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CLONETS – CLOck NETwork Services
Strategy and innovation for clock services over optical-fibre networks

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Deliverable D2.2

Architecture of the core network

Final

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Keywords: optical fibre, network, clock, time, frequency, core architecture

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LIST OF ACRONYMS AND ABBREVIATIONS

AOS	Borowiec Astrogeodynamic Observatory
ACONET	Austrian academic network
BEV	Bundesamt für Eich- und Vermessungswesen, Austrian NMI
CAS	Czech Academy of Science
CE	Commercial Entity
CLONETS	CLOckNETwork Services: Strategy and innovation for clock services over optical-fibre networks project
CMI	Český metrologický institute, Czech NMI
DFN	Deutsches Forschungsnetz, German academic network
DF	Dark fibre
DC	Dark channel
EMRP	European Metrology and Research program
EMPIR	European Metrology Program for Innovation and Research
FAMO	National Laboratory of Atomic, Molecular and Optical Physics
FUNET	Finish academic network
Fucino	Galileo ground station
GasLINE	GasLINE Telekommunikationsnetz- Geschäftsführungs GmbH
GEANT	pan European data network dedicated to the research and education community
GN3plus	GÉANT Innovation Programme
GNSS	Global Navigation Satellite System
GUM	Central Office of Measures (Poland), Polish NMI
H2020	Horizon 2020
JANET	UK academic network
ICOF	International Clock Comparisons via Optical Fibre (GN3+ project)
ITOC	International timescales with optical clocks, EMRP project
ISI	Institute of Scientific Instruments of the CAS, Brno, Czech
Medicina	VLBI station
Matera	VLBI station
LENS	European Laboratory for Non-linear Spectroscopy, Firenze
NEAT-FT	Accurate time/frequency comparison and dissemination through optical telecommunication networks, EMRP project
NMI	National Metrology Institute
NREN	National Research and Educational Networks
NOC	Network Operation Centre
NTP	Network Time Protocol
OADM	optical add and drop multiplexer
OFTEN	Optical frequency transfer - a European network, EMPIR project
PoS	Point of Service
PoP	Point of Presence
PPS	Pulse Per Second
PSNC	Poznań Supercomputing and Networking Centre, Poland
PIONIER	Polish academic network
RF	Radio Frequency
RI	Research Institution
RISE	Research Institutes of Sweden, Swedish NMI
SOS	Source of Service
SP	Service Provider
SU	Service User

SUNET	Swedish academic network
SWITCH	Swiss national research and education network
TIFOON	TIme and Frequency Over Optical Networks, future EMPIR project
T&F	Time and Frequency
TL	Time Laboratory
TM	Transmission Medium
UTC	Universal Time Coordinated
VLBI	Very long baseline interferometry
VTT-MIKES	Technical Research Centre of Finland Ltd., Finish NMI

LIST OF PROJECT PARTNER ACRONYMS

AGH/AGH-UST	Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie, Cracow, Poland
CESNET	CESNET, zájmovésdruženíprávnickýchosob, Prague, Czech Republic
CNRS*	Centre National de la Recherche Scientifique, Paris, France
INRIM	Istituto Nazionale di RicercaMetrologica, Turin, Italy
GARR#	Gruppo per l'ArmonizzazionedelleRetidellaRicerca, Rome, Italy
Menlo	Menlo Systems GmbH, Martinsried, Germany
Muquans	Muquans, Talence, France
NPL	National Physical Laboratory, Teddington, United Kingdom
OBSPARIS¶	Observatoire de Paris, Paris, France
OPTOKON	OPTOKON a.s., Jihlava, Czech Republic
Piktime Systems	Piktime Systems sp z o.o., Poznan, Poland
PSNC	Instytut Chemii Bioorganicznej Polskiej Akademii Nauk – Poznańskie Centrum Superkomputerowo-Sieciowe, Poznan, Poland
PTB	Physikalsch-Technische Bundesanstalt, Braunschweig, Germany
RENATER	Groupementd'interêt Public pour le Reseau National de Telecommunications pour la Technologie, l'Enseignement et la Recherche, Paris, France
SEVENSOLS	Seven Solutions S.L., Granada, Spain
TOP-IX	ConsorzioTOrino Piemonte Internet eXchange, Turin, Italy
UCL	University College London, London, United Kingdom
UP13	Université Paris 13, Villetaneuse, France
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# third party to INRIM
¶ coordinator

EXECUTIVE SUMMARY

The document D2.2 addresses the architecture of a core network for T&F services that interconnects European national metrology institutes (NMI) hosting primary atomic clocks and /or optical clocks and research infrastructures (RI) having high-level needs, using NRENs or other fibre infrastructure provider resources.

The core CLONETS network will be compatible with the overall vision for T&F service delivery and considers the need for compatibility with other hardware and services of the NREN. Here we propose the technologies and a topology of the network by:

- defining the vision of a general Pan-European architecture of the core network, considering a logical and geographical topology
- considering challenges and requirements for the core network arising from different possible solutions when choosing the best variant of the topology of the T&F core network with respect to the performance of the signals, the cost of the deployment of the entire infrastructure and its maintenance, and
- considering the impact of gateways needed for ensuring cooperation among different systems of T&F transfer in one heterogeneous network.

The discussion in this document are limited to the CORE, which is considered to have the highest stability and accuracy for frequency and timing.

The overarching prerequisite of the CORE is the guarantee of bi-directional operation for the T&F link, which means that the forward and backward signal are counterpropagating in the same fibre. This prerequisite applies to all scenarios considered here.

In addition, we assume that fibres either have to be rented from a provider (in case of dark fibre) or that the additional cost arising from the use of a dark channel on a NREN network has to be covered.

Those aspects lead to four scenarios having different impact on the implementation and maintenance of the CORE, on its performance, availability, resilience and costs.

In scenario #1 we consider the operation of the entire CORE based on a **dark channel** on a NREN platform with implementation of T/F services parallel to data traffic.

In scenarios #2 and #3 we assume that a **dark fibre** pair will be leased from a best-price provider. While in scenario #2 the dissemination of the T&F signals will fully be managed by the NMI-consortium, we assume that the management of leased dark fibre of scenario #3 will be integrated into the network operation centre (NOC) of a NREN/GEANT platform.

As an alternative resulting from previous experience within the European Metrology programs EMRP and EMPIR we investigate a heterogenous network based on already implemented **dark fibre and dark channel solutions** in scenario #4.

In order to find the best solution for a sustainable network for time and frequency distribution the consortium members individually rated the different scenarios on a scale between 0 and 10 (best). This ranking led to a recommendation of preferred solutions in view of different preconditions reflecting current experience on existing implementations.

The consortium agrees that eventually the best choice for the implementation of a T&F service is an approach that allows for co-propagation of a phase stabilized optical carrier at 1.5 µm, a stabilized radio frequency, a timing signal such as one-pulse-per-second (pps), and a signal indicating “healthy” & origin of signal (source), preferably in well separated frequency bands.

1 INTRODUCTION

The document D2.2 summarizes work performed in task T2.2.

Task T2.2 deals with the architecture of a core network for T&F services linking the European National Metrology Institutes (NMIs) operating primary atomic clocks and/or optical clocks using NRENs or other infrastructure providers. Eventually research infrastructures (RI) developing and operating optical clocks or other UTC laboratories offering high level time scales will be involved. These institutes will generate the signals distributed by the network or serve as branching point to other users.

