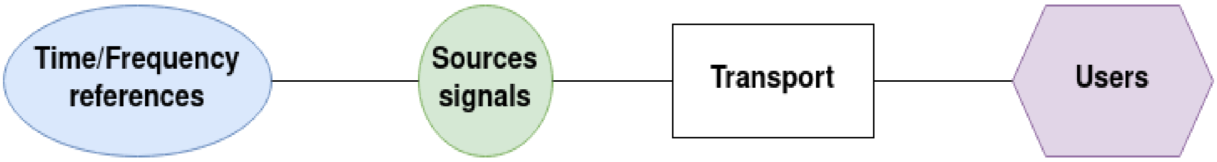

Figure 1: Breakdown of the functionalities of the proposed infrastructure.

A major design constraint is that the network has to be expandable and interoperable. Indeed, based on input from Work Package 3, the scenario we worked on considers that the European research infrastructure relies on existing national networks and provides Trans-National Access (TNA).

As for the association of NRENs in GÉANT, this network model allows for users to be connected to the ECN directly, or indirectly through their national network. Consequently, the design enables TNA for (EU) researchers to a time & frequency reference system implemented by the EU.

From an engineering point of view, one design constraint is that the network has to be interoperable. This is an important design choice, to enable several techniques for distributing T&F signals to co-exist at a given time and to enable future upgrade of the network.

It is also an essential for the design to enable the network to be integrable and expandable to higher, identical and lower levels of integration as indicated in Figure 2. It is therefore highly desirable for national networks to also be expandable to lower levels (from national to regional levels for instance). This feature is also essential for increasing the number of users of the global network via interconnections between networks, while tailoring the operational expenditures to best fit user needs.

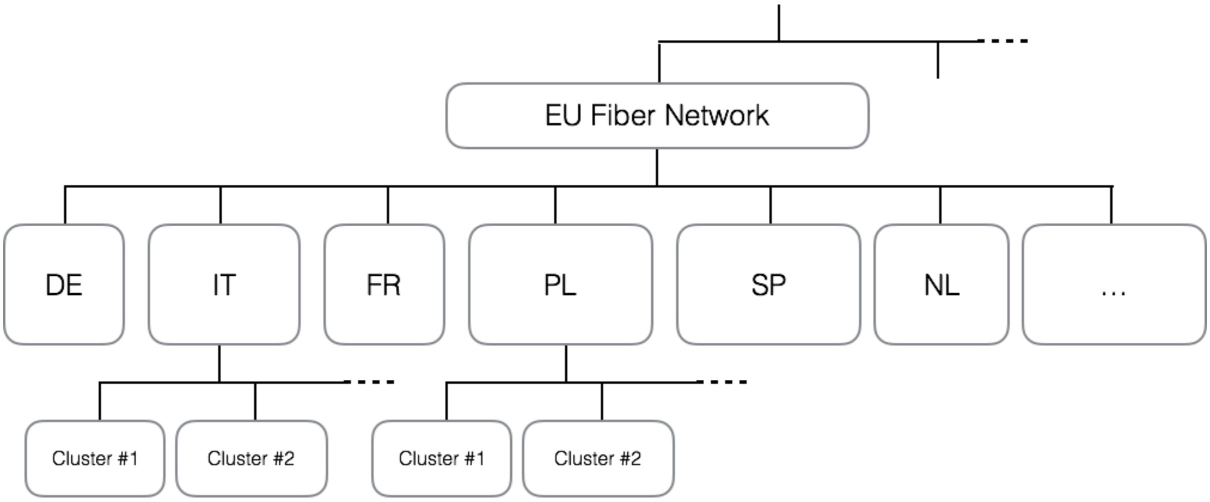

Figure 2: Basic principle of an expandable network via integration. The text in box refers to national implementations (DE: Germany. IT: Italy. FR: France. PL: Poland. SP: Spain. NL: The Netherlands. etc...). It is clear that a network in the UK or Switzerland, formally outside the European Union, must also be connected to the EU network. *Cluster* refers to a cluster of users, possibly a regional/local network below the national level. For instance, the sub-network of REFIMEVE at the university Paris-Saclay in France.

In summary, the system design target is to support T&F services between national networks at the highest, most advanced level of stability and accuracy for the science cases identified in WP1.

We use the requirements and service definitions drawn up by WP1 as input to arrive at the technical system design that fulfills the needs of the science community. More specifically, based on the input from WP1, WP2:

- Identified high-level principles for the infrastructure to address all relevant high-level parameters e. g. topology, physical principles, capacity for parallel use.
- Identified technical solutions for translating these principles into actual hardware and addressing operational parameters such as quality of service, availability, reliability, etc.
- Performed a gap analysis of hardware solutions already available and their respective TRL.
- Proposed methods, tools, and procedures for monitoring, supervising and maintaining the T&F reference system.

The overall system design consists of a European Core Network (ECN) for the precision-distributed T&F-reference to fulfil the needs identified in WP1 to enable parallel use by different scientific communities and multiple users at the same time.

2.1.1 Drafting Technical Background

In subtask 2.1.1 we have developed a first vision of an architecture that supports the highest-level science cases (SC) identified in WP1 and ensures parallel use by different scientific communities and multiple users at the same time.

As a result of intensive discussions with stakeholders and members of WP1, we have identified four types of service, as shown in Figure 3, -leading to two types of requirements:

- For timing and frequency signals
- With respect to absolute (traceable) and relative signals

Deliverable *D1.2 Requirements and Definition* details which service each science case application requires.

For *relative* signals, the measurements between users can be performed in such a way that the signals provided by the network are considered as transfer signals that drop out of any measurement between two users. In contrast to the relative measurements, traceability to the SI-unit of the signals provided by the planned European core network (ECN) is mandatory for any *absolute* measurement performed by users. This traceability is assured by referring the signals to at least one NMI or UTC(k) laboratory. Thus, the network must provide to the user not only signals but also data on the received signal that:

1. Provide timestamps and/or information on the external frequency reference.
2. Provide confirmation of the signal origin for purposes of traceability.

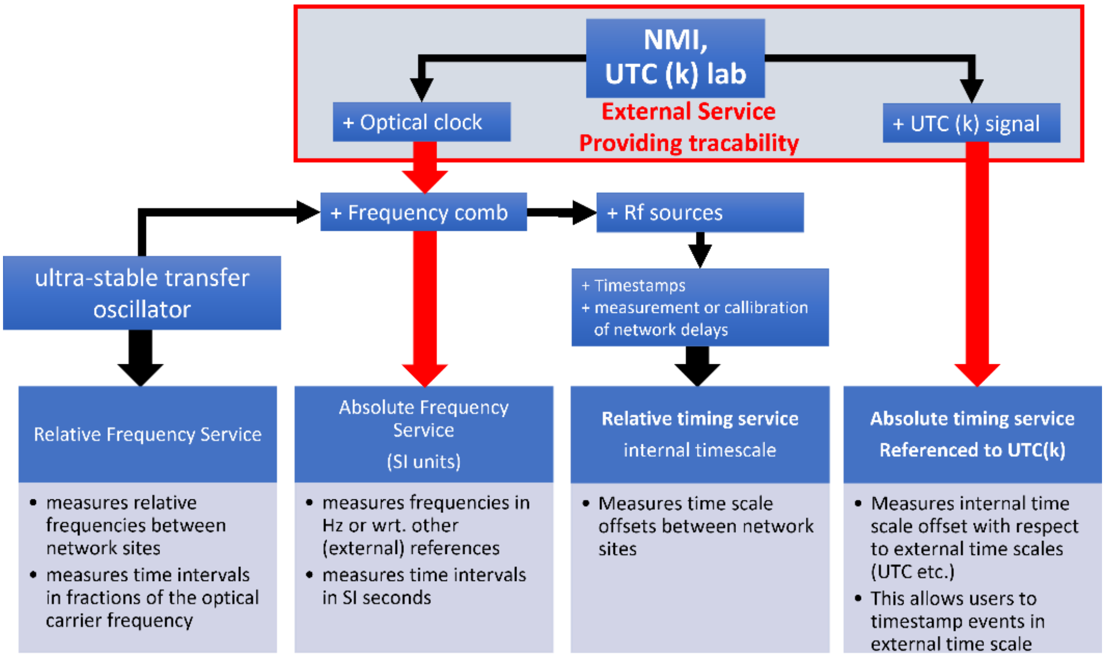

Figure 3: Services provided by the envisioned core network.

Which of the four types of services is needed depends on the specific user application. Thus, the ECN has to provide all of the previously described types of services, and each service respectively has specific network hardware requirements.

Generally, the network hardware requirements increase for each service, left to right as shown in Figure 3. In that sense the relative frequency service can be considered the most basic and primary layer of the network. The hardware solutions and associated technical details required by the ECN at each network layer to provide these four services are discussed in more detail in section 2.1.5. In this section, we outline all the basic signals required by the ECN to provide the four services shown in Figure 3.

A ***relative frequency service*** requires at a minimum that the ECN generates and distributes the optical frequency of ultra-stable transfer oscillators, and a reference frequency in the RF domain where the frequency or path length fluctuations of the fibre connection between any two ECN PoPs is actively compensated.

An ***absolute frequency service*** requires that the ECN provides interfaces with at least one National Metrology Institute (NMI) that provides traceability to the SI-second. The NMI interfaces establish traceability in the ECN by referencing the ultra-stable transfer oscillator of the ECN to either a primary Cs- fountain clock or an optical frequency standard (optical clock) that is internationally recognised as a so-called Secondary Representation of the Second (SRS) by means of a frequency comb.

A ***relative timing service*** requires the ECN to generate and distribute network-internal timescales comprising RF-signals together with timestamps, and controls network delays between any two ECN-PoPs. The RF-signals of the network's internal timescale can be generated from low-noise RF sources (e.g. Rubidium clocks and Quartz oscillators at 100/10 MHz) that are referenced to the ECN ultra-stable transfer oscillator using a frequency comb as an optical frequency divider. Subsequently, using an RF-frequency divider one can generate the required timing signals. Both signals together with the information about the network delays will be available for users at any location of the ECN. From the ECN-generated stabilised RF, in addition to the timing signals distributed over the ECN, it is highly desirable to back-up each PoP of the network with GNSS stabilized RF sources for convenience.

Lastly, an ***absolute timing service*** requires that the ECN's network's internal timescale interfaces be measured with respect to the Coordinated Universal Time (UTC), as realised by an individual UTC timing centre (typically an NMI). The UTC(*k*) timing centres use their atomic clocks to realise a local time scale UTC(*k*). Thus, the task within the ECN is to provide the information regarding the offset between its internal timing signal and a UTC realisation in real time.

All these services need access to the data in real-time or via post-processing. Access to the data should also be provided to users themselves. Virtual Access (VA) to the infrastructure is therefore essential, in compliance with the Open Science policy of the EU.

Next, we discuss briefly the general concept for propagating signals within the network. This concept is based on so-called transfer oscillators [1], which act as flywheels and enable the transfer of signals from one building block to another without loss of performance.

For example, we consider the task of comparing the ν_1 and ν_2 frequencies of two lasers (this also applies to any other oscillators), with a frequency offset $\Delta\ (\nu_2 - \nu_1)$ that exceeds the bandwidth Δ of the left-sided photodiode (PD) or of a frequency counter as depicted in Figure 4. Details on the technical requirements for the photodiode and counter are given in section 2.1.5. In this case, the frequency offset Δ can be measured phase-coherently via a third laser (a so-called *transfer oscillator acting as flywheel*), with a ν_3 frequency lying somewhere in between ν_1 and ν_2, such that the frequency gap, Δ, is split into two smaller offsets Δ_1 and Δ_2. Measuring the offset frequencies Δ_1 and Δ_2 simultaneously is equivalent to measuring the frequency offset Δ. The result $\Delta_1 + \Delta_2$ is independent of the frequency fluctuations of the transfer oscillator. Furthermore, this measurement scheme takes advantage of the benefits of optical heterodyne detection, in which the weak signal (user frequencies ν_1 or ν_2) is mixed with the strong local oscillator (transfer oscillator ν_3) signal via detection on the PD. Thus, it is applicable to frequency comparisons across a network, where lasers 1 & 2 suffer significant loss of signal strength.

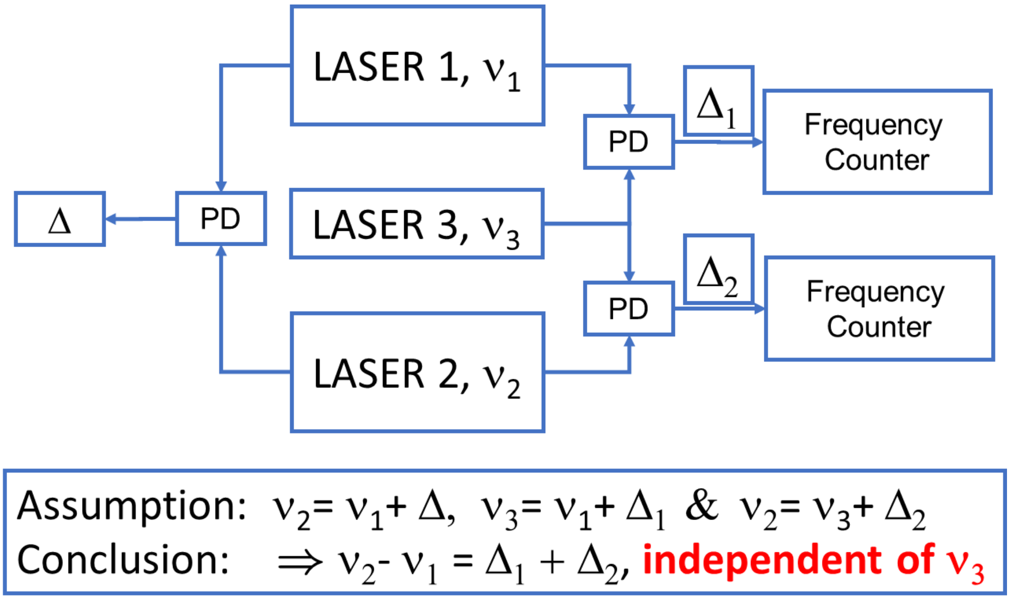

Figure 4: Basic principle of the transfer oscillator concept. Laser 3 acts as flywheel that bridges the frequency gap between laser 1 and 2. Simultaneous measurement of the frequency offsets Δ_1 and Δ_2 is equivalent to measuring the frequency offset Δ.

This basic principle of the transfer oscillator also holds for more complex situations where e. g. the transfer oscillator/laser is replaced by a full frequency comb, which enables the measurement of frequencies that are several 100 THz apart, or for concatenated systems along fibre links. We emphasise here that we envision the ECN to be based on this basic principle of the transfer oscillators acting as flywheels. Henceforth, the transfer oscillator will be referred to as internal oscillator, with frequency ν_{int} instead of ν_3. A typical set-up where the ultra-stable transfer oscillator would be exploited in one fibre segment of the ECN to make a measurement between the users at locations A, B and C is illustrated in Figure 5.

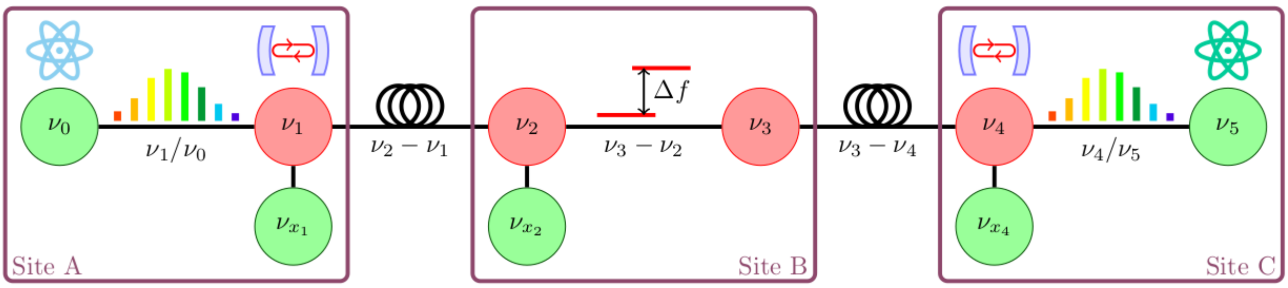

Figure 5: General procedure to compare oscillators across fibre links.

More generally, the comparison of oscillators, by fibre and by other means of time-and-frequency dissemination, is formalised in [2] and used by NMIs to compare microwave and optical clocks within comparison campaigns (see JRP ROCIT deliverables [3]).

For the basic ***relative frequency service***, as depicted in Figure 6 for the case of optical signals, it is necessary to measure the frequency difference between users' oscillators with frequencies ν_1 and ν_2, respectively, at the user locations A and B and the optical frequency ν_{int} of the ultra-stable transfer oscillator provided by the ECN. In a postprocessing step, any frequency fluctuations of the ultra-stable transfer oscillator ν_{int}, can be eliminated provided the frequency readings at both sides A and B are moderately synchronised.

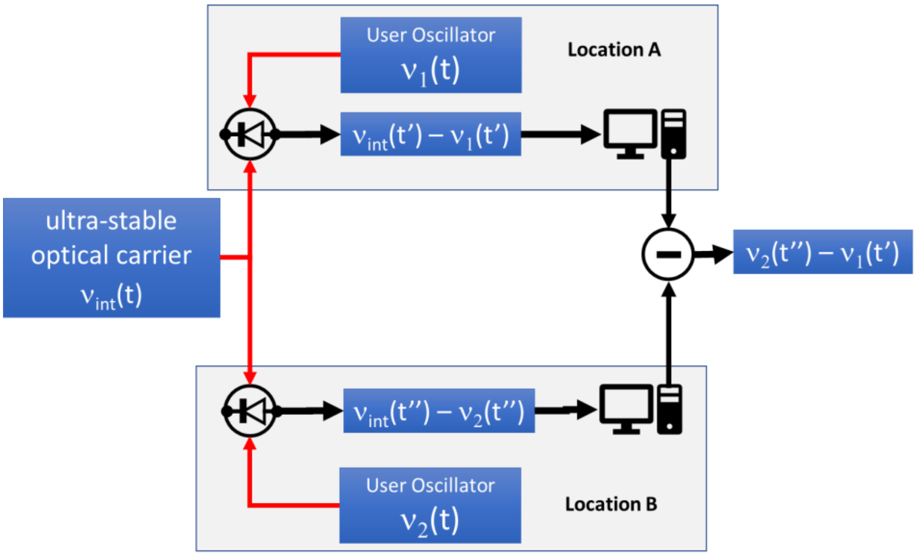

Figure 6: Basic relative frequency service for optical signals provided by the network.

The requirement for synchronisation depends on the drift rate of the transfer oscillator and the desired uncertainty of the measurement. Aiming for a relative frequency uncertainty of the order of 1×10^{-18} and a drift rate 1×10^{-15}/s for a reasonable transfer oscillator requires that the counters at remote sites A and B have synchronised triggers at the level of 1 ms, which is easily achievable by NTP or GPS synchronisation. However, these need to be recorded if one wants to ensure traceable measurements. By replacing the user oscillator/laser of e. g. user 2, by that of an optical clock laser operated by an NMI, the ECN can generate and distribute the ***absolute frequency service***.

A similar approach applies to the ***relative timing service*** depicted in Figure 7 and Figure 8, where the time delay, or phase offset between the internal network time scale and those of the users at locations A and B, have to be measured. However, care has to be taken that all internal delays, including the delay introduced by the fibre links, are known and constant. It has been shown that the delay can be determined with sub-100 ps uncertainty even for fibre links exceeding several hundred kilometres. Replacing the time scale of e. g. user 2 with that of an UTC(k) laboratory (typically an NMI) allows one to calibrate the network time scale offsets with respect to UTC leading to the ***absolute timing service***.

