31-03-2023

Deliverable D2.2
Roadmap for Technical Implementation of the T&F-Reference System

Deliverable D2.2

Contractual Date:	01-10-2020
Actual Date:	31-03-2023
Grant Agreement No.:	951886
Work Package	WP2
Task Item:	Task 2.2
Nature of Milestone:	R (Report)
Dissemination Level:	PU (Public)
Lead Partner:	PTB
Document ID:	CLONETS-M30-004
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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).

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Executive Summary

This document describes in detail the technical implementation of the European T&F reference system as developed in WP2 and presented in D2.1 “Technical Design Report”. This is done by:

- reviewing a fiber infrastructure in Europe that can be used for T&F dissemination;
- reviewing currently existing National Implementations used for T&F dissemination and exploited technologies;
- mapping the ring architecture of the European Core Network to currently existing infrastructure;
- recognising the missing connections, and proposing solutions;
- detailing the interoperability issues resulting from using different transfer technologies and different wavelengths, and proposing solutions;
- proposing the implementation roadmap;
- estimating implementations costs;
- analysing the resilience and redundancy of proposed ring topology, and proposing solutions;
- analysing capabilities of integrating the applications requiring lower-level accuracy and stability than available directly from the European Core Network.

This deliverable incorporates input from the results of WP1, especially deliverable 1.2 “Requirements and Definitions”, as well as the deliverables 2.1 “ Technical Design Report” and 3.1 “Governance and Sustainability”.

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 and 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, we have divided the WP into several tasks and subtasks.

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

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**				M30		

Table 1.1: Work Package 2 partners and scope

1.1 Description of Work

This report comprises the work on Task 2.2 Interoperability at the European level (lead AGH) and its subtasks:

- subtask 2.2.1: Drafting engineering plans;
- subtask 2.2.2: Resilience and redundancy measures;
- subtask 2.2.3: Future integration of lower-level applications.

The results of the subtask 2.2.1 have been summarised in milestone M2.2 "1st draft of an engineering plan" (M18). The milestone was delayed due to a deeper discussion within Task 2.1 and Covid-19 related issues.

Task 2.2 Interoperability at the European level, discussed and developed an engineering model for the hardware building blocks identified in task 2.1.2 and needed for the implementation of the ring-design. This proposed engineering model for the European Core Network (ECN) is meant to facilitate time and frequency measurements at the highest level and allow transfers from one national implementation to another without loss of performance to assure interoperability at the European level. All key hardware building blocks (except for cavities and optical combs) discussed in D2.1, like T&F transfer equipment, optical amplifiers, T&F regenerators, etc., have demonstrated TRL 9, as they have been validated in real conditions (non-laboratory) and are currently operational in clock networks since many years. Cavities and combs have demonstrated TRL 7, whereby they have performed well in laboratory settings as well as harsh environments such as free-fall tests and airplanes but have not yet been validated under operational (non-laboratory) conditions in clock networks. It must be noted, that although the hardware and subsets of the proposed engineering model for the ECN have been tested and are operational since many years, the ECN in its entirety, as proposed here within CLONETS-DS, must undergo future operational testing. For example, to implement and establish the ECN, future funding must account for testing and validation of the interoperation of databases as well as simultaneous transmission of optical, frequency and time signals over the full geographical range of 1000s of km.

Work package leaders together with task leaders have taken on responsibility to achieve consensus on the architectural decisions amongst the project participants. The blueprints have been accepted by the community to facilitate a straightforward implementation once sustainable financial support is guaranteed.

1.2 Relation to other Tasks

Within Task 1.2 an extensive analysis of a number of science cases has been undertaken, leading to distinguishing five main areas where the access to the highest-accuracy time and frequency signals is crucial. These are:

- fundamental science;
- quantum technologies;
- Earth observation / geodesy;
- astronomy;

- position, navigation, synchronization and timing / telecommunication and networks.

Scientific activities within these areas are held in many member states across Europe. The list of all identified locations is summarised in Table 1.2.