The core CLONETS network will be compatible with the overall vision for T&F service delivery developed in task 2.1 and considers the results of a survey among research infrastructures (RI) and industry requiring precise timing or reference frequencies. It considers the need for compatibility with other hardware and services of the NREN. Here we propose the technologies and a topology of the network by:

- defining a general Pan-European architecture of the core network,
- defining gateways which ensure cooperation among different systems of T&F transfer in one heterogeneous network, and
- choosing the best variant of the topology of a T&F core network with respect to the performance of the signals, cost of the deployment of the entire infrastructure and its maintenance.

The discussions in this document are limited to the CORE, which is considered to have the highest stability and accuracy in frequency and timing.

2 OVERALL VISION FOR TIME AND FREQUENCY SERVICE DELIVERY

According to D2.1 each service can be divided into three basic components:

- a service provider (SP) –responsible for providing the service to users,
- a service user (SU) – which needs access to the service,
- and a (fibre-optic) transmission medium (TM) – connecting SP and SU.

Service providers are well-established institutions such as National Metrology Institutes (NMIs) or other UTC-laboratories, which maintain their own time scales, UTC(k).

Service users need access to the network, may act as node for internal purposes, but may have different requirements regarding the type of signals (1 PPS, 10 MHz, optical carrier, etc.), their accuracy, instability, resilience, access to the service, availability, and security.

2.1 Challenges and requirements for the core network

As the envisioned CORE network needs to support very different applications such as remote optical spectroscopy, references for time and frequency equipment (frequency counters, time interval measurements, rf-phase measurements), or applications in dimensional metrology (wavelength interferometry, scanning interferometry, wavelength standards), the CORE needs to support optical carrier frequencies as well as radio frequencies and time stamps (such as 1pps or equivalent) at the same time.

Even though requirements with respect to the performance of the service may be different, some general specifications for the CORE network can be drawn up:

Frequency and timing signals within the CORE end

- must be traceable to frequency and timing references of at least one NMI,
- must provide at least an order of magnitude better accuracy than most advanced user requirements,
- should support highest level applications without degradation of the stability,
- should support lower level applications without need for augmented service,
- should take into account that user requirements will increase in future,
- should provide resilience by redundancy, and
- should provide an intrinsic notification of signal integrity.

2.1.1 Type of T&F signals at SP site disseminated by optical fibre

Service providers (SP) at the CORE level will be European NMIs or designated institutes (DI), that operate primary Cs clocks with appropriate T&F infrastructure such as H-masers, commercial Cs clocks, GNSS receivers, satellite links etc. for monitoring and maintaining UTC(k). Standard operational frequencies are either 10 MHz or 100 MHz derived from H-masers monitored by primary clocks. Occasionally higher frequencies in the GHz range are also accessible. In addition to these radio frequencies, timing information is provided by calibrated 1pps signals at some specific NMI location.

The most advanced NMI in Europe operate optical clocks that allow about two orders of magnitude lower uncertainty and at least three orders of magnitude lower instability with respect to primary Cs-fountain clocks. Such optical clocks are routinely compared to the primary clocks using optical frequency comb technology.

Using optical frequency combs to fix the frequency ratio between the frequency of an optical clock and any laser operating in the spectral bandwidth of the frequency comb one can generate e.g. a stable optical reference frequency in the telecommunication window that can be transmitted over the CORE with little loss. In this way NMIs will provide an optical reference frequency at around 194 THz with unprecedented low instability, directly referenced to a primary or secondary representation of the SI- second.

In addition, this approach allows one to select any transmission channel or wavelength within the typical coverage of the fs frequency comb (typically from S-band to the L band). Thus, in case of necessity, transmission in the L-band could provide an alternative to the heavily occupied C-band, subject to the development of T&F link equipment operating in this band.

At the time of writing the following performance is routinely achieved at the most advanced European NMIs:

Reference frequency	Source	Relative frequency			Direct Traceability to SI-second
		uncertainty	instability @1 s	instability @1 d	
194 THz	Optical clock	Same as optical reference	$<10^{-15}$	$<10^{-17}$	yes
100 MHz	H-maser, or generated from fs- comb	$<10^{-15}$	$<10^{-13}$	$<10^{-15}$	yes
10 MHz	H-maser, or generated from fs- comb	$<10^{-15}$	$<10^{-13}$	$<10^{-15}$	yes
		Timing			
		uncertainty	instability @1 s	instability @1 d	
1 pps	H-maser	a few ns	< 100 ps	<1 ns	yes

Table 1: Typical frequency references at SP site (local end of a TM).

2.1.2 Performance of T&F signals disseminated by optical fibre at a SU site (user)

The most popular frequency sources available at SU sites are based on radio frequency sources such as:

- GNSS disciplined oscillator,
- Commercial Rb clock,
- Quartz crystal oscillator,
- Active H-maser,
- Commercial Cs beam clock.

At the lower level some SU rely solely on the use of GNSS signals or NTP without local backup clock.

The surveys in WP1 and WP3 showed that the implementation of a timing system at SU site is driven by the user's internal application rather than a general awareness of the need for traceability to the SI-system. In this sense, it is clear that the most important parameters of the frequency/timing system are its frequency stability and accuracy. In the survey (see D1.1 and D3.3) RI users indicated that they require short-term stability (1s integration time) at the level around 10^{-12} down to 10^{-15} and a long-term stability (1d integration time) better then 10^{-14}. In terms of frequency accuracy, the survey indicated two peaks; the first one is on the level 10^{-12}, the second one is on the level 10^{-16}.

Overall, the performance of a T&F service is affected by:

- the type of clock which provides the T&F signals at SP-site (see Figure 1),
- the optical fibre technique used to distribute the T&F signals, and

- the capability to interface the SU T&F-signal with that provided by the SP by the optical fibre.

Reference frequency	Source	Relative frequency			Direct traceability to SI-second achievable
		uncertainty	instability @1 s	instability @1 d	
194 THz	Cavity stabilized laser		$<2\times10^{-15}$	$<10^{-10}$	No
10/100 MHz	GNSS disciplined oscillator		$<2\times10^{-11}$	10^{-10}	yes
10/100 MHz	Quartz crystal oscillator (e.g. OXCO 8607)		$<1\times10^{-13}$	$<3\times10^{-12}$	No
10/100 MHz	Active H-maser		$<2\times10^{-13}$	$<1\times10^{-15}$	No
10/100 MHz	Commercial Rb clock	$\pm5\times10^{-11}$	2×10^{-11}	$<2\times10^{-11}$	No
10 MHz	ChipScaleAtomicClock	$\pm5\times10^{-11}$	2.5×10^{-10}	$<5\times10^{-10}$	No
10/100 MHz	Commercial Cs beam clock	$<5\times10^{-13}$	$<2\times10^{-11}$	$<1\times10^{-14}$	By calibration

Table 2: Typical frequency references at SU-site (remote end of a TM).

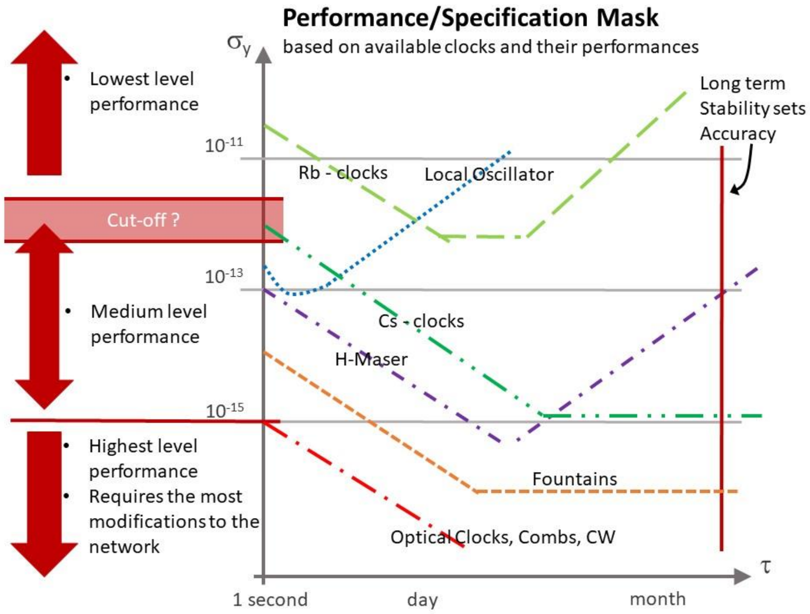

Figure 1: Clock performance (reproduced from D2.1, figure 5). The highest performance is available by using optical clocks or fountains. Commercial caesium clocks and H-masers can be used for medium performance. Lowest performance is achieved by rubidium clocks and local (quartz-) oscillators.