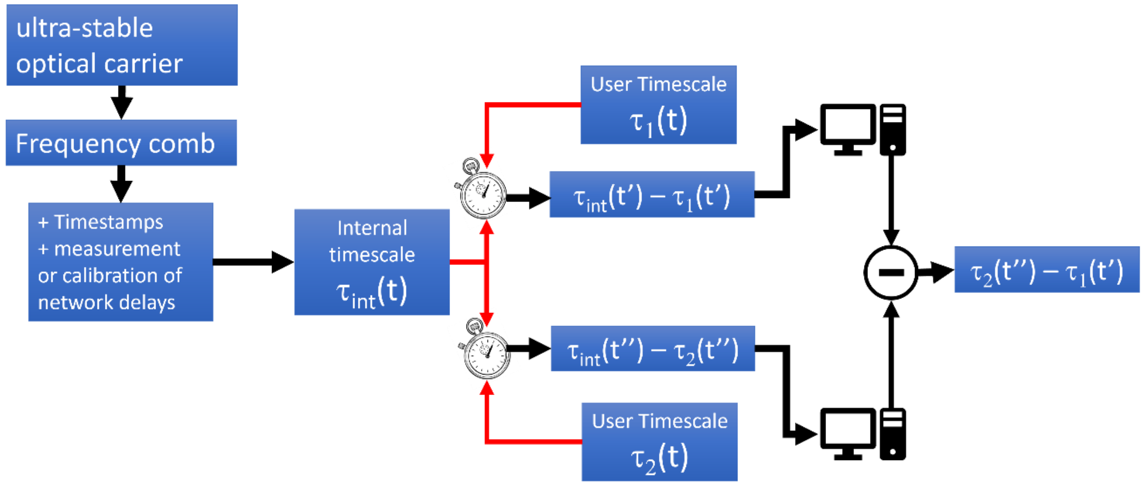

Figure 7: Basic relative timing service provided by the network.
Similarly to what is shown in Figure 3, the postprocessing of the delay measurements at locations A and B eliminated the timing jitter of the network time scale.

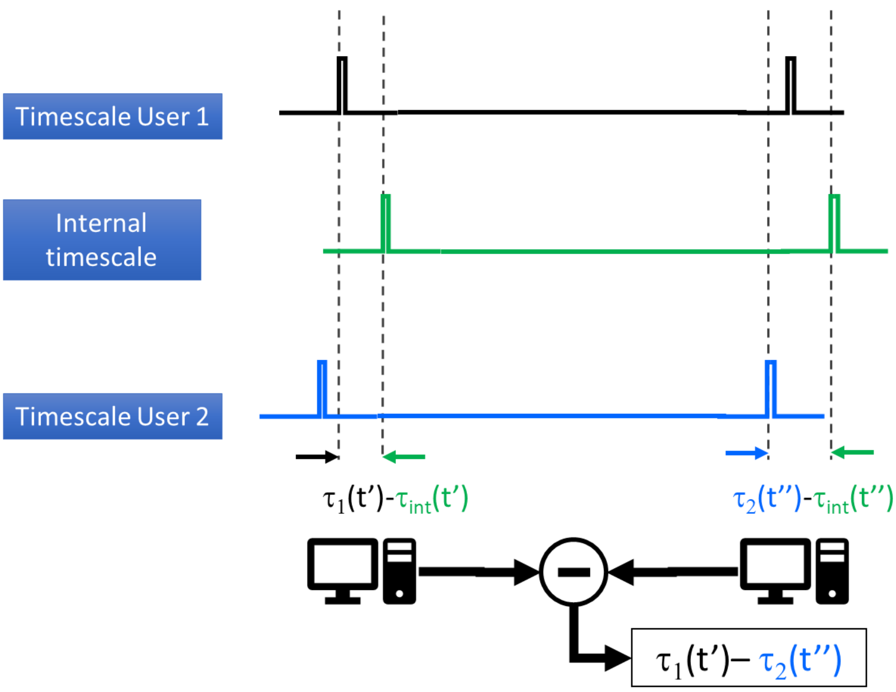

Figure 8: Comparison of user time scales using an internal time scale of the network. At the remote locations A and B, delay (phase) measurements of the user timescale are performed with respect to the network time scale, which is eliminated in post-processing.

2.1.2 Identification of a Generalised Topology

The transfer oscillator concept detailed in the previous section leads to a generalised view of the CLONETS-DS ECN topology as shown in Figure 9. Namely, it dictates that signals from the transfer oscillators, either in the optical or in the RF domain, are transmitted from one Point of Presence (PoP) to the next using bi-directional amplification stages along the link. Traceability to the SI and UTC is established at the selected PoPs with NMI interfaces by measuring the offset between the signals provided by the ultra-stable transfer oscillators of the ECN and an SI-traceable signal; these offset measurements will be made available via the data repository (see section 2.1.5.3). The general role of the PoPs is to receive signals from neighbouring PoPs, maintain the local transfer oscillators in the optical and RF-domain, condition the signals, and forward the signals to the next PoP, or to enable users to access the network signals via user interfaces.

Moreover, we foresee that such PoPs may act as a collocation point for existing or future national subnetworks. Here, the ECN needs interfaces at its boundaries, either because it meets another network, or because it interfaces with a secondary network layer. At the interface, interoperability between networks is ensured by accurately measuring the phase between the two metrological network signals. The required accuracy depends on the science case application addressed by the corresponding network layer of the ECN.

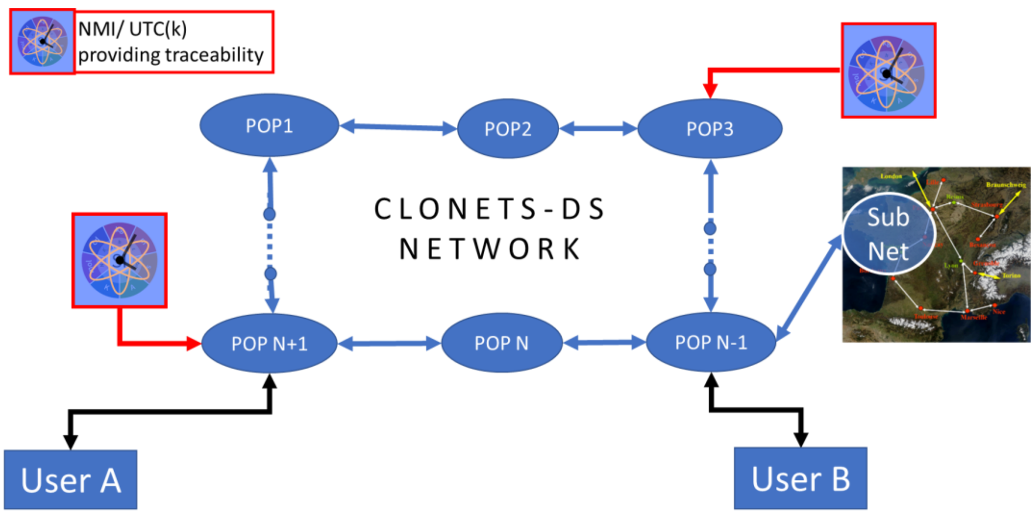

Figure 9: Generalised view of the CLONETS-DS international core network.

The basic idea underlying this approach is that the users can choose any of the PoPs (typically the nearest) for their measurements. The technical details of the typical user interfaces located at any chosen PoP for deriving signals needed by the SU from the ECN are detailed in section 2.1.5. We note here that stabilised fibre links between the PoP and a remote user must be set up and maintained by the user's institution. The National metrology institutes (NMIs) that will be responsible for SI-traceability are listed in Table 3 in Section 3.1.3.

2.1.3 Identification of Core Network Functionalities (Physical Principles)

Following this generalised topology approach, we identified the necessary functionalities as building blocks for the hardware of the network. For each of these hardware blocks we have estimated their TRL level and "best performance level", and propose methods, tools, and procedures for their realisation in Section 2.1.5. The key generalised hardware building blocks shown schematically in Figure 10 comprise:

- Transfer oscillators, e.g. ultrastable lasers and microwave oscillators, acting as *flywheels* that provide reference signals or regenerate signals across the network.
- Timescale generation functionality that provides internal timescales needed for relative and absolute timing services.
- *Bi-directional amplification stages* to compensate fibre loss along the network stretches.
- *Branching connectivity, switching, and eavesdroppers' connectivity,* where stabilised links feed one or more additional links, or build a node for subnets, that transfers time and frequency over the network.
- *NMI Interfaces*, which relate the generated signals for the network to an ensemble of time and frequency standards to allow for SI- traceability.
- *User interface* that allows to extract the signal from the network, and allow users to interconnect with the network signals and perform measurements with other SU
- *Frequency combs* that allow translation from one optical frequency to another without loss of phase coherence (when a unique optical frequency cannot be provided within two subnets).
- *Standard measurement equipment* such as frequency counters, phase steppers, time interval counters, mixers, filters, and amplifiers, to name just a few.
- *Data repository* that records all required frequency and time data in real time according to the EU's FAIR recommendation. This has to function as a single repository but in practice it will certainly be a composite of several, calling for the use of an Application Programming Interface (API), unified naming conventions and data formatting.

A detailed description of the hardware functionalities including requirements and TRLs are given in Section 2.1.5.

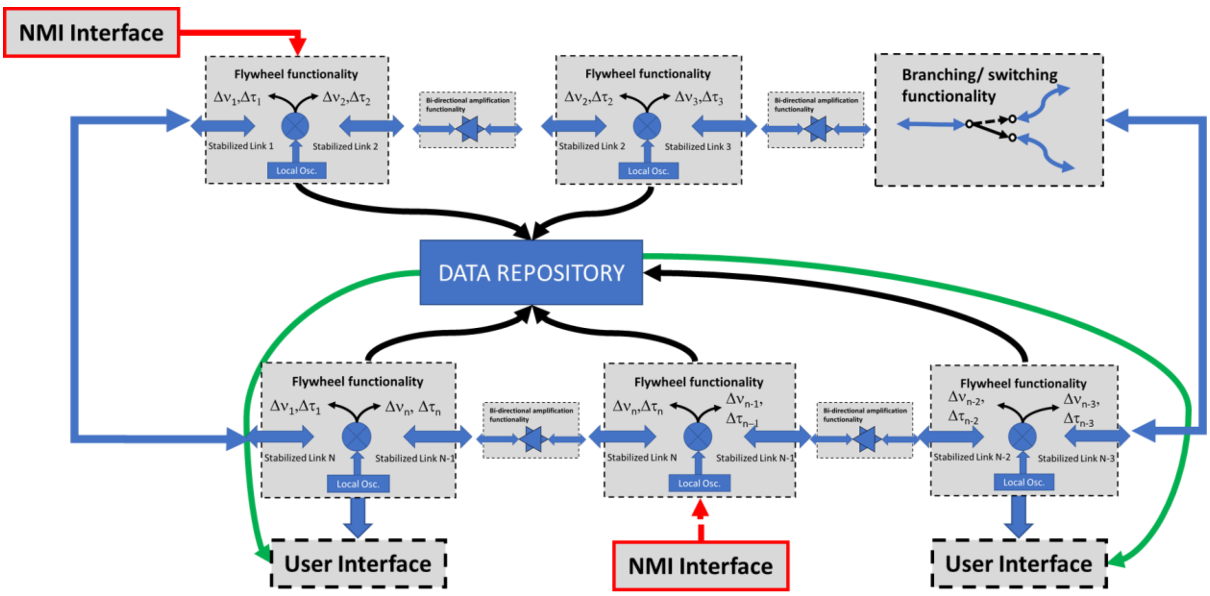

Figure 10: Hardware building blocks for signal generation and dissemination across the network. Flywheel functionality is provided at dedicated PoPs of the ECN, while bi-directional amplification is established along fibres between PoPs as necessary.

2.1.4 Achieving Parallel Use of Common Fibre Routes

As described in more detail later on in the document, it will not be possible to connect all European sites via a single ring structure. We therefore assume that several overlapping ring structures will be necessary to build a pan-European network. An idealised version of this topology is shown in Figure 11.

Wherever possible, the network should rely on already existing national infrastructure and, in the case of missing links and cross-border connections, on NREN/GÉANT infrastructure.

Existing national point-to-point connections should be considered as “in-kind” contributions to the CLONETS-DS network and should interconnect at dedicated PoPs but the operational responsibility should remain at the national level. Deliverable 2.2. discusses in detail the technical issues of interoperability between the diverse existing national fibre networks and the proposed missing fibre networks.

Here we briefly describe the general key features of this overlapping ring topology approach that allows for parallel or sequential developments depending on the ranking of user needs. The key features of the proposed topology are:

- Each ring is linked to at least one, preferably two NMIs with optical clocks
- Each ring shares routes (e.g. with its northern or southern counterpart)
- Each ring allows future extensions within its area
- Each ring allows for linear extensions (Italy, Finland, Spain, Turkey, etc.)

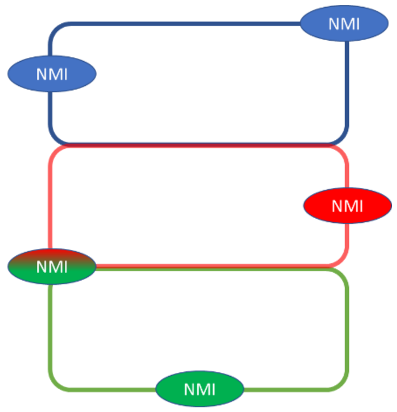

Figure 11: Schematic view of a possible implementation of an overlapping ring topology forming the European core network.

This approach allows the incorporation of existing national implementations and allows the implementation of different techniques such as e. g. ELSTAB [4], White Rabbit [5], or optical carrier depending on user needs. It avoids restrictions related to the availability of dark fibres or only dark channels and does not rely on a predetermined provider (NREN, GÉANT, commercial fibre providers, etc.). While this structure on the one hand is open, expandable, and easily adaptable to the implementation of novel concepts, it also provides a network with shared but well-defined responsibilities at the national level.

Probably the biggest advantage of this approach is that having concatenated linear links between PoPs, which maintain a flywheel functionality, prevents collapse of the whole ring if a linear link between PoPs is not available due to maintenance, malfunctions or upgrades. Furthermore, with this ring topology approach the data exchange via a data repository is easier to handle than direct signal exchange.

In the following sections we give a detailed analysis of the building blocks of the network in a Work Breakdown Structure (WBS) and discuss their corresponding TRLs at the time of writing of this deliverable.

2.1.5 Subsystems and Corresponding TRLs

For each network and dependent sub-network (EU-level, national level, regional/local level), we have identified eight subsystems for T/F dissemination as represented in the diagram in Figure 12 and which are described below.

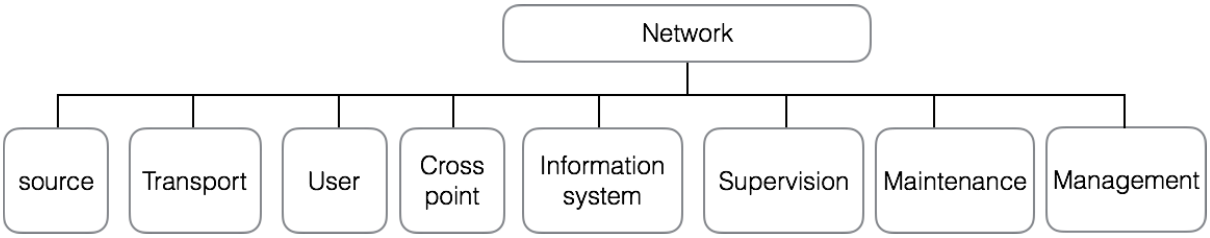

Figure 12: Shown is the Work Breakdown Structure of the network. There are 8 main work units, detailed in the text. The envisioned network comprises several subsystems, that allow to transmit and manage physical signals together with information about the status of each element and allows for online monitoring and maintenance.

Signal source generation: this is the ensemble of hardware, firmware and software that continuously emit signals seeding the network.

Dissemination system: comprises of the hardware, firmware and software that ensure the propagation of the emitted signal from one place to set of remote ends. The essential functionality of the dissemination system is to compensate for the propagation noise and attenuation of the signals in a traceable way and to accurately determine delays of propagation.

User system: includes the hardware, firmware, and software that ensure the delivery of a useful physical signal to an end-user. Depending on the user's need, the physical signal should be traceable to a realisation of the SI second.

Cross-point: the interface of the network to other systems. It comprises an interface to other networks and an interface to time and frequency standards. This is the essential system for inter-operability. The latter is crucial as it aligns the dependency of the network to national standards. In practice, the signals propagating throughout a given national network can be either from an NMI in charge of the elaboration of the national time and frequency standards, or emitted by a third party. In the first case, the NMI is in charge of establishing the hardware, firmware and software that emit the signals, relate them to standards, and publishing the data on the signal source. In the second case, the third party is in charge of establishing the hardware, firmware and software that emit the signals and relating them to one (at least) or several (at best) national standards and publishing the data. The essential functionality is to ensure traceability to standards.

Information system: comprises of the hardware and software (and potentially firmware) that allow access to the data resulting from the signal generation, its propagation, its cross-points, and eventually the user-end. Its main function is to provide users and operators with data and information.

Supervision system: comprises of the hardware, firmware and software that allow remote control over the source system, the transport system, the cross-point system, and eventually user system. Its essential functionality is to ensure the correct operation of the network.

Maintenance system: includes the hardware, firmware and software that use the information system and the supervision system to keep the network up to date, secured, and under operation.

Management system: includes the hardware and software used for the management of the network (coordination between sub-systems, documentation management, and financial aspects). Note: this does not cover the management of a whole T&F-project, other tasks such creating impact, lobbying, etc. are not within the scope of this engineering system analysis.

Each of the systems summarised above and described in detail in the next sections, requires specific hardware. However, most of this hardware has either been directly developed or tested and characterised in previous EU-projects.

2.1.5.1 *Signal Sources: CLONETS-DS main oscillators*

The **signal source** typically comprises ultra-low-noise, cavity-stabilised laser in the optical domain or low phase noise RF or microwave oscillators for the RF domain and frequency combs that translate signals in the optical domain to the RF domain and vice versa.

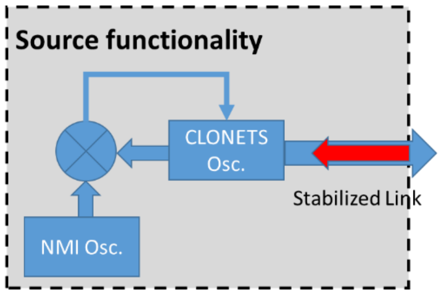

Figure 13: Signal Source: - its functionality provides the signal transmitted over the fibre link and the traceability to a realisation of the SI- Second.

a. In the optical domain, in the transparency window of a single-mode fibre at 1.5µm, the main oscillators are lasers. To provide a phase-coherent optical link, a first design constraint is that the coherence time of the laser exceeds the transit time of the photon in the fibre, which is (in most cases) the round-trip time. The coherence time of a laser can be related approximately to the inverse of the laser linewidth in a given bandwidth of measurement, which for the purposes of this example we will consider to be 1 Hz. The coherence length of the laser can be calculated taking the index of refraction of the fibre as 1.5 and the speed of the light in a vacuum. Considering a factor of 2 for the round-trip time, Figure 14 shows the half-coherence length versus the linewidth in a 1 Hz bandwidth. In Figure 14, the typical linewidths of telecom lasers, spectroscopy lasers and ultra-stable lasers as well as the identifiable distances the perimeter of the Earth and the Earth-to-Moon separation are shown as dashed lines. The green shaded area corresponds to the distance of one hundred to ten thousand km; the maps shown in Section 3 confirm that fibre links in this range are needed.

In addition, we consider the frequency drift and other time-dependent derivatives. The frequency fluctuations are demodulated by the laser link and can be roughly estimated by multiplying them by the propagation time delay. A free-running cavity-stabilised laser may drift by several Hz up to tens of kHz per second, and the typical propagation delay in this design is about 1 to 10 ms. A detailed discussion of this effect can be found in the literature [6, 7]. There are also practical considerations at the user side and at the cross-point: even if the data can be post-processed, the use of the signal is much simpler if the frequency is known and stable.