	Scientific Area	Relevant Locations
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), 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), 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), Onsala (SE), Cheshire (UK), Herstmonceux (UK)
5	Position, Navigation, Synchronisation and Timing / Telecommunication and Networks	Braunschweig (DE), Bremen (DE), Frankfurt (DE), Paris (FR), Amsterdam (NL), Warsaw (PL) all UTC(k)/NMI locations

Table 1.2: List of scientific areas and relevant locations

The findings of WP1, supplemented with the locations of the European NMIs, served as a starting point to shape a vision of the ECN. In Task 2.1 we developed an architecture that supports highest-level science cases (SC) identified in WP1 and assures parallel use by different scientific communities and multiple users at the same time.

The research resulted in the definition of the three-ring topology (containing the northern, the middle and the southern rings) with sub-nets (e.g., French REFIMEVE network) and side-branches (e.g., Italian IQB network and the Spanish and Turkiye side-branches in the future), together with the locations of the ECN core sites. These are shown in Figure 1.1 and summarised in Table 1.3.

Figure 1.1: The ring topology as an example for the envisioned network. Locations shown here are based on science case identified in WP1

As a result of intensive discussions with stakeholders and members of WP1, we have identified four types of services:

- relative frequency service;
- absolute frequency service;
- relative timing service;
- absolute timing service.

These four services are detailed in D2.1, but we note here that they can be categorised:

- in terms of requirements for timing and frequency signals;
- with respect to absolute (traceable) and relative (free running) signals.

The signals need to provide information to the user on the received signal, and on-demand traceability from source to usage.

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

The core network needs interfaces at its boundary, either because it meets another network, or it interfaces to a secondary layer. At the interface, interoperability between networks is ensured if an accurate enough phase measurement between the two metrological networks is made. The required accuracy depends on the scientific application covered by the ECN.

Core Site	Function	Ring assignment
Bern	PoP/ NMI	Southern
Boras	PoP/ NMI	Northern
Braunschweig	PoP/ NMI	Middle/Northern
Brno	PoP/ NMI	Middle
Bruessels	PoP/ NMI	Middle
Delft	PoP/ NMI	Middle
Espoo	PoP/ NMI	Northern
London	PoP/ NMI	Middle
Lublijana	PoP/ NMI	Southern
Paris	PoP/ NMI	Middle/Southern
Prague	PoP/ NMI	Middle
Riga	PoP/NMI	Northern
Torino	PoP/ NMI	Southern
Tallin	PoP/NMI	Northern
Vienna	PoP/ NMI	Middle/Southern
Warsaw	PoP/ NMI	Middle/Northern
Zagreb	PoP/ NMI	Southern
Amsterdam	PoP	Middle
Frankfurt	PoP	Middle
Hannover	PoP	Middle
Onsala	PoP	Northern
Poznan	PoP	Middle
Stockholm	PoP	Northern
Basel	Cross-border PoP	Southern
Modane	Cross-border PoP	Southern
Slubice	Cross-border PoP	Middle/Northern
Strasbourg	Cross-border PoP	Middle/Southern
Suwalki	Cross-border PoP	Northern
Bologna	Branching	LIFT
Karlsruhe	Branching	Middle
Milano	Branching	Southern
Munich	Branching	Middle/Southern

Table 1.3: List of the core locations (based on D2.1, postal addresses are given there)

The outputs of this subtask have been aligned with the Task 3.2 “The sustainability model for the services”, in an iterative process allowing modifications of the engineering plan in accordance with the budgetary calculations. The engineering plan and the project budget will form the basis for the infrastructure implementation proposal.

2 Drafting Engineering Plans

In Task 2.2 we describe the design of an engineering model as well as the deployment strategy supporting the system design as outlined in D2.1 "Technical Design Report" and supporting the specific needs of the scientific community detailed in D1.2 "Requirements and Definitions". The design assures interoperability of already existing national T&F implementations at European level and addresses potential future extensions wherever possible.

Based on the global architecture and the core site locations (D2.1) and the service requirements (D1.2), and also on the extensive knowledge of the European fiber infrastructure by the consortium partners, this subtask drafts an engineering plan that meets the requirements and achieves interoperability at European level by:

- identifying already existing national implementations that fulfil the requirements;
- identifying already existing fiber infrastructure available from GÉANT or NRENs for this project to save time and money;
- identifying missing connectivity between PoPs and user sites identified in WP1;
- determining measures to provide seamless cooperation of different T&F national systems and the proposed European T&F reference system;
- proposing solutions for missing connections for the core network as well as between PoPs and other user sites identified in WP1 and task 2.1.2;
- identifying costs of the proposed connectivity.