If traceability is required, GNSS receivers mostly serve this purpose and allow calibration of the local reference clocks. In such case T&F service delivered by fibre will become a primary (more accurate) source in relation to the GNSS which then can play the part of a secondary/backup source.

The fact that T&F-systems for internal use are already in place at SU-sites and that reference signals can be transmitted by fibre without significant loss of stability and accuracy leads to a scenario where the SU T&F-systems can act as a flywheel that provides sufficient hold-over in case of a failure of the transmission system and thus reduces the restriction for continuous access to T&F signals.

In the following we will assume that a T&F-system at the SU-site will be available and will act as a flywheel in case of a failure of the T&F-system at SP or of the transmission system.

2.2 Logical topology of the CORE

The vision of a T&F-network as proposed in D2.1 is shown in Figure 2.

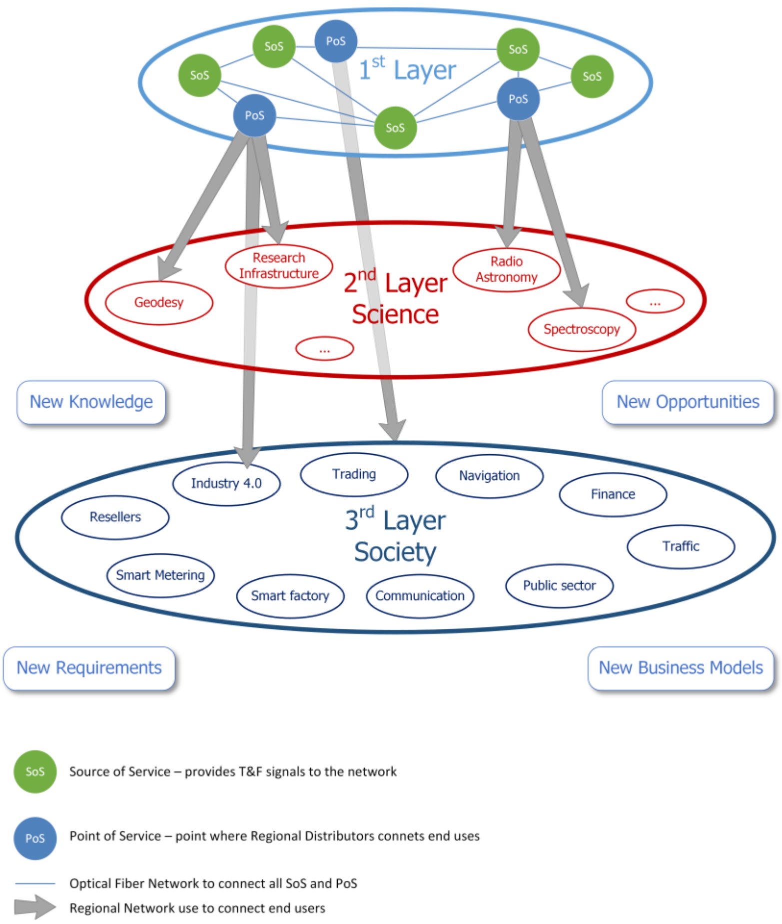

Figure 2: Logical vision T&F service delivery (adopted from D2.1)

The core fibre optic network considered here for D2.2, will be responsible for providing reliable and highest accuracy signals across Europe. Participating institutes will be European NMIs operating primary atomic clocks and/or optical clocks, research infrastructures (RI) developing and operating optical clocks or other UTC laboratories offering high level time scales, as well as NRENs or other infrastructure providers. This part of the network must be built using solutions based on bi-directional transmission allowing noise compensation of the TM.

Within the CORE network, Sources of Service (SoSs), such as European NMIs, provide the TF signals, which are distributed over the network to dedicated Points of Service (PoS) through which users can gain access to the CORE. Such PoS may be directly located at an NMI site or at any RI willing to grant such access. Ideally, beside the NMI one additional PoS will be located in each country connected to the CORE. Point-to-point bi-directional links will provide phase-stabilized connections from one PoP to another. With specifically selected PoPs a redundant structure will be made available that enables that each site receives T&F signals from two independent neighbours. In addition to this topology it may be beneficial to arrange direct links between dedicated sites in order to route signals differently for maintenance or during longer lasting failure of the TM.

The main role of a partner acting as a CORE PoS is to monitor the signals, guarantee their integrity and to distribute signals to end users. They will also be responsible for the calibration of the connection in case of timing distribution (between sites of the CORE or from PoS to the end user).

End users include scientific entities (e.g. Geodesy, RI, Radio Astronomy, Spectroscopy, et.) as well as commercial entities (e.g. Industry 4.0, Smart factory, Communication, Public sector, Finance, etc.). The logical topology of a TF service presented in Figure 2, illustrates the functionalities of a TF service, with the service providers being represented as “Layer 1” and the users as “Layer 2” and “Layer 3”.

2.3 Geographical topology of the CORE

Over the last decade several European NMIs (, see Figure 3a) and research organisations have been involved in the development of appropriate techniques for disseminating reference frequencies via optical fibre either on a national basis or at the European level. Within the European Metrology and Research program (EMRP), the European Metrology Program for Innovation and Research (EMPIR) [NEAT-FT, ITOC, OFTEN, TIFOON[1]] or the GN3plus-project ICOF of the GÉANT Innovation Programme the necessary technologies for time and frequency dissemination have been pioneered and links have been established (see green lines in Figure 3b). These long-standing collaborations between institutes in EMRP, EMPIR and other Horizon2020 projects such as GN3plus and CLONETS are considered as cornerstone of the envisioned CORE network.

The existing links connect either NMIs directly (such as NPL-OBSPARIS-PTB, VTT-RISE, or BEV-CMI) or are intended to serve high-level end user needs, such as the links GUM-AOS-PSNC-FAMO (Poland) or INRIM- Medicina-LENS-Fucino-Matera (Italy).

The evolution of the up to now separated links into the CORE network will require the implementation of several new connections (see Figure 3c) in order to satisfy the requirements presented in 2.1.We propose that the missing links between OBSPARIS and INRIM and that between PTB and GUM (PSNC) should be pursued with highest priority followed by the connections between RISE and VSL (RUG), the extension of the PTB link to MPQ towards BEV, and the incorporation of METAS via cross-border links to Italy and Germany (Kehl) or France (Strasbourg), and the connection GUM-CMI or BEV via AGH and ISI. In order to include the northern route (VSL-RUG-RISE-VTT Mikes) into the CORE an additional connection e.g. from PTB via LUH to Hamburg will be required. In addition, the REFIMEVE network currently under development will allow for the extension towards Spain.

[1] TIFOON (Time and Frequency Over Optical Network) has been selected for funding from the 2018 EMPIR SIB call, and is due to kick off in June 2019.