We specify therefore that the signal to be kept within 100 kHz of its targeted mean frequency value within one day. to achieve this, the laser drift must be below 1 Hz/s. Commercial, off-the-shelf, EU-manufactured products are able to meet this drift specification. In some research laboratories, there is also the option to actively compensate for the frequency drift of the laser by comparing its frequency with that of an H-maser using an optical frequency comb. This solution is expensive but allows the laser to keep within 25 Hz with respect to the atomic standard over one year. This frequency variation can be further reduced when the H-maser is steered by a primary Cs clock. Furthermore, ultra-stable lasers with cryogenic cooling and crystalline mirror exhibit frequency drift below 10 mHz/s. Novel integrated laser designs based on stabilisation using integrated photonics resonators exhibit laser linewidth between 10 Hz and 100 Hz. These lasers might be an interesting alternative to ultra-stable lasers, with prospects of size reduction and cost reduction, but even though they are commercially available, to the best of our knowledge, there are no reports of field-trials of such lasers.

As of today, we conclude that the signal sources in the optical domain are necessarily ultra-stable lasers with long-term frequency stability. The latter very likely requires an additional frequency comb and a linkage to an H-maser or Cs clock. As a matter of fact, currently ultra-stable lasers are the seed for all coherent fibre links to the best of our knowledge.

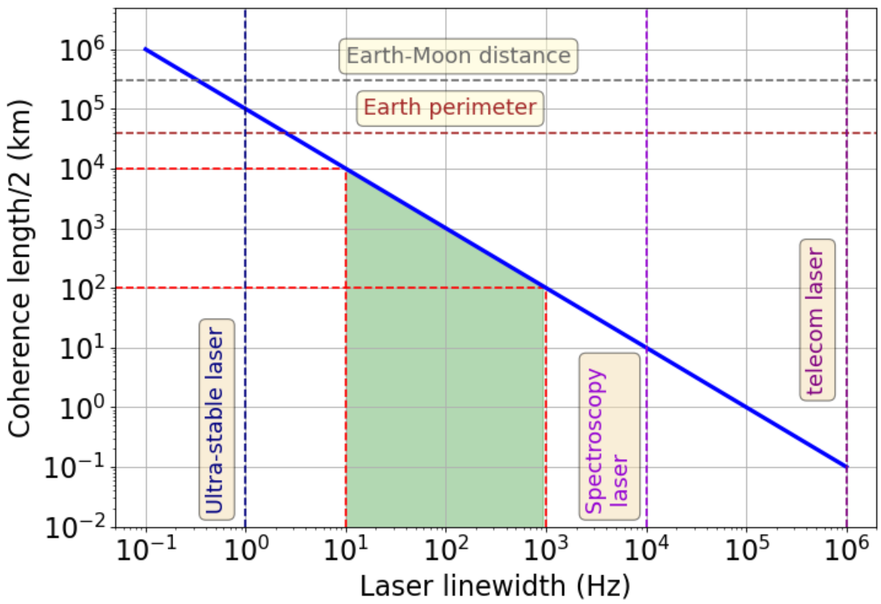

Figure 14: Half-coherence length of a laser as a function of its linewidth in a 1 Hz bandwidth. This sets requirements on the stability of the laser source for the ECN.

b. In the radio-frequency domain, the same design constraints, dictating that the coherence time of the laser must exceed the transit time of the photon in the fibre also hold. A 10 Hz linewidth will correspond roughly to a relative frequency deviation of about 10^{-6} at 10 MHz.

Therefore, there are many off-the-shelf options commercially available. Low-phase noise oscillators with oscillating frequencies at 5, 10 or 100 MHz are common but will need to be disciplined to e.g., GNSS signals using an antenna. For highest performance active or passive masers, cryogenic oscillators, or frequency transfer from an optical ultra-stable laser complemented by a frequency-comb can be used. Commercial solutions are available from EU or Swiss manufacturers, e.g. T4Science (H-Masers), Femto-engineering/Uliss-ST (cryogenic oscillators, https://www.femto-engineering.fr/realisation/oscillateur-cryogenique-ultrastable-uliss), and Menlo (ultra-stable laser + comb). In practice, UTC(k) realisations are using active or passive H-maser, Cs clocks, and micro-phase steppers, see for example [8]. The PPS signal is generally derived from such radio-domain stable oscillators, where one cycle of the radio-signal is picked up.

Accuracy in time is obtained by “alignment” to a realisation of UTC, denoted in the literature as UTC(k), where k stands for the body that establishes and maintains the realisation. For realising the alignment of the locally generated Pulse-Per-Second (PPS) with that of the time standard, the engineering model relies on a precise time interval measurement system and a fine time delays correction system, known as a micro-phase stepper. Precise time interval systems are available from EU manufacturers such as Piktime and Sisiphus (among others).

If the internal PPS signal cannot be related to a national realisation of UTC, the only option is to refer the internal timescale to GNSS signals.

2.1.5.2 *Dissemination system*

Typical fibre links suffer from environmental perturbations such as temperature variations, vibrations etc., that are accumulated along a fibre link and result in a fluctuating frequency of the transmitted optical carrier. These perturbations must be compensated to achieve a signal at the remote end that has the same performance as the local signal.

a. The basic phase noise cancellation system that enables cancellation of the phase noise and delay fluctuations accumulated over a link has been described in detail in [9] and in deliverable D1.5 of the previous CLONETS project, together with a model to predict the residual phase noise of the stabilised link as a function of the link length and the phase noise associated with the free-running fibre.

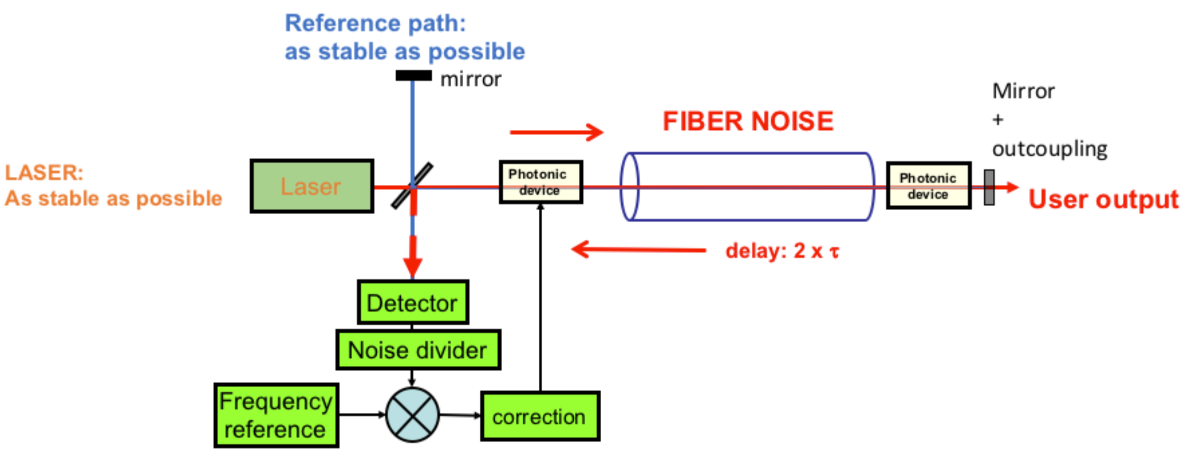

Figure 15: Principle of phase noise cancellation techniques in the optical domain. The main components are: 1. An ultra-stable laser source. 2. A Michelson interferometer with a reference path which is as stable as possible. 3. A detector and compensation unit that can compare the divided fibre noise to the laser noise, and a servo-loop that compares the system with an external RF-Frequency reference. 4. A user output.

For frequency transfer, the phase noise cancellation system measures the delay fluctuations of the wave that propagate in the fibre. In the optical domain, an optical interferometer is used to measure the optical phase, most often based on self-heterodyne techniques [10]. The main components of a noise canceller are represented in Figure 15. In the RF domain, amplitude modulation is imprinted on the optical carrier. For time transfer, the delay of propagation is measured and compensated for.

At the forefront of research, fundamental and technical limitations for frequency transfer were investigated in detail. From the technical point of view, it can be shown that temperature and humidity variations set limits in performance, arising from the sensitivity of the interferometer. Designs based on free-space can reduce this sensitivity and/or post-processing to compensate for the effects, experimentally show performances in the low 10^{-21} range, well below the target of the CLONETS-DS specific objectives.

The signals are transmitted through a single-mode fibre in the field. Another limitation arises from Polarization Mode Dispersion (PMD). This was evidenced experimentally on fibre spools to the level of a few 10^{-20}. For long-range, fibres deployed in the field, a lower value is expected, but this should be confirmed with experiments. As compared to the specific objectives, PMD limitation is not limiting for frequency transfer. For time transfer, the situation was also investigated experimentally. It was found that PMD might be a limitation at the level of a few ps for fibre links of several hundreds of km. Mitigation strategies were also successfully developed [11, 12].

Dissemination systems are laser stations (repeaters), working either in the optical domain or in the RF domain (see details below). These repeaters were developed over the last decade (2010-2015) and are now commercially available, e.g. from iXblue.

b. Amplification

Typically, fibres used for telecommunication exhibit an intrinsic loss of about 0.2 dB/km. For long-haul fibre links, fibre losses due to splices and connectors must additionally be taken into account. These propagation losses are routinely compensated using Erbium doped fibre amplifiers (EDFAs) that provide optical gain of typically 25 dB in the L- band and up to 30 dB in the C-Band, with a gain bandwidth of about 2 THz. Such amplifiers are installed along a link typically at a 80-100 km distance from each other. However, they cannot regularly be used as an amplification solution throughout the ECN, since EDFAs are designed with optical isolators. Optical isolators work well in the mono-directional architecture of long-range telecommunication networks but inhibit bi-directional light propagation in the same fibre. However, bi-directional amplification is the key requirement for realising the phase-noise cancellation system necessary for the ECN as discussed and shown above (see Figure 15).

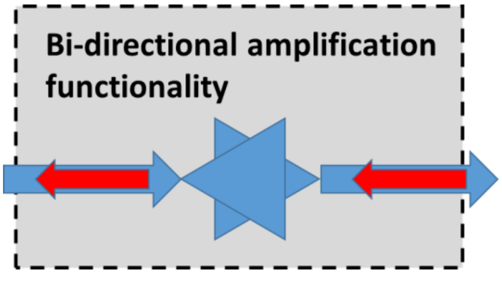

Figure 16: Sketch of a bi-directional amplifier.

Thus, special bi-directional amplifiers had to be developed to allow amplification in both directions. Er-doped fibre, for example, is inherently bi-directional because stimulated emission is direction-independent, and it therefore provides almost the same gain for forward-backward signals.

Over the past decade, several designs for bi-directional amplifiers have been proposed and are now commercially available (Lumibird, Menlo, Piktime, Optokon, IntelDat, OPNT, etc.). Such bi-directional amplifiers are typically deployed on dedicated fibre architecture or shared fibre infrastructure. For REFIMEVE, there are now about 14 years of experience in the field. Details can be found in the relevant deliverables of the NEAT-FT, OFTEN, CLONETS, OTFN (GN4), and TiFOON projects.

Besides EDFAs, **fibre Brillouin amplifiers** (FBA) have been developed over the past 10 years. The gain profile of fibre Brillouin amplifiers (FBA) is about 10 MHz wide, orders of magnitude narrower than EDFAs or Raman amplifiers. The gain is in the order of 30 to 60 dB with pump powers below 20 mW. The gain appears for pump power at about 10—11 GHz offset frequency away from the signal frequency. The gain is strongly dependent on pump signal co-polarisation. Exact values (at the percent value) cannot be predicted as these depend on the type of the fibre. Due to the inherently narrow bandwidth feature of Brillouin amplifiers, their application is limited in practice to optical carrier transfer links only. Fibre Brillouin amplifiers at high gain are not compatible with parallel data traffic. The TiFOON project has been conducting investigations which are still ongoing into possible mitigation strategies.

c. Branching & Switching

Network switching networks refers to the functionality of routing the metrological signal at will as required by the user. Optical switches are standard telecom products developed in the frame of Optical Transport Network for telecommunication. There are several manufacturers of such products, such as Santex, PhotonCom, CrystalLatch (resp. Japan, Canada, UA) with insertion losses below 1 dB when using MEMS technologies, and below 2 dB generally speaking.

The branching functionality refers to a concept introduced in 2010 by G. Grosche [13], so-called eavesdroppers. This functionality corresponds to an element that can be inserted in an existing stabilised link to a first user, which will be referred to as a main line hereafter, in order to send the same signal to a new user, without perturbation of the main line to the first user.

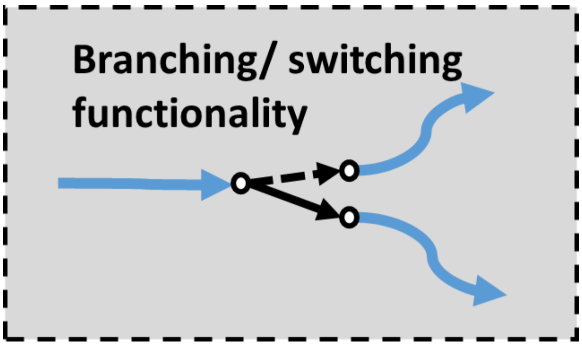

Figure 17: Switching functionality.

Such concepts were developed with various designs. Several implementations in the field over the past decade have been reported in Germany, France, Australia, and China [13,14, 15, 16, 17, 18, 19, 20, 21]. These eavesdroppers are now commercially available from at least one manufacturer.

d. Technical readiness and updates

- The TRL of optical phase noise cancellation techniques reaches TRL9. About 5000 km of fibre links are in almost continuous operation if one considers only the French and Italian networks using this technique. Supervision and maintenance is available commercially from Exail. C-band and L-band solutions are also available commercially. Other research groups have developed their own laser stations, for example groups in Poland and Italy in Europe, and in China and Japan in Asia. These are not yet commercially available to the best of our knowledge.
- Uptime for a 1000-km scale multi-user network has been reported [22, 23].
- Fibre Brillouin amplifiers are of interest to industrial partners. Knowledge transfer is occurring, and industrial products should be available in near future.
- The TRL of RF and time dissemination techniques reaches TRL 9. Here, about 1000 km of fibre links are in almost continuous operation if one considers only Polish and German networks using the ELSTAB technique. In addition, about 2000 km in Italy, France, and The Netherlands, Sweden and Finland using White Rabbit technique.
- R&D has been supported, especially within the EU project TiFOON, towards the integration of RF and pps in a single optical layer. The most advanced report on this to date is [24].
- Multi-branch laser stations are now commercially available.
- Supervision of optical frequency transfer is now commercially available.

e. Design Rules:

A challenge for the design of the ECN is that the level of noise to be compensated is not constant for the European fibre links currently in operation and may vary by several orders of magnitude [25]. Very dense areas and seismic areas exhibit a spectral density of phase noise that can be one or two orders of magnitude larger than in other geographical regions. A study by researchers of Sorbonne University was carried out on the REFIMEVE network where 5 links are under operation simultaneously [26]. The study found that the measured spectral density of phase noise for a link obeys approximately a linear dependence with the physical length of the link with a slope of 2.5 $rad^2 \times Hz/km$ (excluding the D link measurement, see Figure 19).

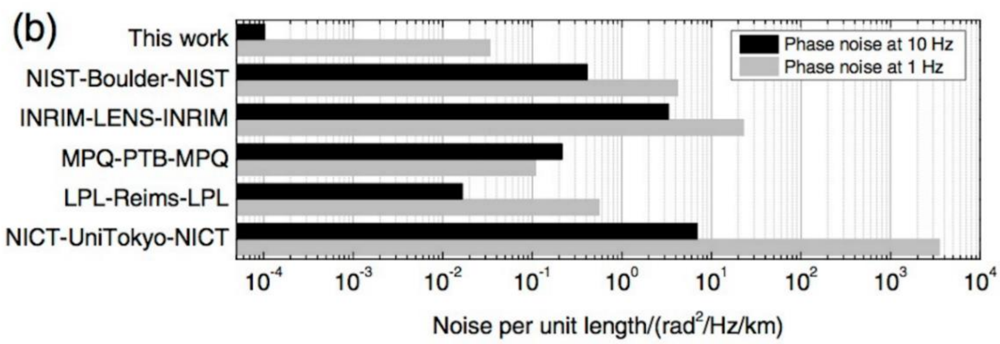

Figure 18: Reported experimental free-running fibre noise to be compensated for in various in-field implementation. Very dense urban area and seismic region shows excess of noise by order of magnitude. Figure extracted from [25].

The numerical value of the prediction is very much dependent on the conditions along the link, such as the required amplifier gain and spectral density of the phase noise of the uncompensated fibre. Thus, the prediction of the white phase noise can vary substantially for different stretches along the same fibre link, and the reader should not stick too much on the numerical value, when designing the compensation system. The reader should not be too concerned with the numerical value shown in Figure 19 when designing his own compensation system. For a more reliable design we recommend the free-running phase noise to be measured for each individual case.

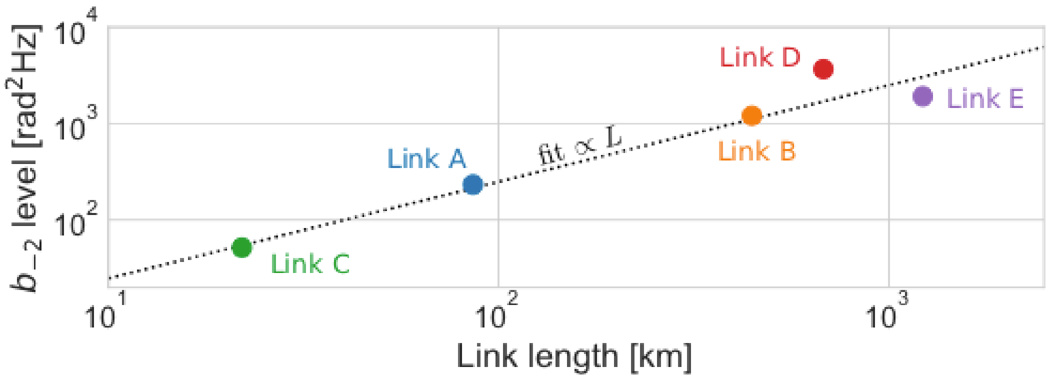

Figure 19: Experimental free-running fibre noise reported in the REFIMEVE network. Figures are extracted from [Tonnes_phD:2022].

By modelling the attenuation of the signal, the expected signal-to-noise ratio, which is the key driver to determine the cycle slip rate of the optical frequency transfer, can be derived. Details of these calculations can be found in the cited study [26]. The main result the study reported is that the maximum range of an optical link using amplifiers (EDFA, FBA, Raman) and repeater laser station is about 2000 km. In practice, the longest span reported so far is about 2000 km with an uptime of about 85% over 5 months. In this particular design, regeneration laser stations (RLSs) were placed with maximum separations of about 600 km.

From the considerations in the previous paragraphs, it is clear that clean-up oscillators in the form of remote-controlled ultra-stable lasers are needed to build the ECN at the European level with links up to 5000 km These laser stations are compatible with all types of amplifiers (EDFAs, Raman, SOA, Fibre Brillouin amplifiers).

For RF and time transfer, the situation is slightly different, as the most mature techniques use intensity modulation. The attenuation of the fibre is then squared at detection (homodyne technique), while the attenuation is linear for optical frequency transfer using heterodyne techniques. In a typical scenario, a distance between the time and RF terminals of about 300-500 km can be expected, assuming the distance between the bi-directional erbium-doped amplifiers is not larger than 70—80 km. For longer distances, RF and time repeaters can be used, which allow the extension of the total distance to more than 1000 km.