The proposed system design also addresses the possibility to use spare capacities of its components for other research purposes, like, for example, quantum key distribution.

It is noted that GÉANT finished implementing the Horizon 2020 project GN4-3N, which is currently continued in GN5-1, that encompasses the procurement and deployment of a long-term optical infrastructure for the Europe's scientific and educational organisations for another 15 years. This provides the in-depth knowledge of the international market situation and technical capacities to plan and implement the fiber infrastructure needed for this project. The same holds for the NRENs on the national level.

2.1 Existing Fiber Infrastructure of GÉANT and NRENs

In this section we present the information about the fiber infrastructure that can be used to build the ECN. This can be divided into the fiber infrastructure that already exists and has already been used for T&F purposes by various scientific institutions (mostly the National Metrology Institutes – NMIs or academia), and the fiber infrastructure that might be provided/made available by the operators of research and education networks, either on the European or on the national level. In the first case the infrastructure is usually operational, fitted with the necessary equipment, so its incorporation in the ECN should be straightforward. In the second case only the access to the stretches of the fibres may be available and the required equipment need to be first bought and installed. In all the cases the interoperability issues have to be taken into account to assure that T&F

signals can be transmitted across various parts of the ECN, especially on the cross-borders and branching points, where either the technology or the wavelengths used for the T&F transfer may differ. Here we also address the problem of links that are currently missing but are required to implement the ECN.

2.1.1 Identification of Existing Infrastructure.

Substantial progress has been observed in last two decades in many countries across the Europe in the area of T&F metrology. This resulted in developing the optical clocks on one hand, and on the other hand the methods and required equipment to exchange the ultra-precise T&F signals using optical fiber links between the laboratories involved in the research. The technology and expertise is now available to be applied on a wider scale. It is thus reasonable to assume that the infrastructure present across Europe ought to be engaged in the ECN wherever possible to take advantage of the existing potential and to save the costs.

The selection of the core sites, detailed in D2.1, has already taken this assumption into account by locating 15 of all 25 PoPs in the European NMIs. The NMIs serve as an external provider 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 essential for providing traceability to the SI second as well as access to time and frequency signals that have so far only been available at NMIs, besides only a few other laboratories worldwide. Future agreement between the ECN and European NMIs is a topic addressed in the WP3 (see deliverables D3.1 "Governance and Sustainability"). In Table 2.1 the NMIs are listed per country with their address.

Table 2.1 gives an overview of the existing fibre links throughout Europe. The meaning of the abbreviations used is:

- Ind Cs – industrial cesium standard;
- Lab Cs – laboratory cesium standard;
- CsF – cesium fountain;
- RbF – rubidium fountain;
- Lab Yb+ – laboratory ytterbium ion standard;
- Lab Yb – laboratory ytterbium neutral atom standard;
- Ud Yb – under development ytterbium neutral atom standard;
- Lab Rb – laboratory rubidium standard;
- Lab Sr – laboratory strontium standard, (Ud Sr – under development);
- Lab In+ – laboratory indium ion atom standard;
- Lab Al+ – laboratory aluminium ion standard;
- Lab Ar13+ – laboratory argon ion standard;
- Lab Ti-Yb – laboratory titanium-ytterbium neutral atom standard;
- Ud Hg – laboratory mercury neutral atom standard (under development);
- H maser – hydrogen maser.

The existing fibre links are to be distinguished between those that distribute T&F signals from an NMI from those that are provided by a National Research and Education Network (NREN) that do not provide time and frequency signals from an NMI.