Future extensions (see red lines in Figure 3d) would allow for increased redundancy and the extension towards Russia and southeast Europe. There is already a link from GUM (Poland) to FTMC (Lithuania), implemented as a dark channel in unidirectional DWDM. In near future a new dark fibre connection between GUM and FTMC will become available (PSNC and LITNET have spare fibres on this route for this purpose). This connection can be a first step towards reaching VTT MIKES (Finland) through METROSERT (Estonia).

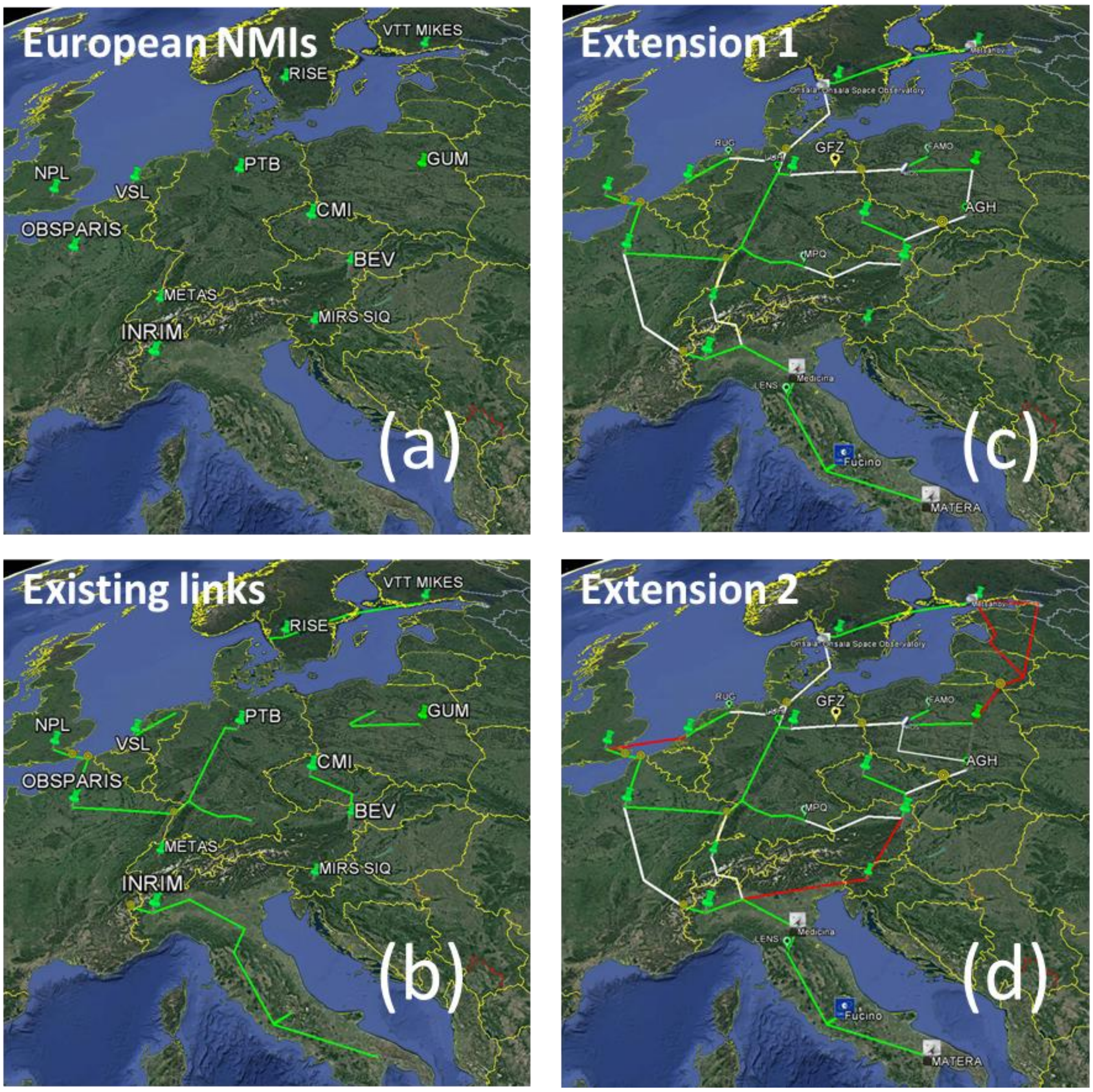

Figure 3: Potential evolution of the envisaged CORE network linking European T&F laboratories and dedicated end users; (a) participating NMIs in central Europe, (b) existing fibre links (green) for T&F distribution and clock comparisons between NMIs or to dedicated end users, (c) Phase_1-extensions (white lines) connecting high level end users, (d) future extensions for redundancy and extensions towards Russia and southeast Europe. Not shown here is the implementation of the REFIMEVE+ network in France and a possible future extension towards Spain. (map source: Google earth).

3 ARCHITECTURE OF CORE NETWORK FOR TIME AND FREQUENCY SERVICE DELIVERY

Each line in Figure 3 has to be composed of a fibre pair in the same cable with a minimum number of connectors. As the fibre attenuation has to be compensated appropriate regenerators, such as bi-directional optical amplifiers or repeater laser stations have to be placed along the transmission lines. Typically, such amplifiers are located in shelters of the network provider. Thus, access to and rack space in the shelters is required. Additionally, remote control needs to be provided for supervision and management of the CORE network.

With the installation of the proper technology this guarantees that user needs as expressed in the surveys in WP1 and WP3 can be met.

3.1 General T&F core network

As mentioned above the CORE needs to support optical carrier frequencies as well as radio frequencies and time stamps (such as 1pps or equivalent) at the same time in order to meet user needs.

To support the applications with the highest performance demands, a frequency instability of better than 1×10^{-15} at 1s reaching below 1×10^{-19} after several hours is mandatory. Moreover, the uncertainty of the frequency received at a PoS should be better than 1×10^{-18} for routine operation and should be traceable to a realization of the SI-second.

For timing applications, the required jitter should be lower than 1 ps for measurement intervals shorter than a few minutes and significantly smaller than few 10 ps for one day averaging. The systems should support traceability to UTC(k) within 100 ps.

In NEAT-FT and OFTEN, technologies for disseminating and comparing ultra-stable optical frequencies and timing signals (10 MHz and 1pps) over fibre links have been developed and demonstrated. TIFOON will address techniques for combined dissemination of optical carrier and timing signals (as well as the question of compatibility with data traffic).

For disseminating such signals over optical fibres two approaches have been established over the recent years. The first relies on the use of *dark fibres (DF)*, where currently the fibre exclusively transmits the T&F signals, the second approach uses a so-called *dark channels (DC)* using a bi-directional time and frequency channel in an otherwise unidirectional data network in parallel.

While the DF-approach can in general be implemented on leased fibres from any provider, the DC-approach requires collaboration with network operators. A natural choice of network operators is based on existing European (GEANT) or National Research and Educational Networks (NREN). However, this approach is in no way restricted to NRENs.

Even though compatibility of time and frequency services with parallel data traffic has been demonstrated in the networks of RENATER (France), PSNC (Poland), CESNET (Czech Republic) and to some extent in SUNET (Sweden), there are still reservations in the NREN community preventing widespread uptake due to additional loss introduced by the necessary optical add and drop multiplexer (OADM) affecting the power management of the network and suspected crosstalk to telecom channels. On the other hand, cross talk from data channels to optical frequency transfer is inevitable due to presence of partial amplitude modulation (modern data channels use QAM modulations). However, both types of crosstalk have never been observed, not even on neighbouring channels, which has been tested in the RENATER network over the last few years. Some NRENs also suffer from collision of 194 THz with their channel plans due to the bandwidth consumed by OADMs as a result of spectral guard-bands. A reasonable alternative seems to be to operate the T&F service in the L-band which is still low loss, for which suitable amplification techniques exist and in which case crosstalk can be significantly reduced due to the large spectral distance from data channels. However, losses remain higher than in the C-band, amplification is less efficient and narrow-line lasers and bi-directional amplifiers for this band have to be established and set-up.