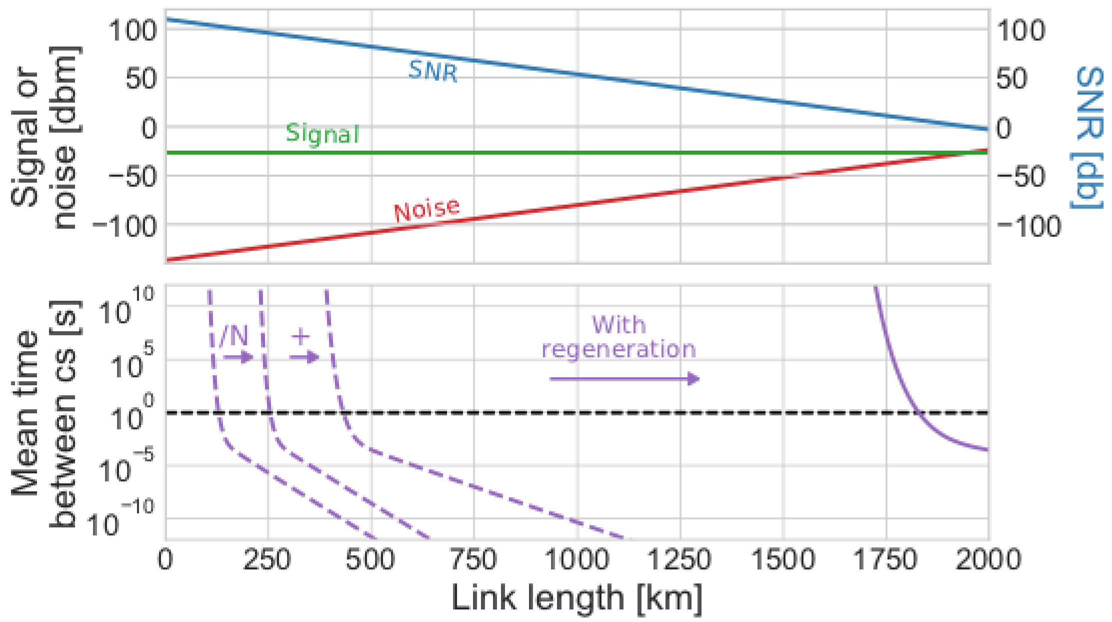

Figure 20: Design study on the distance at which full optical regeneration is needed. Figure extracted from [Tonnes_phD:2022].

2.1.5.1 *Users*

The function of the user module is to stabilise the "last mile" and to provide enough optical power (or RF power) to the user.

The last mile corresponds to a relatively short path, in the order of 1-10 km, connecting the last node of the network to the user's research facility lab. Attenuation might be relatively high, in the order of 1-15 dB, where losses arise mainly from too many connectors. The noise density per km might be higher than on long-haul links (high local acoustic noise, heat pipes, overhead fibre cable, high-voltage cables, etc.). The stabilisation of the last mile relies on the same principle as that of long-haul links (see Figure 15), except that settings might be different and the electronics slightly simplified.

In addition, the user might need higher optical power than delivered by the user output. In that case, there are two options: either the use of a local optical amplifiers and appropriate optical filters, or a phase-lock loop on a user's laser.

User modules

To the best of our knowledge, commercial solutions are available to stabilise the last mile, both in the optical and RF domains, from one and several manufacturers in Europe respectively (Exail, Menlo, PikTime, TimeTech). Amplification at the user end relies on the same commercial products listed above at section 2.1.5.2-b (for more details see Deliverable *D2.2 Roadmap for Technical Implementation*, Table 8).

2.1.5.2 *Cross-Points: Description of the Interface at a Point of Presence (PoP)*

Here we consider the necessary equipment for measurement, monitoring and supervision at specific locations that enable the interconnection of specific equipment, users, or responsibilities in case of cross-border points of presence (PoPs). These **Interface PoPs**:

- Are equipped with full measurement infrastructure
- Provide flywheel functionality
- In some cases may provide source functionality (SI- traceability)
- Are where national optical signals terminate
- Involve bi-national shared responsibility
- Feed the data repository

Interfaces between networks are hosted by shared network PoPs. In practice, these PoPs may be provided by an NREN, an NMI location, or by one of the networks with a last mile connection to join the PoP of the other partner or of an academic user.

At these interconnection points, there are, so far, no frequency gaps to bridge. In any case, the interface must be equipped with an accurate RF reference and a moderately precise enough time scale. If there is no possibility of setting up a GNSS antenna, possible solutions are to transfer via fibre GNSS signals from a neighbouring building, or to design a redundant fibre connection. The ring topology envisioned in this document provides such a functionality.

The floor space required is about 2 square meters in a room with air conditioning.

Within the framework of the ECN, the technical issue is to mitigate the missing signals/data that might occur during maintenance and the management of shared responsibilities. In order to optimally coordinate the contributions and responsibilities of each PoP, reliable oscillators in both the optical domain and the radio-frequency domain should be provided. In this way, signals are always generated locally and can be compared to those of at least one of the partners, while maintaining traceability. The acquisition system as well as the data sharing should be under the responsibility of the ECN, not precluding back-up solutions on a peer-to-peer basis.

Flywheels

Flywheels (FW) are oscillators that allow comparison of disseminated signals by differentiation of the measurements between the $\Delta\nu_1$ and $\Delta\nu_2$ as ($\Delta\nu_{1\text{-}FW}$) and ($\Delta\nu_{2\text{-}FW}$) signals. As long as the measurements are synchronous, the FW is in common mode and disappears from the comparison differentiation.

In such an approach, there are relatively low-level design constraints on the flywheel frequency deviation specification within a 1 Hertz bandwidth, for realising synchronisation throughout the network of at least 1 microsecond. The reasoning and subsequent numerical figures for the required flywheel oscillators are very similar to those detailed in section 2.1.5.1 on signal sources.

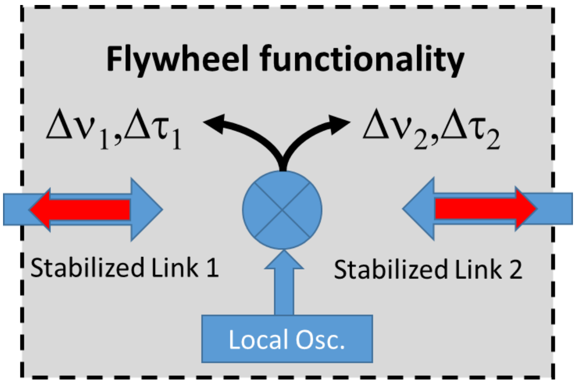

Figure 21:Comparators based on a flywheel in common view.

Bridging modules

To realise full interoperability throughout the ECN, we envision comparators between disseminated signals that are required at interfaces between network layers. This is not an issue in terms of radio-signal and time-signal technology, for which several highly mature off-the-shelf commercial solutions exist. Optical frequency transfer is slightly more challenging as the frequency difference may be as high as several THz. Such a frequency gap may occur for instance to bridge optical frequency transfer at 194.4 THz (France, Italy, Germany, Spain, Austria, UK, Poland, Czech Republic) or 190.7 THz (UK, Switzerland).

The most powerful and precise solution, which covers all possible frequency gaps, is to transfer spectral purity from one signal to another using an optical frequency comb. Note that, depending on the frequency gap to bridge, there are alternative solutions using a compact optical comb and transfer cavities (see for instance [27, 28, 29] to cite a few.)

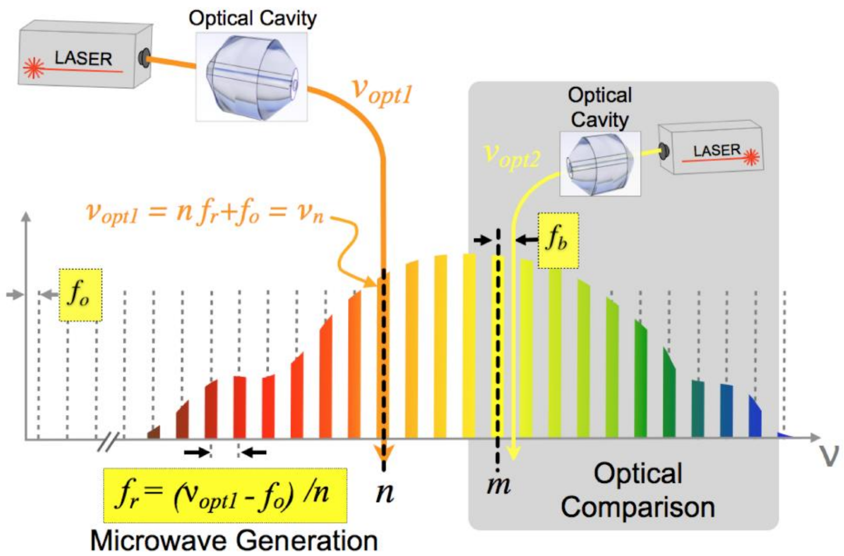

Figure 22: Bridging a large frequency gap with an optical frequency comb [30].

Eavesdropper functionality (see Branching & Switching) is required when a new user is added to the network without changing its topology. This enables functionality to drop the signal from the main "line" and compensates for the fibre propagation noise of the optical link. This functionality includes a supplementary interferometer so that the noise can be compensated for the additional end-user, without disturbing the main line. Such inserted interferometers add interferometric noise. For commercially available interferometers, the noise floor is at the low 1e-17 after 100s integration time, and the compensation for the additional end-user is automated and remotely controlled, without loss of traceability [31].

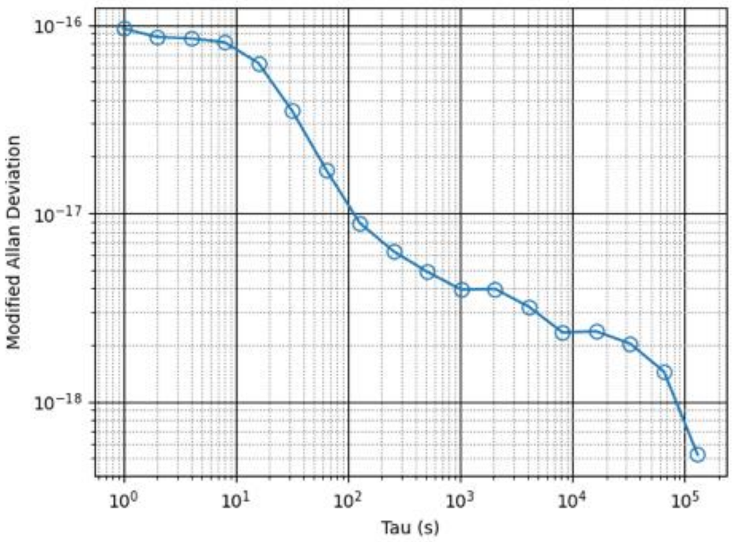

Figure 23: Residual frequency instability of the beat-note between the extraction station output and the main link input (noise floor). Figure extracted from E. Cantin et al., [31].

Eavesdroppers (extraction stations) are now commercially available from Exail.

For RF and time dissemination, this functionality is provided in the ELSTAB technology [32]. It is lacking in the White Rabbit technology, as this relies on an Ethernet tree structure. The only option is to add a White Rabbit switch, which is natively multi-user, at the desired insertion point.

2.1.5.3 *Information System*

The **Information system** must operate in accordance with FAIR (Findable, Accessible, Interoperable and Reusable) principles. The primary role of the central database will therefore be to convert data from one format to the format that will be selected for the ECN. Its secondary role will be to save data and metadata. Yet another of its functions will be to archive the data and the metadata in a data base. This functionality is foreseen for dedicated locations (dPoPs) feeding the data repository

The scientific data (information about the frequency and time delivered by nodes of the network) along with the metadata produced by the ECN will be **Open Access**, according to the EU policy.

A data exchange formalism was developed and used for clock comparisons, with details of what should be reported as physical quantities [2]. From a software engineering point of view, the data format for each subsystem generating data can be quite flexible, but it must be documented and maintained with metadata. In such a design, the data format of a given partner is converted into the one chosen by the ECN. The design of the information system, as detailed below, is based on a pilot study for optical clock comparisons. The main advantages of the system include:

- Can incorporate national implementations
- Allows the implementation of different techniques
- No constraint regarding dark channels or dark fibre
- no predetermined provider (NRENs, GÉANT, commercial providers)
- Open, expandable, adaptable structure

- Shared but well-defined responsibilities
- Easy implementation of novel concepts
- Data exchange is easier to handle than signal exchange
- Concatenated linear links avoid collapse of the whole ring if a part is not available

Data access

To design the information system, we worked on data gathered by the international clock comparisons campaigns run by several Joint Research projects (NEAT-FT, OFTEN, ROCIT) and the supervision system used in REFIMEVE.

The data formats of the subsystems vary in terms of their sampling rates and observables. In addition, these may evolve over time: the data format for clock comparisons has already changed and it can be anticipated that it will again.

We included in the design constraints the interface with other information systems, for example those of the Bureau International des Poids et Mesures (BIPM), GNSS and EGNOS, and TWSTFT, whose data format is outside the purview of the ECN and that may also evolve with time.

We therefore worked on the design of both a relational data base and software that take into account time dependencies.

With reference to the ECN, we distinguished measurements made at nodes and monitoring tools from subsystems, attached to a given transfer technique or signal generation.

Finally, in the context of software design, we defined a node as a physical space (room, lab, data centre zone) where time/frequency information is received by a module (oscillator, station, server, frequency comb, clock, ...), is eventually transformed and sent to another node. The concept of node is independent of the nature of the information (frequency signal, time signal, ntp) and thus is independent of the transfer technique (fibre links, GNSS, white-rabbit, NTP, ...)

After several attempts, by drawing comparisons with real data acquired over fibre network under operation in the EU, we achieved the design summarised below.

Data organisation and acquisition

For each network and dependent sub-networks, we can gather several types of data in a single repository, which calls for a server or a pool of servers to simplify the Information System (IS) and Supervision (see working notations in Figure 24). These types of data include:

- Raw data from acquisition devices stored on local servers all over the network
- Data from CLONETS-DS partners (e.g. in the context of clock comparisons)
- Data from external Information Systems
- Data post-processed from the different types of data mentioned above

This means that the internal data must be periodically collected in a secure way from local servers and organised efficiently in the data repository.

The examples below show of how this is implemented in the French network REFIMEVE. The block- structure shown in Figure 24 reflects the system information structure at network level. Each node of the network contains different types of devices, where each device acquires data sets.

Network data

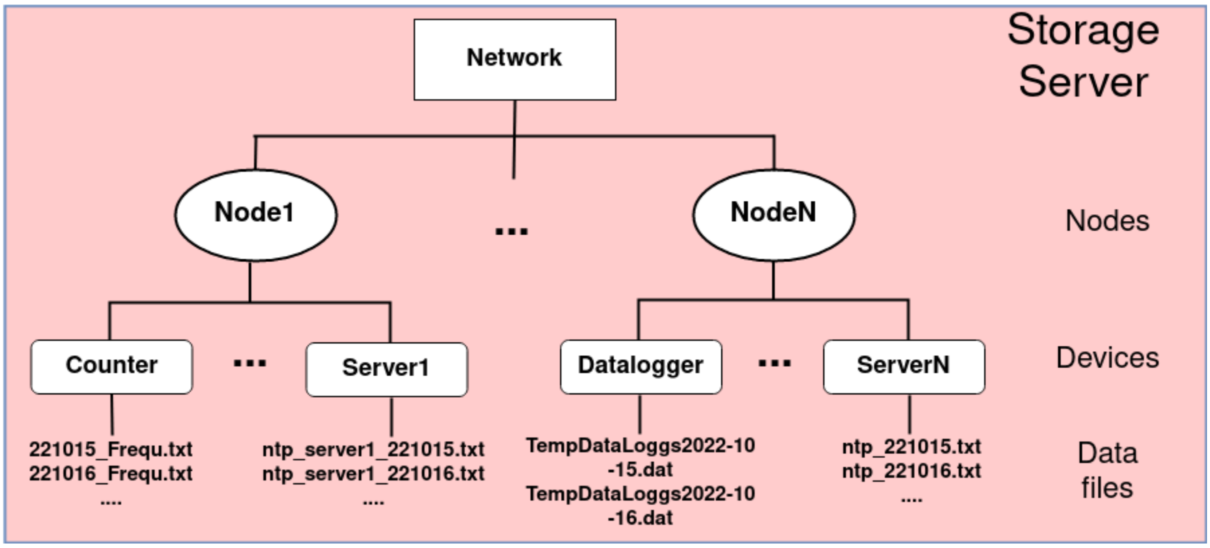

Figure 24: Aggregation of data within one network

Clock comparison campaign

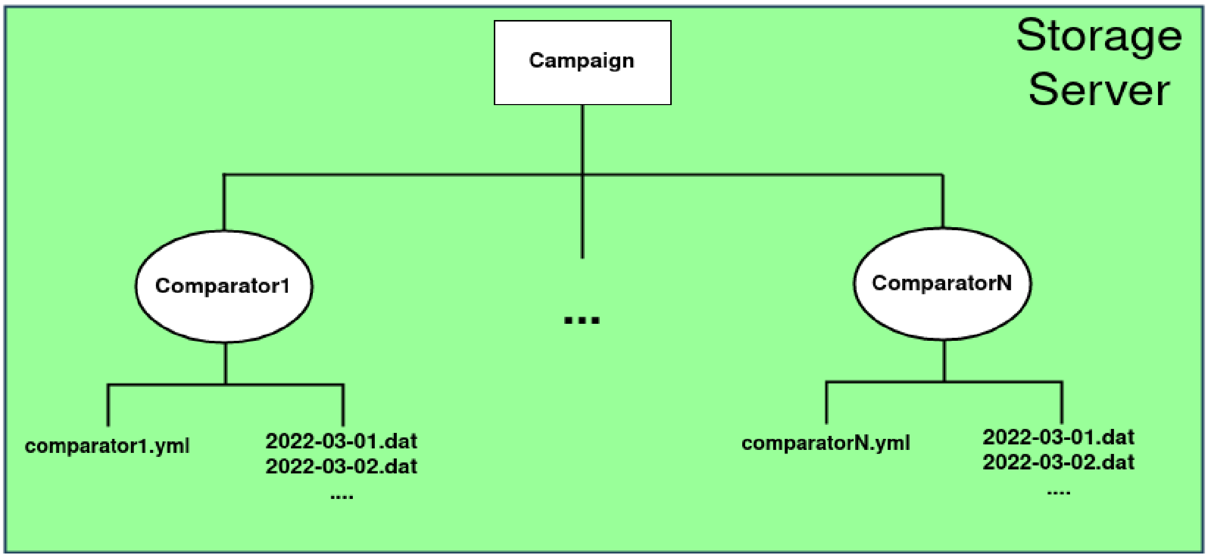

Figure 25: A measurement campaign involving more than one network implies processing data and meta-data from several comparators happening at cross-points. The design includes time-dependent information to comply with the EU FAIR policy.

Data characterisation

To be exploitable, each data set stored in the data repository must be associated with a set of meta-data to allow the characterisation of:

- The work breakdown structure of the network (see Figure 12)
- Data storage: file location, periodicity of file generation, content formats, content level.

A database with models accounting for network features and requirements is needed to store and organise all the necessary metadata.

Below we give an example of database design in the context of a clock comparisons campaign. Modelling for this feature consists in a set of objects with unique identifiers and inner properties. These objects can be linked to others.

A clock comparison ***campaign*** involves several consecutive couples of ***modules,*** called ***comparator outputs****.* Each *comparator output* consists in a dataset of frequency ratios/differences contained in data files that are accessible and readable thanks to their associated *file access* object. Each *module* belongs to a ***node*** of the ***network***.

This work must be extended to all the different aspects of a ***metrological*** network system engineering.