In the past, a large part of the European NRENs have supported or directly participated in the fibre projects mentioned above either by granting access to their own network (RENATER, GARR, CESNET, GEANT, PIONIER, SUNET, FUNET) or during procurement (DFN, JANET, ACONET, SWITCH) (see Figure 4). Thus, it is very likely that the future CORE network will be established in close collaboration with NRENs and the European network GEANT.

In section 3.2 we will consider the implementation of the proposed CORE network in more detail taking into account four different scenarios for the implementation, fibre procurement and sustainability of the network.

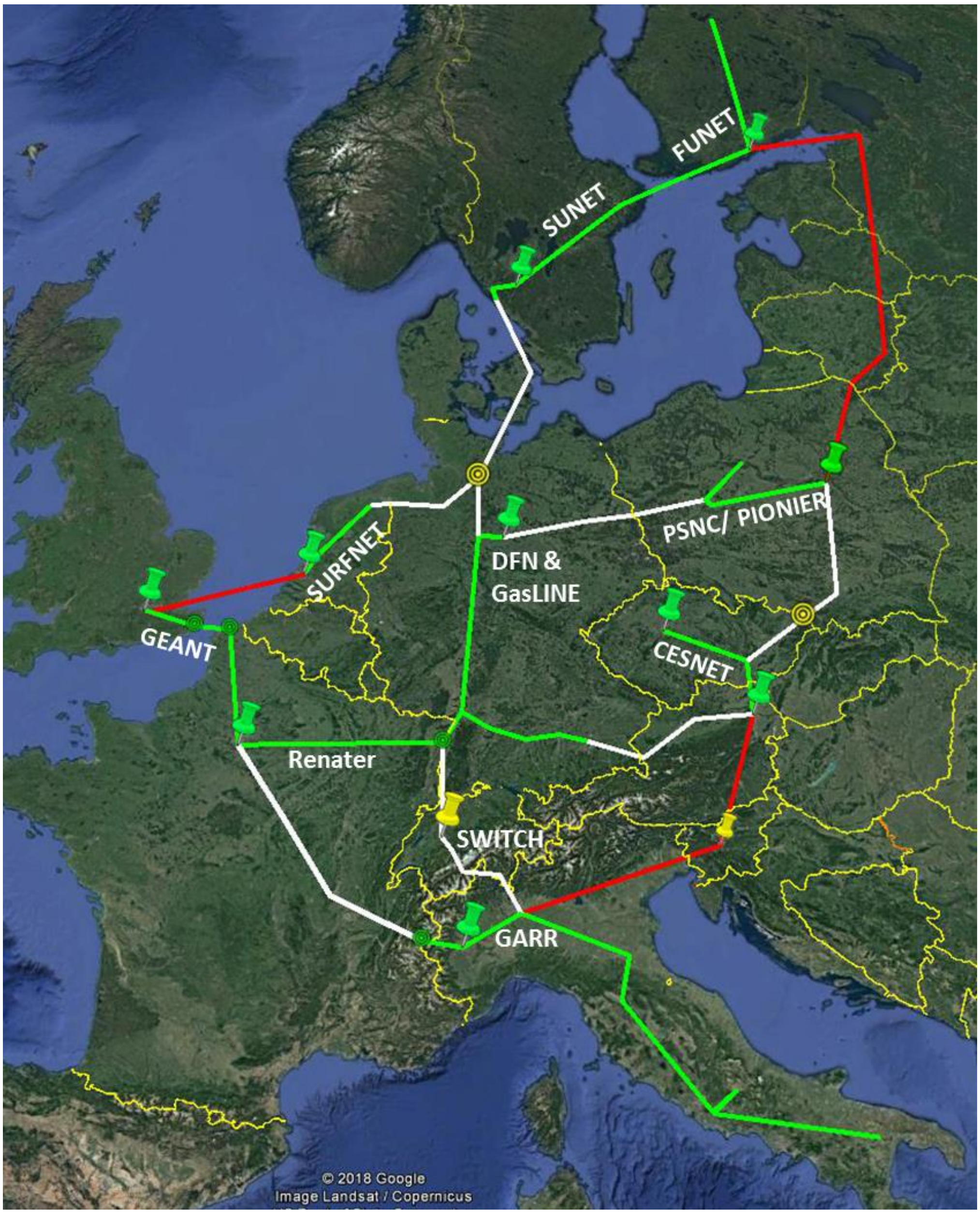

Figure 4: NRENs supporting the envisaged CORE network.

3.2 Possible scenarios of a T&F core network

In this section we will propose and rate different scenarios for the implementation, and maintenance of the CORE considering performance, effort for operation, availability and resilience. This will lead to a ranking of the solutions considered and recommendation of the best variant.

The overarching prerequisite of the CORE is the guarantee of bi-directional operation for the T&F link, which means that the forward and backward signal are counterpropagating in the same fibre. This prerequisite applies to all scenarios considered here.

In addition, we assume that fibres either have to be rented from a provider (in case of dark fibre) or that the additional cost arising from the use of a dark channel on a NREN network have to be covered.

In scenario #1 we consider the operation of the entire CORE based on a **dark channel** on a NREN platform with implementation of T/F services parallel to data traffic.

Using physically separated fibres for T&F and data traffic significant constraints imposed by the data network operators can be overcome. Thus, in scenario #2 and #3 we assume that a dark fibre pair will be leased from a best-price provider.

While in scenario #2 the dissemination of the T&F signals will fully be managed by the NMI-consortium, we assume that the management of leased dark fibre of scenario #3 will be integrated into the NOC of a NREN/GEANT platform. In this way the benefits of a dark fibre and the experience of network operators can be exploited.

As an alternative, resulting from previous experiences within the European Metrology programs EMRP and EMPIR, we have investigated in scenario #4 a heterogeneous network based on already implemented dark fibre and dark channel solutions.

3.2.1 Benchmarking Scenarios

In order to find the best solution for a sustainable network for time and frequency distribution the consortium members individually rated the different scenarios on a scale between 0 and 10 (best) with respect to the

- overall performance such as
  achievable instability, accuracy and resilience,
- technical aspects such as
  flexibility to incorporate different technologies in parallel, constraints of optical power, attenuation due to installation of additional equipment, technical restrictions due to the necessary amplification of the T&F signals, possible crosstalk or interference between signals,
- network managing aspects such as
  supervision and remote control of installed equipment including power management, effort for operating the network and a NOC on a 24/7 basis, access to the shelters, long-term enrolment and IRU contracts for fibre, life cycles of equipment, staff training, implementation of legal structures for the service, and effort for the implementation and maintenance of the service,
- costing aspects such as
  renting of the fibres, hardware and installation costs, human resources, and additional costs due to technical constraints.

For the successful implementation of the network, the following overall issues apply to all scenarios and have been taken into account for a ranking of the individual scenarios:

- access to the shelters along the transmission lines has to be guaranteed during installation and for routine maintenance,
- amplification of the T&F signal using dedicated, bi-directional amplifier techniques such as developed in the EMRP/EMPIR projects NEAT-FT and OFTEN is mandatory,
- remote control of amplifiers and equipment needs to be implemented either as in-line communication with regeneration of the communication signal, typically every 80 km, or via UMTS or similar,
- the responsible NOC should be able to supervise amplifiers and equipment for the proper power management and to shut down T/F services on demand,
- the limited life span of IRU fibre contracts and of optical equipment may lead to rerouting of the network and redeployment of some hardware equipment.