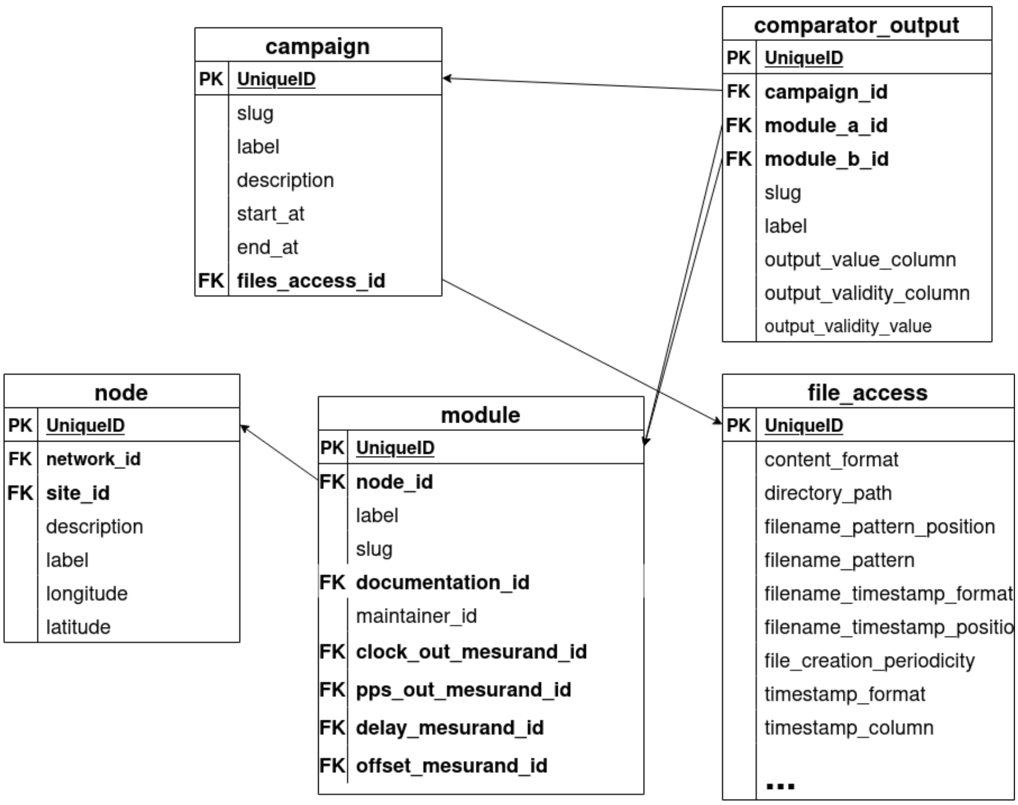

Figure 26: Example of a relational database design diagram, where dependencies between subsystems are formalised. PK stands for Primary Key. FK stands for Foreign Key.

Data exploitation

A ***resource*** defines a set of metadata that a user can request to obtain information on the network engineering system.

An ***observable*** is a dataset that helps monitor the network or to access and improve the performance of a specific scientific task (clock comparison, fibre links performance, counter synchronisation, server synchronisation, room temperature, …). Such an observable is produced from raw or post-processed data.

A resource can be associated to one or several observables.

For a given identified resource we developed a software within REFIMVE allowing to:

- Query the necessary metadata
- Fetch the relevant data in the *data repository* (see Data collection above)
- Process the data using the software business logic associated with the requested resource

Software design

The software design must conform with the database design. An example of software class design is given in Figure 27 below.

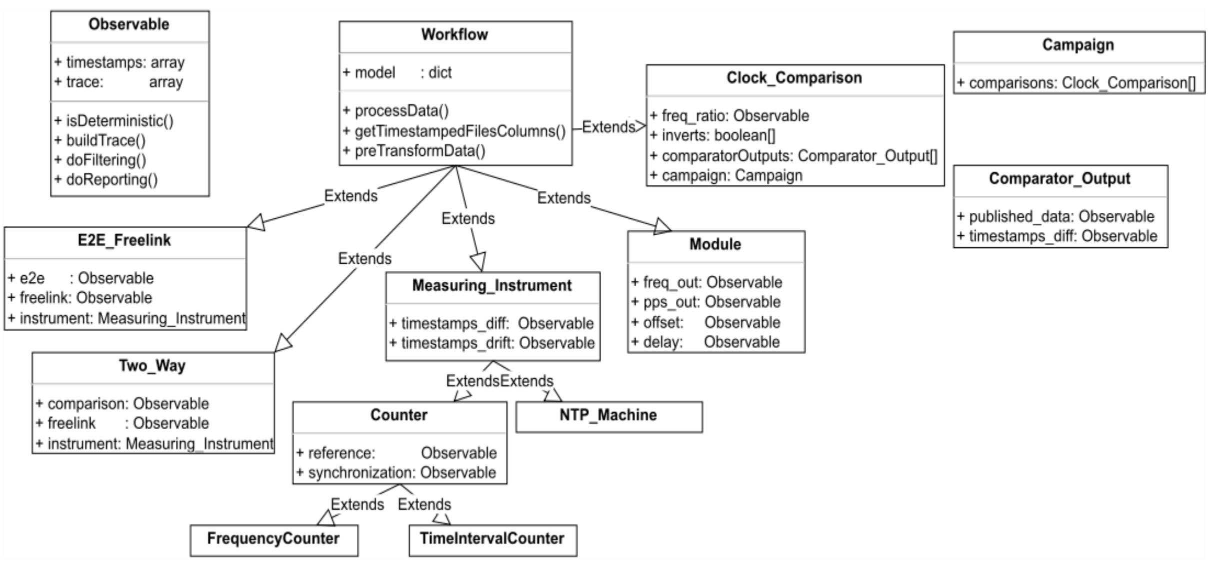

Figure 27: Global view of the software first-level design. Based on functional analysis, extensions to other transfer systems (e.g., two-way, GNSS-based, etc.) are included in the design. The boxes represent the type of data that can be aggregated from various subsystems, such as frequency measurements by counters and status information given by other hardware (as for instance NTP clients, RLSs, switches,…)

Data processing

Regardless of which *resource* is processed by the software, the **processing workflow** remains relatively similar (see Figure 28). This is evident in the software class design (see Figure 27 above) where many classes are just extensions of a main class called "*Workflow*".

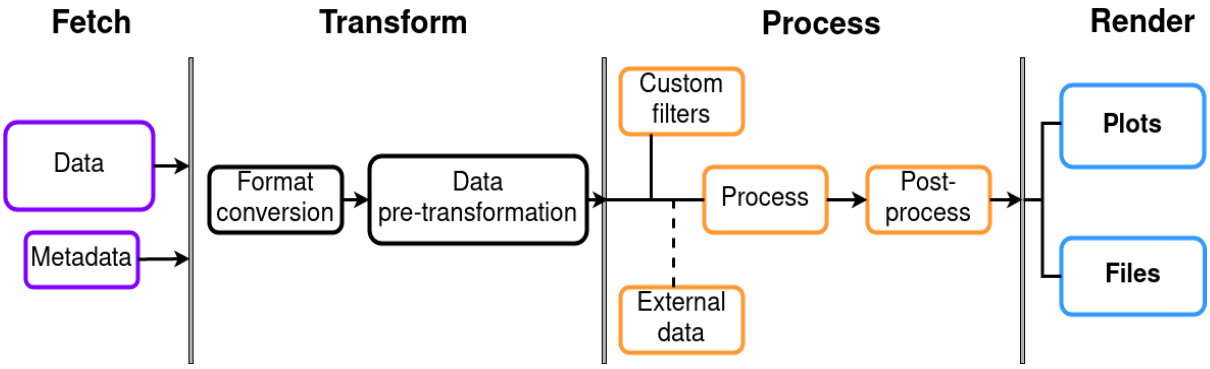

Figure 28: General design of the processing engine. The data are first fetched, then mapped to the chosen format, processed and post-processed, and finally mapped to the user's request, e.g. a plot file as shown in the figure under render.

In more detail, the processing workflow steps include:

- Fetch
  - Data: *data files* in the *data repository*
  - Metadata: *database* information
- Transform
  - Format the timestamped data to the standard format of the processing engine
  - Convert timestamps to UTC
  - Convert timestamps to MJD
  - Convert the data files to correct data types: float, integers, booleans, …
  - If necessary, operate a pre-transformation of the data to feed the *observables* before processing
- Process
  - For each *observable* (derived from a data set), retrieve its custom associated filtering parameters
  - If necessary, additionally retrieve data from external Information Systems (external contractors, seismograph networks, weather forecast, …)
  - Build the post-processed data trace (relative frequency, time difference, …) versus UTC
  - Proceed to the filtering to assess the quality of the data
  - Report results as a set of indicators (uptime, mean, ...)
- Render
  - Plots: trace, distribution, Allan deviation …
  - Data files

Data sharing

The ECN infrastructure is maintained by many stakeholders with various areas of responsibility and spheres of action. These stakeholders each own complementary information that when considered in its totality gives an overview of the whole infrastructure. Sharing relevant information between partners is therefore crucial in order to multiply the power of analysis of the infrastructure and thus improve its quality of service.

On the other hand, the ECN infrastructure aims to be a pan-European time and frequency reference system at the service of the European scientific community. Establishing an open data policy will therefore broaden its scientific impact.

The Information System must be able provide information to clients upon request, including:

- Metadata from the database
- Static data from raw files
- Dynamic data from (post)processing

Several communication protocols are used, as described below.

a. Application Programming Interfaces (APIs)

An API can be called by any program with right of access. There are different types of API calls: Create, Read, Update, Delete (CRUD).

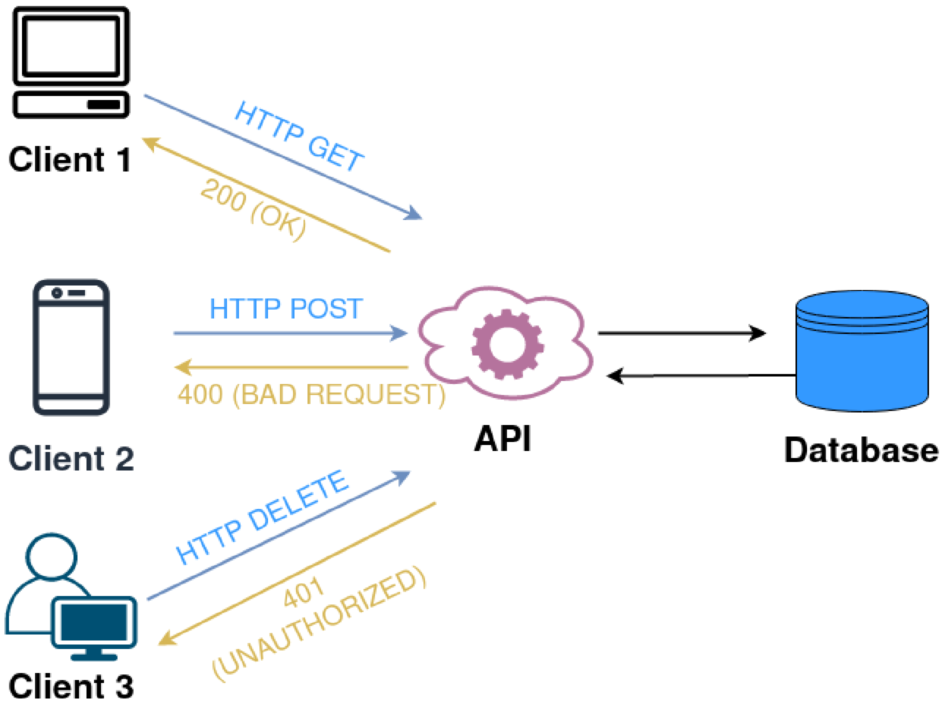

Figure 29: Synopsis of communication between machines. Machines are represented as computer, personal terminals, and externals servers. Requests are received and transmitted to the backend server and its database through an API.

Here we give an example of API communication between the Information System and a client.

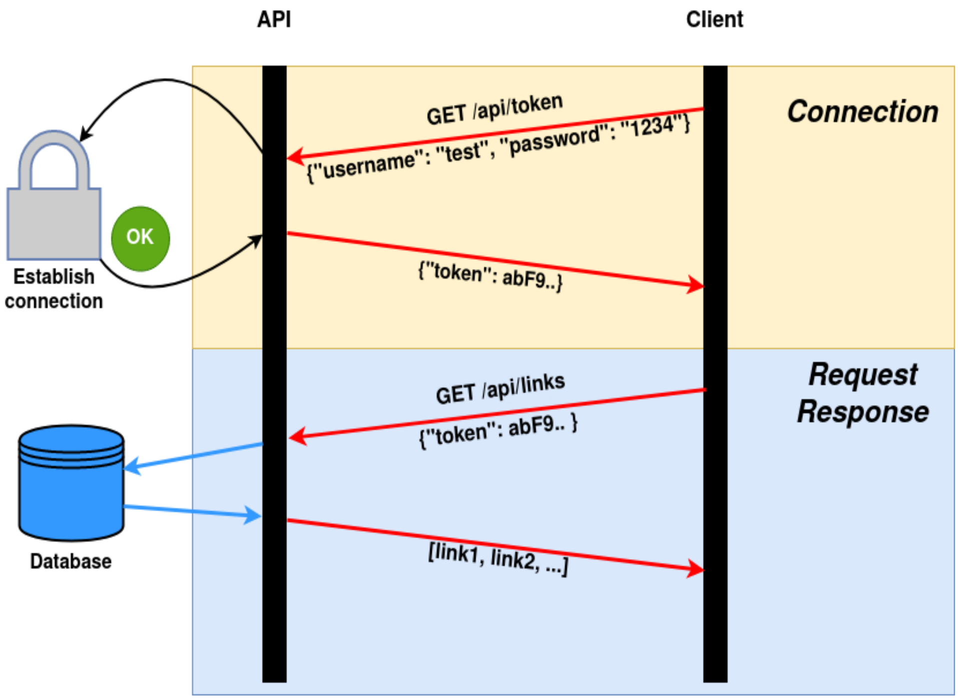

Figure 30: Security layer design. Example of an API request, including the password authentication phase. A unique token is provided to the client to allow automatic identification in future requests.

b. File Transfer

Depending on the number of columns per file in the *data repository*, the file size of one day of data measurements can be from **600 kB** to **several MB,** which can rapidly lead to very large sizes as several weeks/months/years of data may need to be shared with a single user. For this kind of usage, ***APIs*** (see above) are limited.

For the purpose of sending files to clients, Secure File Transfer Protocols **(SFTP)** are used.

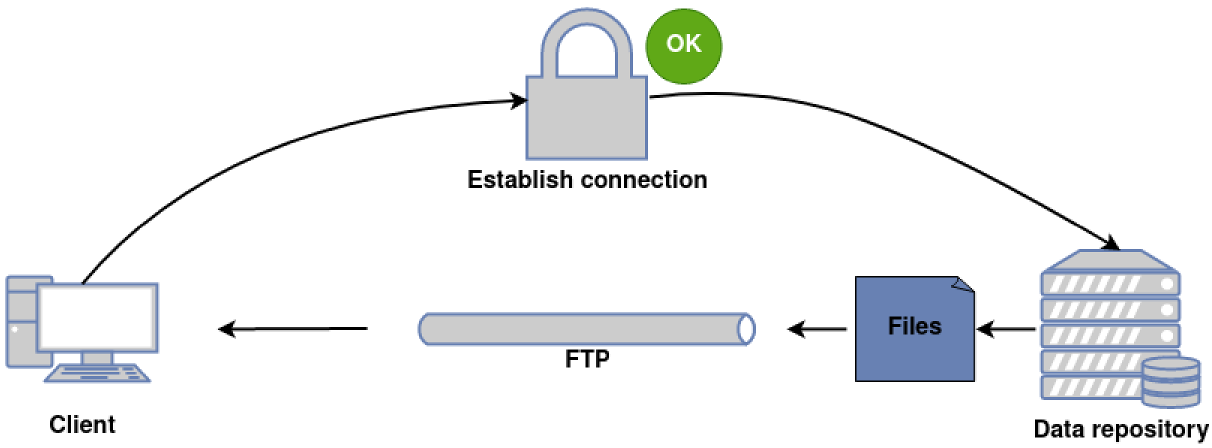

Figure 31: Communication layer design in the context of file transfers

Irrespective of the *resource* to be shared, only the correct users should be able to establish a connection with the API or the data repository and access it. This raises the question of data security.

A complete Information System

In previous sections, the following elements of an information system have been described:

- Formalising the system engineering of the ECN infrastructure.
- Transforming the formalism into a concrete data management solution with a data processing engine in order to automate:
    - The computation of clock comparisons and other scientific features.
    - The assessment of the performance of a network in terms of stability and precision of the transported signal.
- Sharing the data between the ECN's internal stakeholders and external clients.

To address data management challenges, we presented different separate solutions. However, these solutions and tools need to work harmoniously together as a **complete Information System.** A first successful attempt to implement such a system has been made in the REFIMEVE project, with the aim of expanding it to a pan-European scale.

An example of a complete Information System is given below.

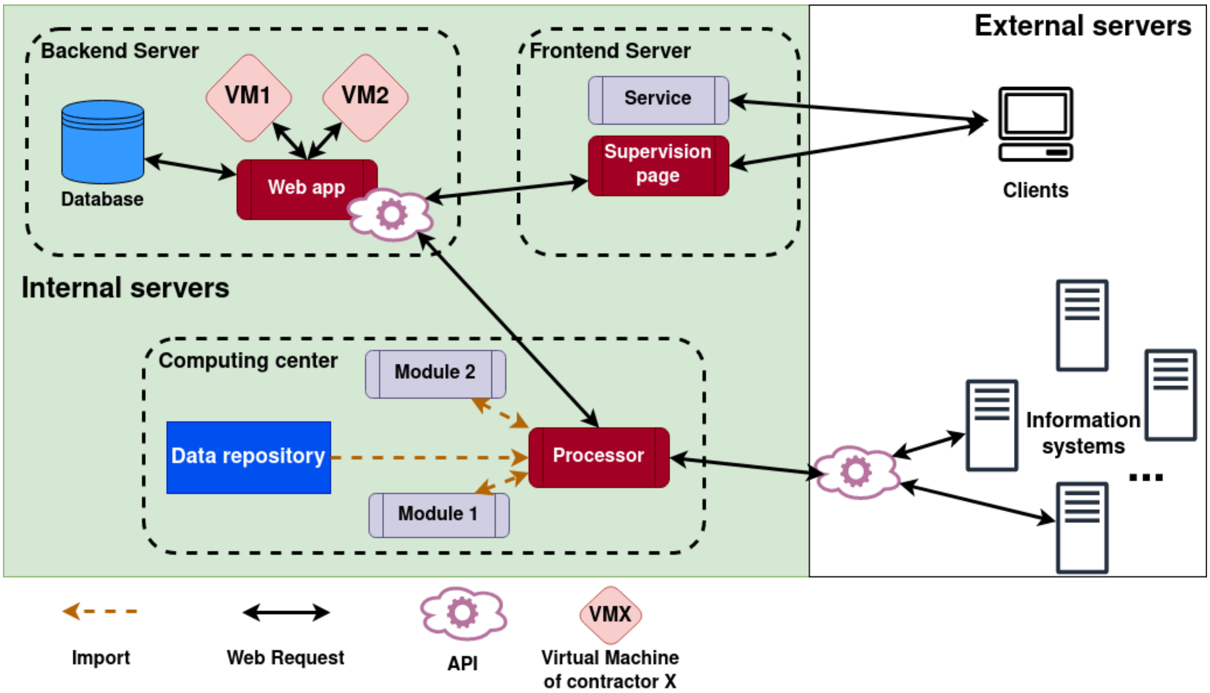

Figure 32: Design of a complete information system. This includes a frontend server, a backend server and dedicated equipment to process and store the data. Connections to external servers are also an essential functionality derived from the general design of a network by aggregation.

The main elements of a complete information system are:

- Computing centre:

  - Data repository: frequency counter files, clock comparison files, …
  - Processor and Modules: python custom packages and modules to process business logic and retrieve data from external IS
- Backend server:
  - Database: metadata storage
  - Contractors' Virtual Machines (VM): hosting their Information Systems
  - Web app: web application that fetches resources from the database, contractors' Information systems, and our data storage
- Frontend server:
  - Community services: wiki / chat / share…
  - Daily supervision: supervision webpage

Securing the Information System

CLONETS-DS data is sensitive and access to it should be controlled. Issues of security arise in particular for requests by users for data and / or complete file downloads .

a. Three-step access management

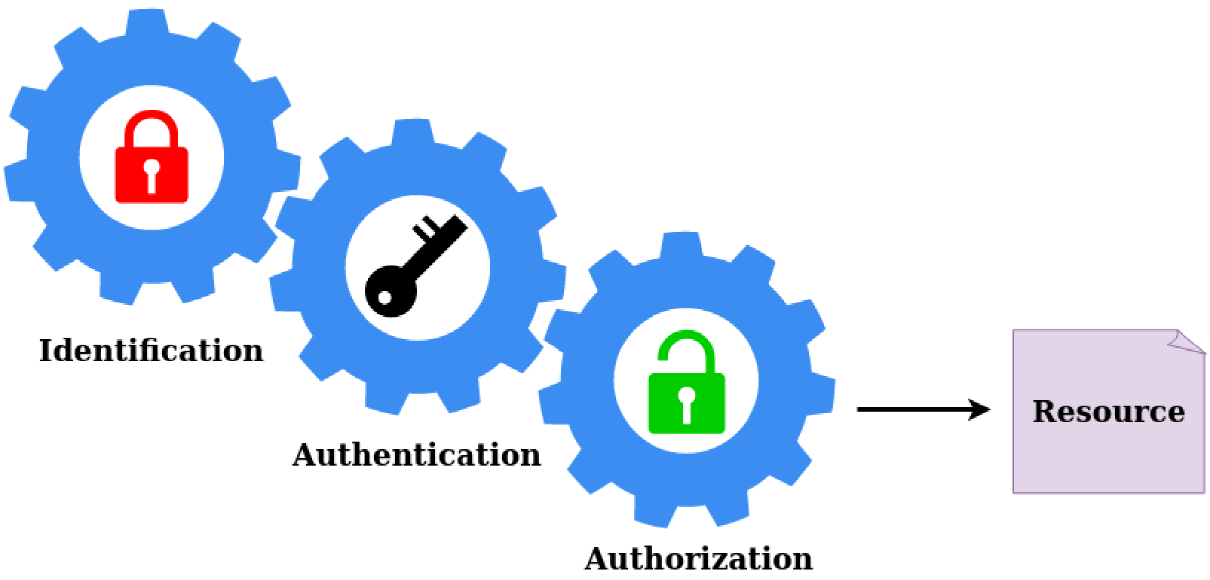

Figure 33: Three-step access management.

A three step process is required in order to secure the data acquired from the ECN network and users:

1. Identification

The user asserts their identity to the Information System using a unique identifier: username, email, phone number etc.

2. Authentication

The user needs to prove their identity through supplying one or more credentials: password, access token, SMS code, email link etc., some of which require encryption in the *database.*

3. Authorisation

The Authorisation mechanism determines the ***access levels*** of a user to a given resource. this step occurs after successful authentication.

b. A single system to define access levels

The Time and Frequency architecture to be supported by ECN involves many stakeholders with different scopes of responsibility. There are three areas of complexity in defining access levels:

- The nature of stakeholders varies, as an individual person can be part of a unit belonging to one or several institutions in the broadest sense (external contractor company, research unit, ...)
- A stakeholder may need access to data that does not fall within its scope of responsibility and scope of responsibility is not the only parameter to define access levels in ECN.
- The nature of the information accessed, via services or tools, can range from network metadata to data files from the data repository (see Figure 32). These different sources of information are not found in the same location (physically or numerically speaking). This holds true both at a network and pan-European level.

Considering the complexity of the network and its corresponding Information System, it is impossible to envisage putting in place different systems of verification for each tool/service/data folder. Conversely, a centralised system presents the following main advantages:

- Single system to maintain
- Single system to protect/secure
- Single credential to remember per user
- Single profile per user for the whole Information System

This is why we chose to set up a user charter on the backend server, making it possible to:

- Assure conformity between the access rules of the user charter with the access rules set up on the server, which hosts the data repository (see Figure 34).
- Define access rules for the services provided by the Information System
- Enable the software modules we develop to fetch user information to make customised and evolving decisions.

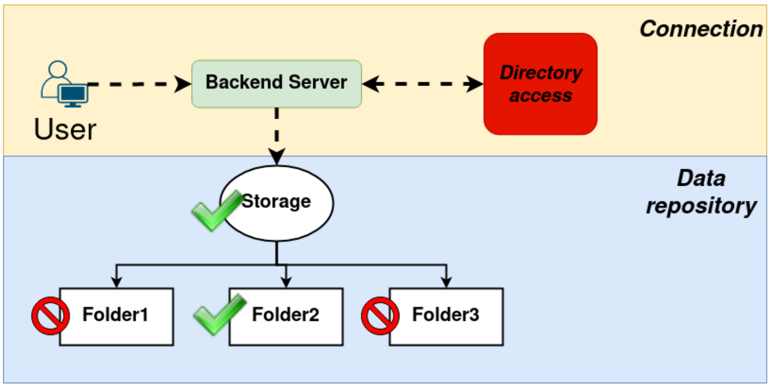

Figure 34: Example of access level rules applied to a data repository.

2.1.5.4 *Supervision System*

From an engineering point of view, the supervision system relies on:

- The capacity to communicate with the deployed equipment of each subsystem
- The hardware capacity to communicate and receive control commands
- A network operating centre
- A computing centre
- The capacity to manage dependencies between subsystems

To communicate with the deployed equipment, the fibre infrastructure can be used. Fibre links carrying data traffic parallel to the ECN can be established. In order to avoid single points of failure, the equipment should be accessible via data traffic fibre links from the previous location as well as from the next location, which aligns well with ECN ring topology. When the fibre links of the ECN are established in partnership with an NREN, connectivity is organised by the NREN.

The hardware must have an ethernet interface, and a local operating system to allow secured connections. The hardware must be compatible with SNMP traps (Simple Network Management Protocol), a protocol used in the network to communicate machine-to-machine.

The network operating centre continuously monitors the vital signs of the network, logging their status (on/off, temperature, voltage outputs of power supplies,…) as defined by the manufacturer, and raises the alarm when a device deviates from its normal operating conditions.

The computing centre integrates information from all over the network (see the previous section 'Information System') and calculates the performance of the delivered signal to the users. The computing centre must be able to identify possible reasons for dysfunction, and raise the alarm and call for maintenance accordingly.

Proposed solutions for monitoring the T&F reference system

Most if not all the devices commercially available for dissemination feature communication and remote control and SNMP trap capacity.

Connectivity to equipment is sometimes provided by an NREN, and at other times designed and set up by a laboratory/NMI (at various wavelengths). In the case of a partnership with an NREN, the network operating centre can be jointly used, whereby the NREN can host the supervision system of a given subcontractor.

Manufacturers generally provide monitoring systems with their equipment, such as a client-server software, monitoring tools and webpage interfaces. In some cases, open software such as Nagios and Zabbix is customised and used (see for example the WRiTE project [5]). Such monitoring systems are under already in operation at least in France, Italy, and Poland.

However, three issues must be addressed:

- Firstly, the signal source is not usually compatible with machine-to-machine capacity. In some research laboratory / national metrology institute(s), efforts were made to continuously measure the frequency of the delivered signal and these data were integrated in a computing centre but there is still no capacity to remotely control the signal source. Some EU manufacturers have developed remote control of the laser/maser source. However, these new features have not yet been implemented in an active metrological network, to the best of our knowledge.
- The second issue is that the user system presents a problem, in that as part of the user set-up it is under the responsibility of the user and not of the network operator. This implies that remote access to the user system might create network security issues. This technical challenge can be overcome, but to date no clear guidelines or a best practice guide exist, to the best of our knowledge.
- Finally, a solution is required to enable communication between supervision software. One possible solution is to use an API (Application Programming Interface). Within this pilot study we were able to exchange information between subsystems, such as for instance the laser source and dissemination systems. Nevertheless, there is still work ahead to enable the computing centre to take action on the equipment and optimise the supervision system.

2.1.5.5 *Maintenance System*

Once the network is built, the system must be maintained to provide consistent services to scientific users. All the subsystems mentioned above must be maintained: the source, the transportation, the user modules, the cross-points, the information system and the supervision system. There are three classes of maintenance: preventative, repairs, and replacements.

The average time for failure of the source and transportation systems is about 10 to 15 years, according to the components' specifications. As a matter of fact, repairs are rare: for instance, in REFIMEVE, the oldest repeater laser stations (industrial grade) have been in continuous operation for 7 years. Among about 50 bi-directional amplifiers set-up in the REFIMEVE network, only 5 underwent repairs. Other parts of the instrumentation need to be routinely repaired, checked and replaced, such as frequency counters, distribution amplifiers, spectrum analysers, etc. …. Short repair times require testing and qualification of spare instrumentation prior to installation.

The primary maintenance activities in terms of short time scales between "repairs", relate to maintaining phase and frequency locks of laser sources, RF sources and transport systems, as well as remote instrumentation relaunch. The cross-points need regular checks and should be considered as particularly sensitive spots.

It should be mentioned that maintenance also deals with firmware updates, which are essential for a system with remote control, and the update of the operating systems of computers and equipment in the network.

Last, but not least, maintenance concerns fibre cuts, which happen quite often on a large fibre network. For instance, in REFIMEVE, there are typically between 1 to 10 fibre cut(s) per year over 2x3500 km of deployed fibre. Repairing the fibre is usually managed as part of the contract granting access to the fibre, and the repair times will depend on the contract (essentially shorter repair times equal higher costs).

The number of full-time jobs required for maintenance of the ECN within a single country is less than 1, but this single full-time employee must possess a wide range of skills and knowledge of diverse subsystems. A substantial part of this activity includes work in the field, about 30 to 60 days (including preparation and reporting and documentation) for a national network.

Proposed solutions for maintenance of the T&F reference system

The organisation of a comprehensive pan-European maintenance of the ECN would be challenging. A proposed solution is to delegate the task to the individual national networks for the maintenance of the cross-points. The maintenance of the sources and the transportation systems should be subcontracted directly to manufacturers or to those NRENs that play a major role in the ECN by providing fibres or operational capability.

2.1.5.6 *Management system*

The management system is crucial for coordination between subsystems, with subcontractors and with national networks. The management system is mainly concerned with the governance of the regulatory and decision-making bodies and the management of the financial aspects.

These aspects are specifically addressed in Work Package 3 and in Deliverable *D3.1 Governance and Sustainability*, which:

- Sets out principles of cooperation between partners that will underpin the setup and potential evolution of the community membership, and lays the groundwork for all governance of the CLONETS Research Infrastructure.
- Defines the conditions for joining or leaving the infrastructure.
- Proposes an organisational structure for CLONETS, including principles of cooperation between partners along with their rights and obligations, and assignment of specific roles.
- Derives a policy framework for using the services of the infrastructure.
- Provides a financial strategy for the implementation phase and the viable sustainability of the CLONETS infrastructure.

3 Definition of Core Sites (Subtask 2.1.2)

So far, in sections 1 and 2 of this document, we have described the overall technical design of the ECN without focusing on which PoP locations across Europe will be required to meet the users' needs. In this section we detail where the hardware described above should be located and the necessary fibre links to connect these locations and achieve the proposed ring topology.

Based on the science cases and PoPs set out in WP1 Deliverable *D1.2 Requirements and Definition*, as part of task 2.1.2 we carried out a prioritisation of core sites and the associated future extensions of the ECN. It is assumed that at each core site all necessary equipment for interfacing with scientific users (SUs), performing T&F measurements, monitoring and supervision must be made available. As described in section 2.1.1, users access to the T&F reference system either to perform direct measurements against the signals provided by the ECN or to extract the signal and transmit it to their own user site.

Also as part of task 2.1.2, a 1st phase implementation of the ECN that will feed the roadmap for the engineering plan for *D2.2 Roadmap for Technical Implementation* has been drawn up. Since the science cases, users and associated research institutes across Europe can change over time, extending access to the ECN must also be considered. Therefore, a scenario for a 2nd phase has been drafted, which will also be included in Deliverable D2.2. This subtask additionally worked in close collaboration with WP3, T3.2 to balance budgetary implications of the estimated total cost of ownership for the design decisions.

3.1.1 Identification of Science Case Users and Associated PoPs

In WP1, as described in more detail in Deliverable *D1.2 Requirements and Definition*, feedback in the form of questionnaires and interviews was collected from 68 organizations representing 13 countries throughout Europe and expertise in different fields of research including fundamental physics, metrology (e. g. optical clocks), geodesy, very long baseline interferometry (VLBI), telecommunication, and navigation.

In an iterative process, the feedback collected from the questionnaires, interviews and during a stakeholder workshop was used to critically assess the science areas and create a consolidated list of 5 Science Cases and 16 associated applications with the highest stakeholder need and impact.

This consolidated list of Science Cases and their associated applications is as follows:

Science Case 1: Fundamental Science

- Precision spectroscopy to search for new physics beyond standard model (BSM) physics
- Improvement of optical clocks
- Redefinition of the SI-second

Science Case 2: Quantum Technologies

- Improving real-world QKD

- Developing new protocols
- Entanglement distribution beyond QKD

Science Case 3: Earth Observation / Geodesy

- Height system unification
- Satellite gravity mission validation
- Geodetic network consistency

Science Case 4: Astronomy

- Radio interferometry and VLBI in astronomy
- Laser Ranging
- Pulsar timing

Science Case 5: Telecommunication and Networks / Position, Navigation, and Timing

- Optical timescales
- Position, Navigation & Timing, PNT
- Resilience for GNSS
- Supervision of Telecommunication networks and Synchronisation (5G or 6G)

An ECN can enable scientific advancements for these science cases which would not otherwise be possible because, as confirmed by the stakeholders, these require:

a. a comparison of time and frequency signals from multiple sources via a network;
b. and/or time and frequency signals that exceed the performance that can be realised by single research institutions, despite major efforts and investments into installations of commercial time and frequency products.

The locations associated with each science case are shown in the maps in figures 35 and 36: the maps in Figure 35 show the Points of Presence for each of the five individual Science Cases; Figure 36 shows all PoPs for all five science cases as well as those of the French REFIMEVE network [33].

The PoPs for each science case are listed in Table 2.

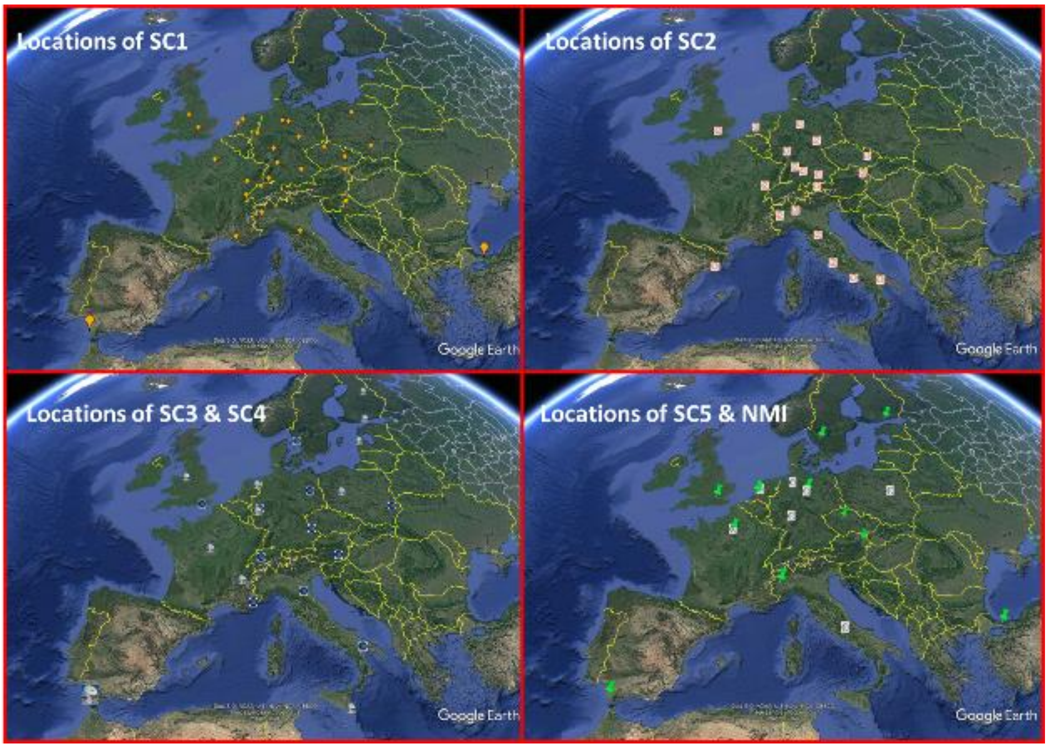

Figure 35: Map of stakeholders for the five individual science cases SC 1—5 identified in WP1.

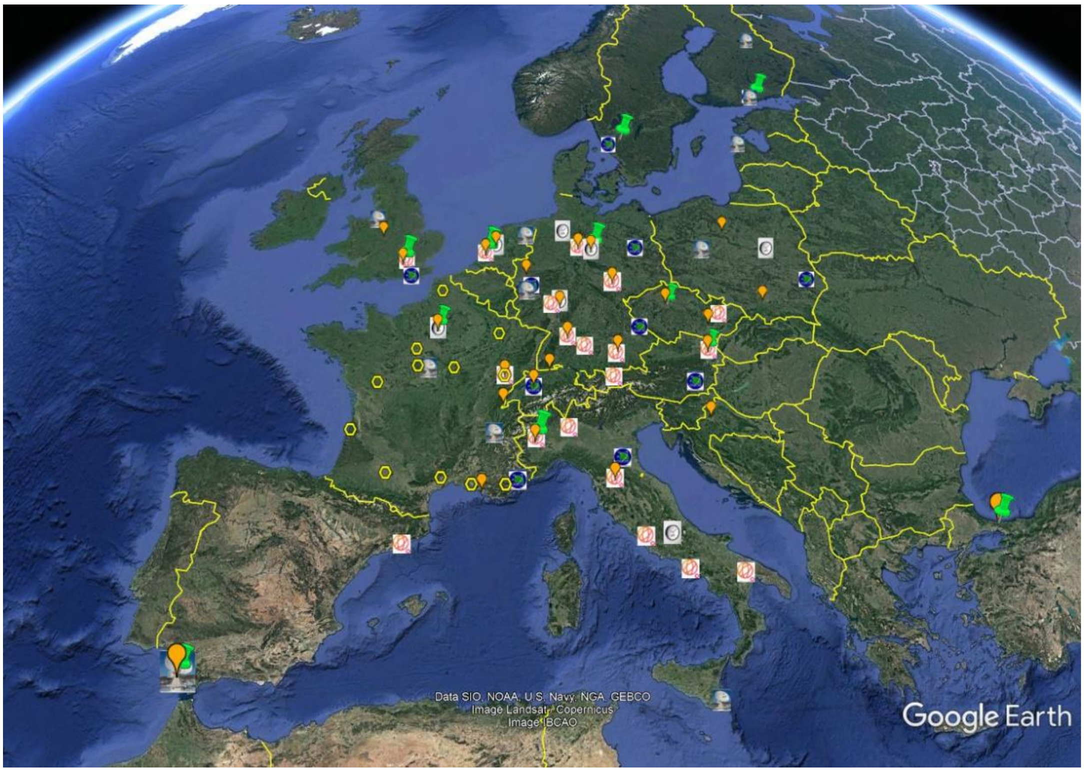

Figure 36: Locations of Science Cases 1-5 across Europe including locations of the REFIMEVE Network in France.