In the following paragraphs the results of the internal survey are presented.

Scenario #1

The operation of the entire CORE is based on a **dark channel** on a NREN platform with implementation of T/F services parallel to data traffic. This scenario is based on the experience obtained from the development and recently started implementation of the REFIMEVE+ network in France.

For the successful implementation in **a network with parallel data traffic**, the following additional issues have to be taken into account:

- the circumvention of every network node of the data network using optical add and drop multiplexers (OADM) is mandatory,
- so far not all NRENs have agreed to accept introducing the necessary OADMs and the use of bi-directional amplifiers on the dark channel as either the transmission qualities are squeezed to the edge and no longer give up any reserves or the risk to the data channels is not considered absolutely negligible by some[2]. As a safety measure for avoiding any suspicion of cross talk between data and T&F signals one may consider surrounding the T&F channel by guard channels on either side,
- the maximum allowed input power is in general limited to $P_{max} < 0$ dBm in order to comply with the parallel data transmission,

On the positive side, the fact that the envisaged T&F links overlap with existing NREN routes, and the experience of NRENs on managing networks including already existing NOCs, might lead to a significant reduction of the costs for fibre rent, installation and maintenance.

Scenario #2

In this scenario we assume that a dark fibre pair will be leased from a best-price provider. The dissemination of the T&F signals will be fully managed by the NMI-consortium.

The overarching benefit of this approach is that it provides lower loss per span (because e.g. OADMs are not required, and network nodes don’t need to be circumvented), generally allows for higher input power (typically $P_{typ} \approx 10$ dBm) as there is no compliance with data traffic, and it allows a maximum of flexibility with respect to the chosen technology of the transfer. As the dark fibre grants access to all channels simultaneously, optical frequency transmission can

[2] It should be noted that RENATER has investigated this issue together with OBSPARIS and no interference or data corruption has been observed so far. However, for very dense DWDM (25 GHz), with lots of channels active and/or special modulation formats, no tests have been performed yet, and cross talk eventually could become a problem.

easily be separated from rf signals and signals required for timing such as 10/100 MHz and 1 pps based timing by using different and well-spaced channels. Direct management of all channels of the fibre guarantees the highest degree of freedom in implementing amplifier techniques and overall performance in terms of achievable instability and accuracy.

However, one of the major concerns of scenario #2 (as well as for scenario #3) is related to significantly higher costs due to the fibre lease (as it is not shared with other services), and the establishment and maintenance of a department devoted solely to the network management (NOC). At present NMIs lack such knowledge as well as the financial resources to operate a NOC with specifically trained staff. In addition, effort to establish the legal structure to manage the network will be not negligible. As the implementation of the hardware and its cost are related to the actual routing of the fibres, long-term enrolment and contracts exceeding the typical life spans of IRU contracts of the NRENs are required.

Scenario #3

In this scenario we consider again the use of dark fibres, but in contrast to Scenario #2 we now assume that the procurement and management of the leased dark fibre is integrated into a NREN/GEANT platform.

Using physically separated fibres for T&F and data traffic, significant constraints imposed by the data network operators can be overcome, while at the same time the benefits of a dark fibre and the experience of network operators and sharing of the network operation centres can be exploited.

The joint experience of NMI staff, trained on T&F aspects and that of NREN staff, familiar with the operation of large networks, will lead to a powerful and sustainable service. In addition, NRENs already have a good overview and well-established business relations with fibre providers. Thus, one can assume that procurement of fibres under the authority of NREN will lead to price reductions otherwise not achievable, although costs will remain higher than in scenario #1.

Overall Scenario #3 benefits from all positive aspects of Scenario #2, in addition, it avoids a major part of its negative.

Scenario #4

In this scenario we investigated a heterogenous network based on already implemented dark fibre and dark channel solutions.

This scenario is similar to the currently implemented fibre link between PTB, OBSPARIS and NPL where the German part from PTB to the University of Strasbourg (UoS) is based on a dark fibre approach with dedicated fibre Brillouin amplifiers (FBA), while the link from UoS to OBSPARIS uses a dark channel provided by the French NREN RENATER with Erbium-doped fibre amplifiers (EDFA), and the link from OBSPARIS to NPL is based on a leased dark fibre with EDFA.

This scenario seems to be the most realistic and may be the fastest to implement, since the infrastructure already in place on the links mentioned above might be used and renting of fibres come on a moderate price. However, technically it could be more complicated, because the same dark channel for transmission might not be available on the entire network, calling for gateways, wavelength switching devices and other specific devices, leading to diverse equipment and solutions on different sub links.

3.2.2 Summarizing result of the internal survey

- Signals that should be transmitted are
  - a phase stabilized optical carrier at 1.5 µm,
  - a stabilized radio frequency at 10, 100MHz- up to 10GHz,
  - a 1 (10, 100) pulse per Second signal, and
  - a signal indicating "healthy" & origin of signal (source).
- Frequency and timing signals within the CORE have to be
  - traceable to frequency and timing references of at least one NMI or UTC(k),
  - to provide at least an order of magnitude better accuracy than most advanced user requirements,
  - should support highest level applications without degradation of the stability,
  - should support lower level applications without need for augmented service,
  - should take into account that user requirements will increase in future,
  - should be resistant to failures of individual T&F signal sources and to interruptions of the transmission lines,
  - should provide resilience by redundancy, and
  - should provide an intrinsic notification of signal integrity.
- The optical carrier should provide a
  - frequency instability $<1\times10^{-15}$ at 1s reaching below 1×10^{-19} after several hours
  - frequency uncertainty received at a PoS $<1\times10^{-18}$ for routine operation
  - and should be traceable to a realization of the SI-second.
- The timing signal,
  - should not exceed a timing jitter < 1 ps for measurement intervals shorter than a few minutes and < few 10 ps for one day averaging,
  - should provide traceability to UTC(k) within 100 ps.
- None of the different scenarios shows a significant difference in terms of achievable instability and accuracy for the dark channel or the dark fibre approach.
- The consortium is well aware of the work performed so far on a national basis, specifically that related with scenario #1 and #2. This effort will continue and will become particularly relevant for distributing T&F to users.
- Leased dark fibre (Sc. #2 or #3) has been regarded as the more flexible solution for the envisaged T&F network. However, these solutions will have the highest costs due to the costs for renting fibres from vendors.
- There is no significant difference between Sc. #2 and #3 with respect to the overall performance for supervision by NMI or by NREN/GEANT. However, considering the experience of NREN/GEANT in operating large networks, the choice would clearly be in favour of Scenario #3, where the NOC for T&F service would be part of NREN/GEANT

- Incorporating already existing implementations into the envisaged network was considered a technically more challenging solution but as the most efficient with regard to cost and effort for installation.

3.2.3 Estimating costs for establishing the CORE network

In the following we try to estimate costs for the deployment of the CORE network including hardware costs, fibre rent and manpower and for a sustainable operation of the network.

We restrict ourselves to the first implementation phase based on the mandatory point to point connections. Later extensions are excluded at the present stage.

The selection of routes potentially forming the first phase of the CORE network has been discussed extensively in view of already existing links, strategic points for future extensions, the fact that GEANT is planning to extend its network footprint across Europe in the coming years, the locations of the most advanced UTC(k)- laboratories and possible synergies with radio astronomy stations.