Science Case	Points of Presence (PoPs)
1 Fundamental Science	Vienna (AT), Bern (CH), Geneva (CH), Villigen (CH), Prague (CZ), Braunschweig (DE), Darmstadt (DE), Düsseldorf (DE), Garching (DE), Hannover (DE), Jena (DE), Mainz (DE), Stuttgart (DE), Cadiz (ES), Besancon (FR), Marseille (FR), Paris (FR), Zagreb (HR), Florence (IT), Torino (IT), Amsterdam (NL), Delft (NL), Krakow (PL), Torun (PL), Istanbul (TY), Birmingham (UK), London (UK).
2 Quantum Technologies	Olomouc (CZ), Hannover (DE), Mainz (DE), Munich (DE), Stuttgart (DE), Ulm (DE), Vienna (AT), Innsbruck (AT), Barcelona (ES), Besancon (FR), Torino (IT), Matera (IT), Firenze (IT), Roma (IT), Milano (IT), Napoli (IT), Delft (NL), London (UK), all 27 European members states of the Europe Communication Infrastructure (EuroQCI).
3 Earth Observation / Geodesy	Bonn (DE), Wettzell (DE), Browiec (Poland), Herstmonceux (UK), Potsdam (DE), Grasse (F) Onsala (S), Zimmerwald (CH), Matera (I), Medicina (I), Ny Alesund (N), Metsahovi (FIN), Graz (AT).
4 Astronomy 	Graz (AT), Zimmerwald (CH), Effelsberg (DE), Potsdam (DE), San Fernando (ES), Kirkkonummi (FI), Grasse (FR), Grenoble (FR), Nancay (FR), Medicina (IT), Noto (IT), San Basilio (IT), Matera (IT), Ventspils (LV), Westerbork (NL), Borowiec (PL), Piwnice (PL), Onsala (SE), Cheshire (UK), Herstmonceux (UK).
5 Telecommunication and Networks/ Position, Navigation, and Timing 	Braunschweig (DE), Bremen (DE), Frankfurt (DE), Paris (FR), Amsterdam (NL), Warsaw (PL), all UTC(k)/NMI locations.

Table 2: List of science cases and potential users.

3.1.2 Mapping a Ring Topology onto Science Case (SC) PoPs

As introduced in 2.1.4, we propose an overlapping ring topology approach to the ECN in order to connect the majority of the points of presence across Europe associated with the five science cases, as shown in Figure 36. Specifically, we propose here that the ECN should comprise three rings covering the northern, middle and southern regions of Europe, as shown in

Figure 37. The three rings should co-share the overlapping sections on their north or south sides, respectively, as introduced in the simplified schematic in Figure 11 and shown in detail in the European map in Figure 38. This overlapping ring topology allows for parallel or sequential development depending on the priority of user needs and effort required for the completion of individual rings.

As seen in Figure 38, an ECN constructed as an overlapping ring topology could provide access to the majority of PoPs associated with the science cases. Furthermore, each ring of the ECN has been planned so that it includes at least two NMIs with optical clocks. The PoPs not explicitly linked via this proposed three-ring ECN infrastructure, e.g., Innsbruck, Austria, could nonetheless be provided service if the ECN is extended within the country. This is particularly relevant, for example, for service provision in Spain and Turkey, in which case a linear extension similar to the Italian LIFT network could be added.

It is also notable that this proposed European Core Network would be ground-breaking in that it would interlink all VLBI stations across Europe via a fibre network that supports optical time and frequency distribution. We anticipate that such interlinking of VLBI stations via a fibre network will benefit areas of astronomy that exploit observations from multiple sites and/or using multiple techniques. A prime example is VLBI for astrometry, where it will allow improved data analysis with the potential for new discoveries and possible improvements to the celestial reference frame. Moreover, this proposed ECN would interlink telecommunications PoPs across Europe and pave the way for Galileo, a global navigation satellite system, to exploit optical clocks based at ground stations.

Figure 37: Achieving SC coverage using three-ring topology to connect users across Europe*
*Northern Ring (white), Middle Ring (red), Southern Ring (orange) together with the French REFIMEVE network (yellow) and the Italian LIFT network (green).

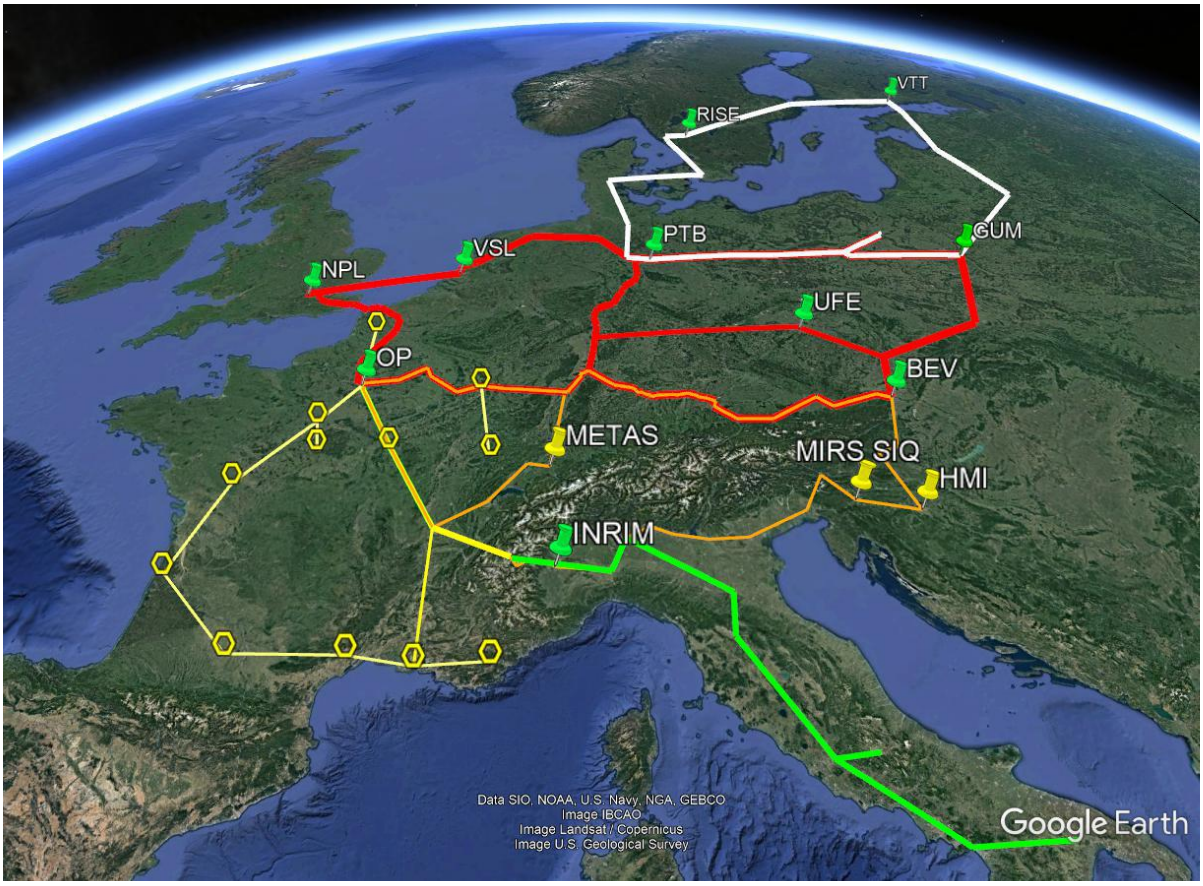

Figure 38: View of the proposed European core network (ECN) as an overlapping ring topology, with northern (white), middle (red) and southern (light orange) rings. The overlapping links between the northern and middle rings and the middle and southern rings are shown in pink and orange, respectively.

3.1.3 Existing Infrastructure and Missing Links.

When defining the core sites detailed in the next section, we first considered that to a large extent existing infrastructure across Europe, for example the National Metrology Institutes (NMIs) and the fibre links that provide point-to-point connectivity between RIs and NMIs, should form part of the ECN.

NMIs serve as external providers of Universal Coordinated Time (UTC(k)) and maintain the most cutting-edge optical clocks and ultrastable lasers worldwide. Integrating the NMIs into the ECN would be necessary for providing traceability to the SI second as well as access to time and frequency signals that have so far only been available at national metrology institutes or a few laboratories around the world. Future agreements between the ECN and the European National Metrology Institutes are addressed in Work Package 3.

Table 3 below lists the NMIs by country along with their addresses.

Country	NMI Name	NMI Address
Austria	BEV	Bundesamt für Eich- und Vermessungswesen (BEV), Arltgasse 35, A-1160 Vienna, Austria
Czech Republic	UFE	Institute of Photonics and Electronics (UFE), CAS, Chaberská 57, 18251, Praha 8 - Kobylisy, Czech Republic
France	OBSPARIS	Laboratoire national de métrologie et d'essais (OP), Système de Références Temps-Espace, 61 Avenue de l'Observatoire, F-75014 Paris, France
Germany	PTB	Physikalisch- Technische Bundesanstalt (PTB), Bundesalle 100, D-38116 Braunschweig, Germany
Italy	INRIM	L'Istituto nazionale di ricerca metrological (INRIM), Strada delle Cacce 91, 10135 Torino TO, Italy
The Netherlands	VSL	VSL, Thijsseweg 11, 2629 Delft, Netherlands
Switzerland	METAS	Eidgenössisches Institut für Metrologie (METAS), Lindenweg 50, CH-3003 Bern-Wabern, Switzerland
Poland	GUM	Central office of meausres (GUM), ul. Elektoralna 2, 00-139 Warszawa, Poland
UK	NPL	National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK
Finland	VTT	VTT MIKES, Tekniikantie 1, 02150 Espoo, Finnland
Sweden	RISE/SP	RISE; Brinellgatan 4, 504 62 Borås, Sweden
Lithuania	FTMC	State research institute Centre for Physical Sciences and Technology (FTMC), Savanorių ave. 231, LT-02300 Vilnius, Lithuania

Table 3: Postal address of NMIs providing UTC(k) likely to contribute to the envisaged CORE network for time and frequency

Table 4 gives an overview of existing fibre links across Europe. Note that some existing fibre links distribute time and frequency signals from NMIs while others belong to NRENs that do not provide such a service. This is detailed in table 2.4 and table 2.5 of deliverable D.2.2.

NMIs have developed and achieved outstanding results in time and frequency dissemination via optical fibres for over 10 years, through project funding primarily from EURAMET, the European

Association of National Metrology Institutes, supplemented by institutional and/or national funding. These links are listed in Table 4, Column 2 (Existing T&F fibre links). Due to the project-funded nature of these fibre links from the NMIs to national users and other NMIs, their assured long-term use for the purposes of the ECN varies. We have graded the status, at the time of writing this report, of the long-term availability of the fibre links in the following way and this information is noted in Table 4, Column 3:

- 0: no long-term funding scheme
- 1: long-term funding assured for 5 years or less
- 2: long-term funding assured for 10 years or less
- 3: long-term funding assured for over 10 years

Furthermore, many countries have taken further steps to ensure long-term funding not only for these individual fibre links but also for a comprehensive national fibre network for time and frequency dissemination. These proposed national fibre networks for time and frequency dissemination are at various stages of completion and are listed in Table 4, Column 4. The National Research and Education Networks (NRENs) also play an important role in establishing a long-term national fibre network for time and frequency dissemination that supports novel applications in fundamental research. Table 4, Column 5 lists the NRENs of the European countries for reference.

A map of the existing links detailed in Table 4 is shown in Figure 39 alongside the REFIMEVE network (yellow). Also shown in Figure 39 are the missing fibre links required to complete the overlapping ring topology as shown in Figure 38. All the missing fibre links that would be required to complete the proposed ECN are intercontinental links. These are listed in Table 5 along with a detailed breakdown of the missing links. The priority assigned to the missing links in Table 5 is assigned based on a phased implementation of the proposed rings. The middle ring should be completed with the highest priority because it establishes many overlapping fibre links, intercontinental links and access to a large percentage of the science users in combination with REFIMEVE and LIFT. The priority of the southern link, northern link and extentions are ranked according to the percentage of science users granted access, from highest to lowest respectively.

	Country	Existing T&F fibre links	Long-term availability*	Proposed national fibre networks for T&F	National NRENs
1	Austria	from BEV to Innsbruck and BEV to Brno	1 3	In progress	ACOnet,
2	Czech Republic	from UFE to ISI, Vienna, Bratislava and Cieszyn	3	Czech Infrastructure for Time and Frequency (CITAF)	CESNET
3	France	many links, also cross-border	3	REFIMEVE	RENATER
4	Germany	from PTB to Hannover, Garching and Paris, France	1	None	DFN
5	Italy	from INRIM to Sicily and Modane, France	3	Italian Quantum Backbone	GARR
6	The Netherlands	from VSL to ESTEC, Groningen	2	In progress	SURF
7	Switzerland	from METAS to Basel; from Basel to Zurich	2 2	In progress	SWITCH
8	Poland	GUM-AOS; FAMO; OC test link Toruń – Poznań	3	In progress	PIONIER
9	UK	from NPL to Birmingham and Paris, France	1 1	NDFF	JANET / Jisc
10	Finland	From VTT to Kajani and SP, Sweden	3 1	None	FUNET
11	Sweden	From SP to Onsala and Stockholm	2 2	None	SUNET
12	Lithuania	From GUM (PL) to Vilnus	0	None	
	web address				
	ACOnet (Austria) CITAF (Czech Republic) REFIMEVE (France) DFN (Germany) IQB (Italy) PSNC (Poland) NDFF (United Kingdom)		https://www.aco.net/backbone.html?L=1 https://citaf.org/en/index https://www.refimeve.fr/index.php/en/ https://www.dfn.de/en/ https://www.inrim.it/en/node/654 https://www.psnc.pl/ https://www.ndff.ac.uk/		

Table 4: Overview of existing fibre links in Europe
*0: no long-term funding scheme - 1: long-term funding assured for 5 years or less - 2: long-term funding assured for 10 years or less - 3: long-term funding assured for more than 10 years

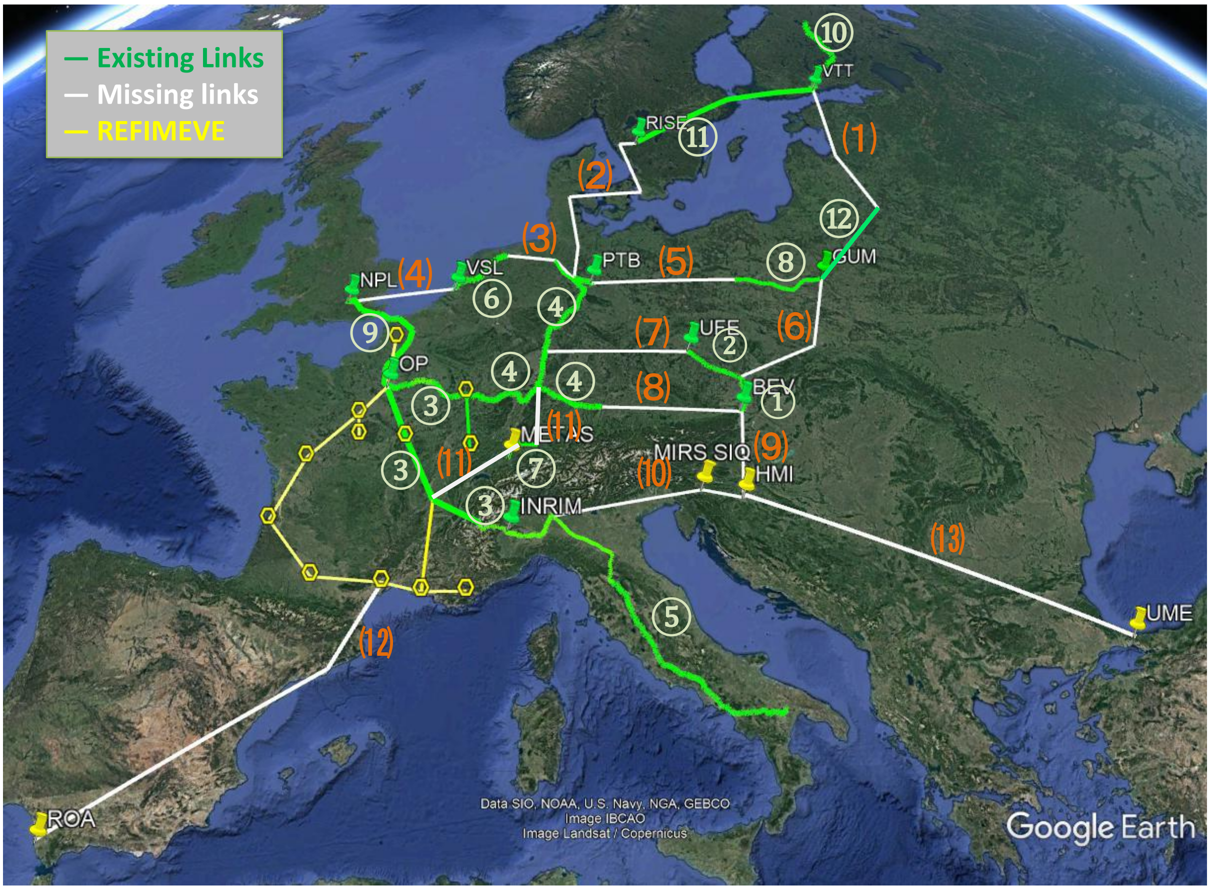

Figure 39: Map showing existing links (green) and missing links (white) that would enable the envisaged ring topology. The numbers in circles refer to the positions in Table 4 (existing NIs), whereas the numbers in parenthesis to the positions in Table 5 (missing links). The REFIMEVE network currently under development in France is shown in yellow.

	Intercontinental Link	Required connections	Ring	Priority
1	Poland – Finland	GUM (Warsaw) – Lithuania – Latvia – Estonia (Tallin) – VTT (Espo)	Northern	5
2	Sweden – Germany	SP (Boras) – Onsala – Denmark – Hamburg – Hanover	Northern	6
3	Germany – The Netherlands	DTAG (Bremen)– Groningen	Northern	9
4	The Netherlands – UK	Amsterdam – London – NPL	Northern	7
5	Poland – Germany	PSNC (Poznan) – Slubice – Berlin – PTB (Braunschweig)	Middle	1
6	Poland – Czech Republic	ISI (Brno) – AGH (Karkow) – GUM (Warsaw)	Middle	1
7	Czech Republic – Germany	CMI (Prague) – Frankfurt	Middle	10
8	Austria – Germany	BEV (Vienna) – Munich (MPQ)	Middle	3
9	Austria – Croatia	BEV (Vienna) – Zagreb (DZM)	Southern	4

	Intercontinental Link	Required connections	Ring	Priority
10	Croatia – Slowenia – Italy	Zagreb- Milano	Southern	8
11	France – Switzerland	Lyon – CERN[1] –METAS (Bern) – Strasburg	Southern	3
12	France – Spain	Toulouse- Cadiz (ROA)	side branch	11
13	Zagreb – Istanbul	Zagreb - UME	side branch	12

Table 5: List of missing fibre links required to provide access to nearly all institutions carrying out research on the 5 science cases identified by WP1 showing tentative implementation priority.

3.1.4 Definition of the European Core Network

We conclude this deliverable by defining the core sites and their function within the European Core Network. The roadmap introduced in *D2.2 Roadmap for Technical Implementation* is based on these core sites, which have been chosen because they serve a fundamental role in the ECN. Core sites should enable connection to an NMI or several users, or provide a cross-border link (responsibility shift e.g., Strasburg), and/or good branching station.