Table 3 gives an overview of the clocks available at the institutes most likely participating in the development of the T&F service, based on their past individual activities and collaborations. Here we are considering only NMI/UTC(k)- laboratories that are fairly close to possible extensions of the GEANT GN4 routes London-Paris-Milan-Vienna-Prague-Warsaw-Poznan-Berlin-Amsterdam-London.

NMIs operating Maser + Fountains (+ Optical Clocks)						
Institute City Country	**Address**	**Oscillators and UTC clocks**			**Optical Clocks**	Optical Clocks, anticipated developments and other remarks
		Cs-comm.	Maser	Atomic Fountain/ Other high perf.	Sec. Rep. of the Second	
NPL Teddington, United Kingdom	Hampton Road, Teddington Middlesex, TW11 0LW	2	2	2	3	• $^{88}Sr^{+}$ – well advanced • $^{171}Yb^{+}$ – well advanced • ^{87}Sr – well advanced
LNE-SYRTE Paris France	61 Avenue de l'Observatoire, F-75014 Paris, France	26	4	4 2	3	• 2 x ^{87}Sr – well advanced • ^{199}Hg – advanced
INRIM Turin, Italy	Strada delle Cacce 91, 10135 Torino TO, Italy	6	4	2	2	• ^{171}Yb – well advanced • (Sr (neutral) – being built)
BEV Wien Austria	Arltgasse 35, A-1160 Vienna, Austria	2	1			• Part of NEAT-TF • Comparison to UTC(TP) via fibre-link through CESNET and ACOnet and ACOnet
IPE/CAS Prag Czech Republic	Institute of Photonics and Electronics, CAS Chaberská 57, 18251, Praha 8 - Kobylisy, Czech Republic	6	1 (at ISI)		1	• IPE (UFE) is associated with CMI • Part of NEAT-TF and CMI is part of OFTEN (EMPIR) • Comparison to UTC(BEV) via fibre-link through CESNET and ACOnet • $^{40}Ca^{+}$ - single/multi-ion at ISI Brno, transmitted to IPE by coherent link
GUM Warsaw Poland	ul. Elektoralna 2, 00-139 Warszawa, Poland	11	5	1(+1)*	2**	• More performant clocks are being developed at AOS and FAMO. • * fountain clocks are available at AOS & PSNC, one not yet fully operational. • ** FAMO has developed two ^{88}Sr optical clocks, which were compared to UTC(PL) and UTC(AOS) through OPTIME • OPTIME – fibre links connect UTC(PL), UTC(AOS), PSNC, KL FAMO and OPL
Astrogeodynamic Observatory Borowiec Poland	Drapałka 4, 62-035 Borowiec, Poland			1 (+1)*		• *fountain clocks are available at AOS & PSNC, one not yet fully operational.
PTB Braunschweig Germany	Physikalisch-Technische Bundesanstalt, Bundesalle 100, D-38116 Braunschweig, Germany	3	5	2 2	3	• ^{87}Sr – well advanced • ^{87}Sr – transportable / well advanced • $^{171}Yb^{+}$ – well advanced • (^{229}Th – being explored) • ($^{27}Al^{+}$ – being explored) • (Yb+ Multi-ion – being explored)
VSL Delft The Netherlands	VSL Thijsseweg 11, 2629 Delft, Niederlande	4				• Part of NEAT-TF • Experience with White rabbit time transfer

Table 3: Selection of NMIs in Europe providing UTC(k). Many of them are operating high performance microwave as well as optical clocks, have long-standing collaboration in T&F distribution over fiber networks and could be easily linked to possible GEANT network extensions.

Table 4 gives a rough estimate of the link length for the European CORE network and the number of amplifiers required for compensation of the fibre attenuation. We assume that T&F signals on average have to be amplified every 80 km and that the optical frequency signals have to be recovered every 350 km using e.g. repeater laser stations (RLS).

		Distance	**No. of in-line ampl.**	**No. of RLS**
Start	**End**	**km**	**#**	**#**
London (NPL)	Paris (OBSPARIS)	750	10	3
Paris (OBSPARIS)	Braunschweig (PTB)	1450	19	6
Paris (OBSPARIS))	Torino (INRIM)	850	11	3
Torino (INRIM)	Vienna (BEV)	1285	17	4
Vienna (BEV)	Prague (IPE)	550	7	2
Prague (IPE)	Warsaw (GUM)	1200	16	4
Warsaw (GUM)	Braunschweig (PTB)	1050	14	4
Braunschweig (PTB)	Amsterdam (VSL)	500	7	2
Amsterdam (VSL)	London (NPL)	500	7	2
	total	**8135**	**108**	**30**

Table 4: Approximate distance between PoS of the CORE in km and a rough estimate of the number of amplifiers and repeater laser stations required for operation.

For simplicity of the cost estimates and better comparison, we estimate a total length of the fibres contributing to the CORE network of 10 000 km. We assume an annual rental fee of 0.2 € per Meter (considered realistic on average) for the dark fibre approach and about 0.05 € per Meter (considered optimistic i.e. at the lower end of the range) for the dark channel approach for a contract life time of 10 years. As costs for amplification we assume 10 000€ per amplifier and 70 000 € for a repeater laser station. Manpower costs are estimated on FTE basis assuming an average cost of 60 000 € per FTE.

Thus, for the entire CORE network we estimate hardware costs of 3.2 M€ and an annual fee of 2.0 M€ for the dark fibre approach and 0.5 M€ for a dark channel.

Since the fibre renting costs largely deviate between Scenario #1 and #2 or #3, we continue to consider two options when estimating the required investment.

Cost estimate for implementation as dark channel					
Estimated cost for	**Hardware single investment**	**Hardware replace-ment p.a.**	**Fibre/ channel rent p.a.**	**Human resources FTE**	**Integrated cost over 5 years**
deployment of the entire infrastructure	3.180.000 €				
Implementation phase (5 years)	3.180.000 €		500.000 €	24	12.880.000 €
Maintenance phase (5 years)		159.000 €	500.000 €	15	7.795.000 €
Integrated cost over 10 years					**20.675.000 €**

Table 5: Cost estimate over 10 years life span for scenario #1.

Cost estimate for implementation as dark fibre					
Estimated cost for	**Hardware single investment**	**Hardware replace-ment p.a.**	**Fibre/ channel rent p.a.**	**Human resources FTE p.a.**	**Integrated cost over 5 years**
Deployment of the entire infrastructure	3.180.000 €				
Implementation phase (5 years)	3.180.000 €		2.000.000 €	24	20.380.000 €
Maintenance phase (5 years)		159.000 €	2.000.000 €	15	15.295.000 €
Integrated cost over 10 years					**35.675.000 €**

Table 6: Cost estimate over 10 years life span for scenario #2 or #3.

In case the entire CORE network would be based on Scenario #1 (dark channel) we estimate a total investment of 21 M€ over 10 years, when assuming that about 5% of the installed hardware needs replacement after the first 5 years of deployment phase. Contributions are listed in Table 5.

In case the entire CORE network would be based on Scenario #3 (dark fibre) we estimate a total investment of 36 M€ over 10 years, when assuming that about 5% of the installed hardware needs replacement after the first 5 years of deployment phase. Contributions are listed in Table 6.

In Figure 5 we show the envisaged network connections based on point-to-point links between UTC(k)- laboratories. Yellow polygons indicate PoPs of the REFIMEVE network currently being established in France. In addition, we indicate European VLBI and radio astronomy stations close to the envisaged links, or those that are already linked to an NMI such as the Italian VLBI stations Matera and Medicina, or those planned to link as those in northern Europe (Onsala, Metsähövi and Kajaani). Table 7 lists postal address and GPS coordinate of institutes shown in Figure 5.

3.3 T&F Gateways

At present, there exist a few different solutions for T&F transfer by optical fibres in Europe (ELSTAB, White Rabbit, bi-directional optical carrier, uni-directional optical carrier, RF-over-fibre, frequency comb transfer) adapted to specific user needs. Up to now such solutions do not co-exist on a single fibre. However, using a dedicated fibre for the T&F service with collocation and cooperation of different systems will require defining specific gateways that allow to switch between such solutions.

Such gateways do not yet exist and would need to be developed prior to the implementation of the CORE. Even if in principle possible to implement, this would have significant impact on the number of required channels in Scenario #1, resilience, the maintenance and supervision of the network, and would raise the total cost.

Considering this, one way out of this is to use different frequency bands in a dark fibre where different implementations can coexist without interfering with each other.

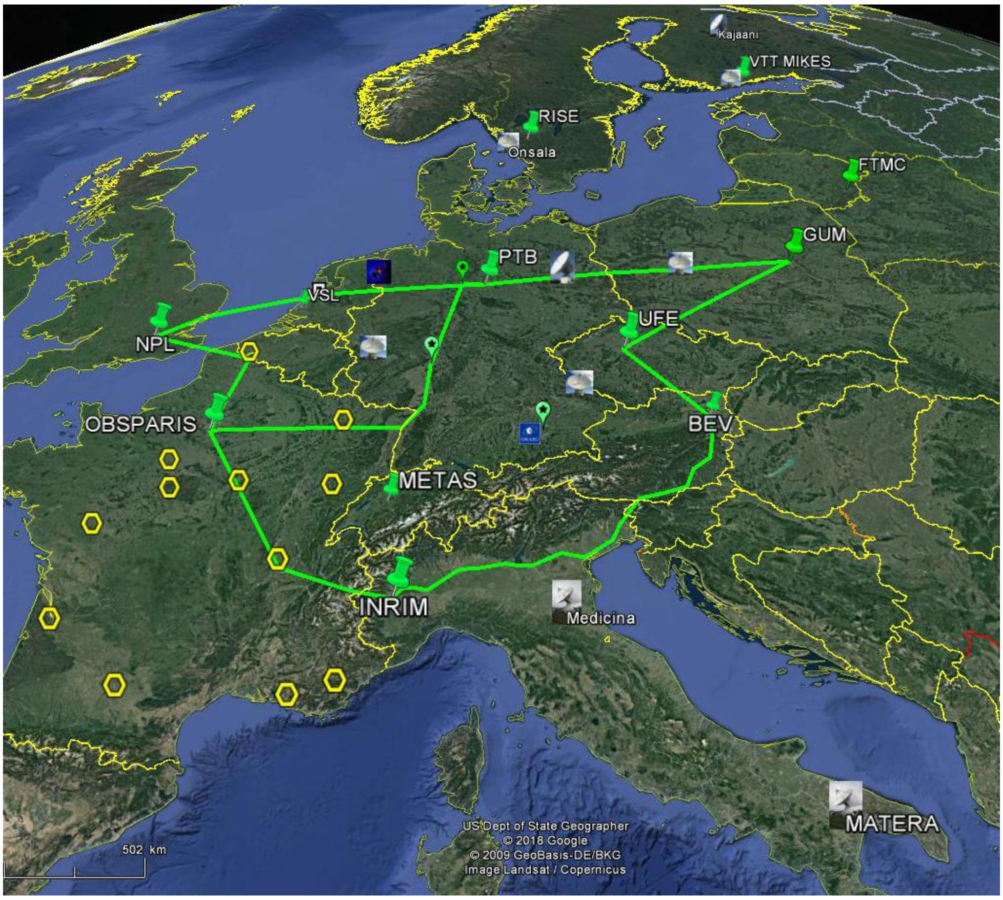

Figure 5: Map of the first implementation phase of the envisaged CORE network connecting UTC laboratories ( ) in Europe. In addition, radio astronomy stations ( ) and the PoPs of the REFIMEVE network ( ) are shown.

NMI	Address	GPS COORDINATE
NPL	National Physical Laboratory, Hampton Road, Teddington Middlesex, TW11 0LW, UK	0°20'39.01"W, 51°25'37.38"N
OP	Laboratoire national de métrologie et d'essais - Système de Références Temps-Espace, 61 Avenue de l'Observatoire, F-75014 Paris, France	2°20'6.18"E, 48°50'08.74"N
INRIM	L'Istituto nazionale di ricerca metrological, Strada delle Cacce 91, 10135 Torino TO, Italy	7°38'16.24"E, 45°0'52.29"N
BEV	Bundesamt für Eich- und Vermessungswesen, Arltgasse 35, A-1160 Vienna, Austria	16°19'8.94"E, 48°12'32.64"N
UFE	Institute of Photonics and Electronics, CAS, Chaberská 57, 18251, Praha 8 - Kobylisy, Czech Republic	14°27'12.35"E, 50° 7'51.29"N
GUM	Central office of meausres, ul. Elektoralna 2, 00-139 Warszawa, Poland	21° 0'3.24"E, 52°14'29.26"N
PTB	Physikalisch- Technische Bundesanstalt, Bundesalle 100, D-38116 Braunschweig, Germany	10°27'51.19"E, 52°17'35.59"N
VSL	VSL, Thijsseweg 11, 2629 Delft, The netherlands	4°23'13.69"E, 51°59'08.83"N
METAS	Eidgenössisches Institut für Metrologie, Lindenweg 50, CH-3003 Bern-Wabern, Switzerland	7°27'49.55"E, 46°55'28.20"N
MIKES	Tekniikantie 1, 02150 Espoo, Finnland	24°49'27.70"E, 60°10'50.71"N
SP	Research Institute of Sweden, Brinellgatan 4, SE-504 62 Borås, Sweden	12°53'34.43"E, 57°43'00.70"N
FTMC	2017 State research institute Centre for Physical Sciences and Technology, Savanorių ave. 231, LT-02300 Vilnius, Lithuania	25°10'58.49"E, 54°38'36.32"N

Table 7: Postal address and GPS coordinates of NMIs providing UTC(k) likely to contribute to the envisaged CORE network for time and frequency.

4 CONCLUSION

The consortium agrees that a phase stabilized optical carrier at 1.5 µm, a stabilized radio frequency, timing signal such as one-pulse-per-second (pps), and a signal indicating “healthy” & origin of signal (source) should be provided by the service, The frequency and timing signals have to be traceable to at least one NMI or UTC(k) laboratory and should provide at least an order of magnitude better accuracy than most advanced user requirements. The service will greatly benefit from support of NRENs and GEANT as they are well experience in operating large networks and have a better market overview of vendors. Thus, the consortium considers a long-term relationship between science & education networks with T&F providers (NMI/UTC(k)) as highly desirable.

As a result of the intensive internal discussion, the CLONETS consortium recommends that

- a European consortium of NMI, NREN/ GEANT, RI and industry further pursues this research in a coordinated manner,
- the consortium takes action to establish a sustainable European fibre link infrastructure that covers the needs for frequency or timing signals of specific end users, by providing
    - a phase stabilized optical carrier at 1.5 µm,
    - a stabilized radio frequency, timing signal such as one-pulse-per-second (pps), and
    - a signal indicating “healthy” & origin of signal (source)

  to selected, well defined points of presence, and
- that these fibres shall be collocated and incorporated with existing NREN/GEANT infrastructure

The CLONETS consortium urges GEANT and European NREN

- to support these actions by providing dedicated fibres on the novel implementation of the GEANT network.

and urges the European Commission and national authorities

- to provide sufficient sustainable funding for these activities.