Furthermore, based on the topology presented in section 2.1.2, we are convinced that these core sites will enable the realisation of the ECN across Europe with the potential for further expansion. For example, due to its low number of users, San Fernando, located in the southwest corner of Spain, would not be a cost-effective core site in Phase 1, during which the ECN is being built and established. We address in further detail how the existing fibre network infrastructures can be interconnected to realise the ECN in Deliverable D2.2. Nevertheless it should be noted here that REFIMEVE would serve as a sub-net providing strategic fibres for the EU Network. The political and regulatory constraints involved when setting up the ECN in this way as well as the cost analysis are addressed in detail in Work Package 3.

[1] Lyon-Grenoble-CERN is operational since March 2023.

Core Site	Function	Address[2]
Bern	PoP/ NMI	METAS, Eidgenössisches Institut für Metrologie Lindenweg 50, CH-3003 Bern-Wabern
Boras	PoP/ NMI	RISE; Brinellgatan 4, 504 62 Borås, Sweden
Braunschweig	PoP/ NMI	PTB, Bundesallee 100, D-38116 Braunschweig
Brno	PoP/ NMI	ISI, Institute of Scientific Instruments, Královopolská 147, 612 00 Brno-Královo Pole, Czech republic
Bruessels	PoP/ NMI	SMD, FPS Economy, DG Quality and Safety, Metrology Division (SMD), Koning Albert II laan 16, 1000 Brussels, Belgium
Delft	PoP/ NMI	VSL National Metrology Institute Thijsseweg 11, 2629 JA Delft, The Netherlands
Espoo	PoP/ NMI	VTT MIKES Metrologia, Tekniikantie 1, 02150 Espoo, Finland
London	PoP/ NMI	NPL, National Physical Laboratory Hampton Rd, Teddington TW11 0LW, UK
Lublijana	PoP/ NMI	*MIRS/SIQ,* Slovenian Institute of Quality and Metrology/Metrology, Mašera-Spasićeva ulica 10, SI-1000 Ljubljana, Slovenia
Paris	PoP/ NMI	LNE-SYRTE - Observatoire de Paris, 61, avenue de l'Observatoire, 75014 Paris, France
Prague	PoP/ NMI	UFE, Institute of Photonics and Electronics of the Czech Academy of Sciences, Chaberská 1014/57, 182 00 Praha 8-Kobylisy, Czech Republic
Riga	PoP/ NMI	LATMB, LNMC Metrology Bureau, Kr. Valdemara street 157, 1013 Riga, Latvia
Tallin	PoP/ NMI	Metrosert, AS Metrosert, Teaduspargi 8, 12618 Talinn, Estonia
Torino	PoP/ NMI	INRIM, Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 91, 10135 Torino
Vienna	PoP/ NMI	BEV, Bundesamt für Eich- und Vermessungswesen Arltgasse 35, 1160 Wien, Austria

[2] NMI addresses according to https://www.euramet.org/contact-search

Core Site	Function	Address[2]
Vilnius	PoP/ NMI	FTMC, Centre for Physical Sciences and Technology: Metrology Department, A.Goštauto str. 11, 01108 Vilnius, Lithuania
Warszaw	PoP/ NMI	GUM, Central Office of Measures, Elektoralna 2, 00-139 Warszawa
Zagreb	PoP/ NMI	DZM, State Office for Metrology, Capraška 6, 10000 Zagreb, Croatia
Basel	Cross-border PoP	To be defined, e.g. GÉANT PoP
Malmo	Cross-border PoP	To be defined
Modane	Cross-border PoP	LSM, Laboratoire Souterrain de Modane, Carré Sciences, 1125 Rte de Bardonnèche, 73500 Modane, Frankreich
Ogrodniki	Cross-border PoP	Hołny Meyera 3A, 16-500 Holny Mejera, Poland
Slubice	Cross-border PoP	DFN- PSNC, Kosciuszki 1, PL 69-100 Slubice, Poland
Strasbourg	Cross-border PoP	Université de Strasbourg, Direction du numérique, Pôle Datacentre et Campus Connectés, 14 rue René Descartes, FR-67084 Strasbourg
Suwalki	Cross-border PoP	ul. Noniewicza 10, pok. 013 Sulwalki, Poland
Bologna	PoP, Branching	INAF- Istituto di Radioastronomia - Stazione di Medicina, Via Fiorentina, 3513, 40059 Medicina BO, Italy
Karslruhe	PoP, Branching	KIT, Karlsruher Institut für Technologie, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen
Milano	PoP, Branching	Istituto di Fotonica e Nanotecnologie – CNR (INFN) Piazza Leonardo da Vinci 32, 20133 Milano
Munich/ Garching	PoP, Branching	MPQ, Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching
Amsterdam	PoP	University of Amsterdam, Laser Lab, Science Park 904, 1090 GL Amsterdam
Copenhagen	PoP	To be defined
Frankfurt	PoP	To be defined, e.g. GÉANT PoP
Hannover	PoP	Leibniz University, Welfengarten 1, 30167 Hannover, Germany
Hamburg	PoP	To be defined, e.g. GÉANT PoP

Core Site	Function	Address[2]
Helsinki	PoP	Metsähovi Radio Observatory, Metsähovintie 114, 02540 Kirkkonummi, Finnland
Kajaani	PoP	VTT Technical Research Centre Ltd., Tehdaskatu 15, 87100 Kajaani, Finnland
Onsala	PoP	Onsala Space Observatory, 439 92 Onsala, Sweden
Poznan	PoP	Jana Pawla II 10, 61-139 Poznan, Poland
Stockholm	PoP	To be defined

Table 6: List of potential sites of the core network.

4 Conclusions

In this deliverable we have outlined a first version of a Time-and-Frequency (T&F) architecture for a European network that supports the high level science cases (SC) that have been analysed and defined in WP1. The aspiration of CLONETS-DS is that this network should extend across Europe and serve as a European Research Infrastructure that enables dedicated T&F services, providing users with reference time and frequency signals by using deployed optical fibres that allow the compensation of phase perturbations and propagation delays.

In section 2.1.2, we have provided a bird's eye view of a generalised topology for the technical design of the ECN, starting from the description of the general concept of the services we have identified in collaboration with WP1 down to the necessary hardware.

The necessary functionalities and details of the hardware required for the network in the form of building blocks from which we derived some key design goals have been described in section 2.1.3.

One of the key design aspects considered was that the network should wherever possible rely on pre-existing national infrastructure and, in the case of missing links and cross-border connections, on NREN/GÉANT infrastructure.

The second major design consideration related to the fact that the network should cover the majority of the scientific users identified in WP1. With this in mind, it became clear that a single ring structure would become to complicated to maintain at the required high level of performance.

Thus, we decided to propose several overlapping ring structures that allow for parallel or sequential developments depending on the ranking of user needs. The key features of the proposed topology are that each ring is linked to at least one, or preferably two NMIs with optical clocks, shares routes with its neighbouring (e.g. with its northern or southern) counterpart, and allows future extensions within its area or for linear extensions.

In section 2.1.5 we have described each of the subsystems introduced in 2.1.3 in greater detail, estimated their current TRL and presented procedures for monitoring, supervision and maintenance of the network.

In Section 3 we have addressed Subtask 2.1.2 of the CLONETS_DS proposal by defining the core sites of the network that would allow to cover most of the science cases described in WP1. This is supplemented by detailed maps indicating user locations for each of the 5 science cases. Information about already existing time & frequency infrastructure in Europe based on national activities and identify missing links between those national implementations has been included in sections 3.1.3.

Section 3 concludes with a list of potential core sites and their function within the European Core Network that can serve as input to the roadmap introduced in *D2.2 Roadmap for Technical Implementation*. These core sites have been chosen because they serve a fundamental role that will enable the realisation of the ECN across Europe with the potential for further expansion. The selection of the core sites was guided by the consideration that they should enable connection to an NMI or to several users, or provide a cross-border link, and/or a good branching station.

Glossary

ACES	Atomic Clock Ensemble in Space
AOS	Astrogeodynamic Observatory of Polish Space Research Centre
ASI	Agenzia Spaziale Italiana, Italian space agency
BEIDOU	Chinese Global Positioning System
BIPM	Bureau International des Poids et Mesures
CAGR	Compound Annual Growth Rate
CCL	Consultative Committee for Length
CCTF	Consultative Committee for Time and Frequency
CERN	European Organization for Nuclear Research
CGS	Centre for Space Geodesy
CIPM	Comité international des poids et mesures
CLEO	Conference on Lasers and Electro-Optics
CNES	Centre National d’Etudes Spatiales (The French space agency)
CPEM	Conference on Precision Electromagnetic Measurements
CLONETS	H2020 project CLOck NETwork Services for Strategy and innovation for clock services
DEMETRA	H2020 project for EGNSS Timing/Synchronisation
DFN	Deutsches Forschungsnetz
DOI	Digital object identifier
DMP	Data Management Plan
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-doped Fibre Amplifier
EFTF	European Frequency & Time Forum
ELSTAB	Electronically stabilised time and frequency distribution systems
ELT	European Laser Timing Experiment
EMRP	European Metrology and Research Programm
EMPIR	European Metrology Programm for Innovation and Research
EN	European standard
ENREN	European National Research and Education Network
EquipEx	Equipement d’Excellence

ESA	European Space Agency
ESFRI	European Strategic Forum on Research Infrastructures
EURAMET	European association of national metrology institutes
FAIR	Findable, Accessible, Interoperable and Reusable
FBA	Fibre Brillouin Amplifier
FIRST-TF	Facilities for Innovation, Research, Services, Training in Time & Frequency
FPQ	Forschungszentrum für Präzisionsmessungen und Quantenmaterie
FSWG	joint working group on frequency standards
GALILEO	European global navigation satellite system
fs-frequency	Femtosecond- frequency comb
GARR	Italian Research & Education Network
GCPM	General Conference on Weights and Measures
GDRP	General Data Protection Regulation
GÉANT	pan-European data network dedicated to the research and education community
GN4	Current phase of the GÉANT project
GGOS	Global Geodetic Observing System
GLONASS	Russian global navigation satellite system
GNSS	Global Navigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System, US global navigation satellite system
GRACE	Gravity Recovery And Climate Experiment
GSA	The European GNSS Agency
GUM	Polish National Metrology Institute
ICOF	International Clock Comparisons via Optical Fibre, a GÉANT project
ICT	information and communication technology
IEC	International Electrotechnical Commission
ECN	European Core Network
IFCS	International Frequency Control Symposium
INAF	Istituto Nazionale di Astrofisica, Bologna Astronomical Observatory
IQ	Institute for Quantum Optics
ISOLDE	Isotope Separator On Line Device at CERN
ITU	International Telecommunication Union
ISS	International Space Station
KL FAMO	Polish National Laboratory for Atomic, Molecular and Optical Physics

KPI	Key Performance Indicator
LabEx	Laboratoire d’Excellence
LENS	European Laboratory for Non-linear Spectroscopy
LIFT	the Italian Link for Time and Frequency
LPL	Laboratoire de Physique des Lasers, University Paris 13 (part of CNRS)
LLR	Lunar Laser Ranging
MeP	Mise en pratique, practical realisation of the metre
MPQ	Max Planck Institute for Quantum Optics
MWL	Microwave link
NGGM	Next-Generation Gravity Mission
NIR	Near-InfraRed
NMI	National Metrology Institute
NREN	National Research and Education Network
NRO	Nançay Radio Observatory
OC	Optical clock
OFTD	Optical frequency and time distribution
OPTIME	Polish time and frequency dissemination system based on optical fibre
OSO	Onsala Space Observatory
PHARAO	space cold atom clock
PIONIER	Polish National Research and Education Network
PoP	point of presence
PTTI	Precise Time and Time Interval Meeting
PSNC	Poznan Supercomputing and Networking Centre
PTB	Physikalisch-Technische Bundesanstalt
REFIMEVE+	Réseau FIbré Métrologique à Vocation Européenne (The 56rench link project)
RENATER	French National Research and Education Network
RF	radio frequency
RI	Research Infrastructure
RLS	Regeneration Laser Station
SC	Science Case
SI	System international, International System of Units
SLA	Service Level Agreement
SLR	Satellite Laser Ranging
SME	Small and medium sized enterprise

SRS	Secondary Representations of the Second
SU	Scientific User
T&F	Time & Frequency
T2L2	Time Transfer by Laser Link
TAI	International Atomic Time
TC-TF	EURAMET Technical Committee for Time and Frequency
TGF	CCTF/WG-ATFT Task Group focusing on the Fibre Links
TRL	Technology Readiness Level
TWSTFT	Two-Way Satellite Time and Frequency Transfer
UAV	Unmanned Aerial Vehicles
UTC	Coordinated Universal Time
VGOS	VLBI2010 Global Observing System
VIS	Visible
VLBI	Very Long Baseline Interferometry
WDM	Wavelength Division Multiplexing
WG-ATFT	CCTF Working Group on Coordination of the Development of Advanced Time and
WG-PSFS	CCTF Working Group on Primary Frequency Standards
WG-SP	CCTF Working Group on Strategic Planning
WG-TAI	CCTF Working Group on International Atomic Time
Zenodo	https://www.zenodo.org/

References

1 J. Stenger, H. Schnatz, C. Tamm, and H. R. Telle, “Ultra-Precise Measurement of Optical Frequency Ratios,” Phys. Rev. Lett., vol. 88, p. 73601, 2002, doi: 10.1103/PhysRevLett.88.073601.

2 J. Lodewyck, R. Le Targat, P.-E. Pottie, E. Benkler, S. Koke and J. Kronjäger Physical Review Research 2, 043269 (2020)

3 http://empir.npl.co.uk/rocit/project-outputs/

4 P. Krehlik, Ł. Śliwczyński, Ł. Buczek, J. Kolodziej, and M. Lipiński, “ELSTAB – Fiber-Optic Time and Frequency Distribution Technology: A General Characterization and Fundamental Limits,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 63, no. 7, pp. 993–1004, 2016-07, doi: 10.1109/TUFFC.2015.2502547.

5 http://empir.npl.co.uk/write/

6 W.-K. Lee, F. Stefani, A. Bercy, O. Lopez, A. Amy-Klein, and P.-E. Pottie, “Hybrid fiber links for accurate optical frequency comparison,” Appl. Phys. B, vol. 123, no. 5, p. 161, 2017-05, doi: 10.1007/s00340-017-6736-5.

7 D. Xu, O. Lopez, A. Amy-Klein, and P.-E. Pottie, “Non-reciprocity in optical fiber links: experimental evidence,” Opt. Express, vol. 29, no. 11, pp. 17476–17490, 2021-05, doi: 10.1364/OE.420661.

8 https://www.bipm.org/documents/20126/59466374/10_Table4_TAR20.pdf/0ae3ed2f-f998-9398-fc96-6d12f406f8f6.

9 N. R. Newbury, P. A. Williams, and W. C. Swann, “Coherent transfer of an optical carrier over 251 km,” Opt. Lett., vol. 32, pp. 3056–3058, 2007, doi: 10.1364/OL.32.003056.

10 K. Predehl et al., *Science*, **336**, 6080, 2012, doi: 10.1126/science.1218442

11 P. Krehlik, H. Schnatz, and Ł. Śliwczyński, “A Hybrid Solution for Simultaneous Transfer of Ultrastable Optical Frequency, RF Frequency, and UTC Time-Tags Over Optical Fiber,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 64, no. 12, pp. 1884–1890, 2017-12, doi: 10.1109/TUFFC.2017.2759001.

12 P. Krehlik, Ł. Śliwczyński and Ł. Buczek, "Electrical Regeneration for Long-Haul Fiber-Optic Time and Frequency Distribution Systems," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 68, no. 3, pp. 899-906, March 2021, doi: 10.1109/TUFFC.2020.3016610.

13 G. Grosche, “Eavesdropping time and frequency: phase noise cancellation along a time- varying path, such as an optical fiber,” Opt. Lett., vol. 39, pp. 2545–2548, 2014, doi: 10.1364/OL.39.002545.

14 Gao, C. et al., “Fiber-based multiple-access ultrastable frequency dissemination.” Optics Letters 37, 4690 (2012).

15 Schediwy, S. W. et al., “High-precision optical-frequency dissemination on branching optical-fiber networks.”, Optics Letters 38, 2893 (2013).

16 Bercy, A. et al., “In-line extraction of an ultrastable frequency signal over an optical fiber link.”, J. Opt. Soc. Am. B, JOSAB 31, 678–685 (2014).

17 Zhang, S. & Zhao, J., ”Frequency comb-based multiple-access ultrastable frequency dissemination with 7 × 10 - 17 instability.”, Opt. Lett., OL 40, 37–40 (2015).

18 Bercy, A., Lopez, O., Pottie, P.-E. & Amy-Klein, A., “Ultrastable optical frequency dissemination on a multi-access fibre network.”, Applied Physics B 122, (2016).

19 Hu, L. et al., “Multi-node optical frequency dissemination with post automatic phase correction.,”J. Lightwave Technol. 1–1 (2020) doi:10.1109/JLT.2020.2976167.

20 Jiang, Z., Yin, F., Cen, Q., Dai, Y. & Xu, K., "Stable downlink frequency transmission from arbitrary injection point with endless and quick phase error correction.", Opt. Express 28, 33690 (2020).

21 Xue, R., Hu, L., Shen, J., Chen, J. & Wu, G. Cancellation., "Journal of Lightwave Technology 39, 4638–4645 (2021).

22 E. Cantin, M. Tønnes, R. L. Targat, A. Amy-Klein, O. Lopez, and P.-E. Pottie, "An accurate and robust metrological network for coherent optical frequency dissemination," New J. Phys., vol. 23, no. 5, p. 53027, 2021-05, doi: 10.1088/1367-2630/abe79e.

23 M. B. K. Tønnes, F. Schuller, E. Cantin, O. Lopez, R. Le Targat, A. Amy-Klein and P.-E. Pottie, Metrologia 59, 065004(2022)

24 P. Krehlik, Ł. Śliwczyński, Ł. Buczek, H. Schnatz and J. Kronjäger, "Optical Multiplexing of Metrological Time and Frequency Signals in a Single 100-GHz-Grid Optical Channel," in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 68, no. 6, pp. 2303-2310, June 2021, doi: 10.1109/TUFFC.2021.3053430

25 C. Clivati et al., "Optical frequency transfer over submarine fiber links," Optica, vol. 5, no. 8, pp. 893–901, 2018-08, doi: 10.1364/OPTICA.5.000893.

26 M. B. K. Tønnes *et al* 2022 *Metrologia* **59** 065004 **DOI** 10.1088/1681-7575/ac938e https://hal.science/hal-03838745v1/preview/Tønnes_2022_Metrologia_59_065004.pdf

27 Joonyoung Kim, Giuseppe Marra, David S. Wu, David J. Richardson, and Radan Slavík, "Wavelength conversion technique for optical frequency dissemination applications," Opt. Lett. **41**, 1716-1719 (2016) doi: 10.1364/OL.41.001716

28 Pierre Grüning, Amine Chaouche-Ramdane, Karim Manamanni, Thinhinane Aoudjit, Vincent Roncin, and Frédéric Du-Burck, "All-fiber ring-cavity for frequency stability transfer at 1.55 µm," Appl. Opt. **58**, 1502-1507 (2019) , doi:10.1364/AO.58.001502

29 Hill, J., Safavi-Naeini, A., Chan, J. *et al.* Coherent optical wavelength conversion via cavity optomechanics. *Nat Commun* **3**, 1196 (2012). https://doi.org/10.1038/ncomms2201

30 Fortier, T., Kirchner, M., Quinlan, F. *et al.* Generation of ultrastable microwaves via optical frequency division. *Nature Photon* **5**, 425–429 (2011). https://doi.org/10.1038/nphoton.2011.

31 E. Cantin et al., EFTF 2021 abstract, "Local distribution of an ultrastable and accurate frequency reference using eavesdropping on an optical fiber link",

32 L. Sliwczynski and P. Krehlik, "Multipoint joint time and frequency dissemination in delay-stabilized fiber optic links," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 62, no. 3, pp. 412-420, March 2015, doi: 10.1109/TUFFC.2014.006773.

33 https://www.refimeve.fr/index.php/en/