Country	NMI Name	NMI Address	Available T&F infrastructure
Austria	BEV	Bundesamt für Eich- und Vermessungswesen (BEV), Arltgasse 35, A-1160 Vienna, Austria	Ind Cs, H maser fiber link access
Czech Republic	UFE	Institute of Photonics and Electronics (UFE), CAS, Chaberská 57, 18251, Praha 8 - Kobylisy, Czech Republic	Ind Cs, H maser fiber link access
France	OBSPARIS	Laboratoire national de métrologie et d'essais (OP), Système de Références Temps-Espace, 61 Avenue de l'Observatoire, F-75014 Paris, France	Ind Cs, Lab Cs, CsF, RbF, Lab Rb, H maser, Lab Sr, Lab Ti-Yb, Ud Hg, Ud Yb fiber link access
Germany	PTB	Physikalisch - Technische Bundesanstalt (PTB), Bundesalle 100, D-38116 Braunschweig, Germany	Ind Cs, Lab Cs, CsF, H maser, Lab Yb+, Lab Sr, Lab In+, Lab Ar13+, Lab Al+ fiber link access
Italy	INRIM	L'Istituto nazionale di ricerca metrological (INRIM), Strada delle Cacce 91, 10135 Torino TO, Italy	Ind Cs, Lab Cs, CsF, H maser, Lab Yb, Ud Sr fiber link access
The Netherlands	VSL	VSL, Thijsseweg 11, 2629 Delft, Netherlands	Ind Cs, H-maser
Switzerland	METAS	Eidgenössisches Institut für Metrologie (METAS), Lindenweg 50, CH-3003 Bern-Wabern, Switzerland	Ind Cs, Lab Cs, H maser, CsF
Poland	GUM	Central office of meausres (GUM), ul. Elektoralna 2, 00-139 Warszawa, Poland	Ind Cs, CsF, H maser, access to Lab Sr in Toruń fiber link access
UK	NPL	National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK	Ind Cs, CsF, H maser, Lab Sr, Lab Yb+, fiber link access
Finland	VTT	VTT MIKES, Tekniikantie 1, 02150 Espoo, Finnland	Ind Cs, H maser
Sweden	RISE/SP	RISE; Brinellgatan 4, 504 62 Borås, Sweden	Ind Cs, H maser
Lithuania	FTMC	State research institute Centre for Physical Sciences and Technology (FTMC), Savanorių ave. 231, LT-02300 Vilnius, Lithuania	Ind Cs fiber link access

Table 2.1: Postal address of NMIs providing UTC(k) likely to contribute to the envisaged CORE network for time and frequency (based on BIPM annual report and D2.1)

The NMIs have developed and demonstrated outstanding results for T&F dissemination via optical fibres for over 10 years via projects funding primarily from EURAMET, The European Association of National Metrology Institutes. This project funding has been reinforced by institutional and/or national funding, to support the funding of fibre links for the development of time and frequency dissemination via optical fibres. These links are listed in Table 2.2, column 2 (Existing T&F fibre links). Due to this project-oriented basis for establishing these fibre links from the NMIs to national users and other NMIs, they have varying grades of assured long-term use for the ECN. 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 noted it in Table 2.2, 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 from more than 10 years.

Furthermore, many countries have taken further steps to ensure not only long-term funding for these fibre links established to provide T&F dissemination, but a comprehensive national fibre network for T&F dissemination. These proposed national fibre networks for T&F dissemination are at various stages of completion and are listed in Table 2.2. The National Research and Education Networks (NRENs) play an important role in establishing a long-term national fibre network for T&F dissemination that supports novel applications in fundamental research. Table 2.2, column 5 lists the NRENs of the European countries for reference.

	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 (IQB)	GARR
6	The Netherlands	from VSL to ESTEC, Groningen	2	In progress	SURFNET
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	NLPQT, PIONIER-LAB 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	
	<u>web sites:</u>				
	ACOnet (Austria)	https://www.aco.net/backbone.html?L=1			
	CITAF (Czech Republic)	https://citaf.org/en/index			
	REFIMEVE (France)	https://www.refimeve.fr/index.php/en/			
	DFN (Germany)	https://www.dfn.de/en/			
	IQB (Italy)	https://www.inrim.it/en/node/654			
	PSNC (Poland)	https://www.psnc.pl/			
	NDFF (United Kingdom)	https://www.ndff.ac.uk/			

Table 2.2: Overview of the existing fibre links in Europe (reused from D2.1)

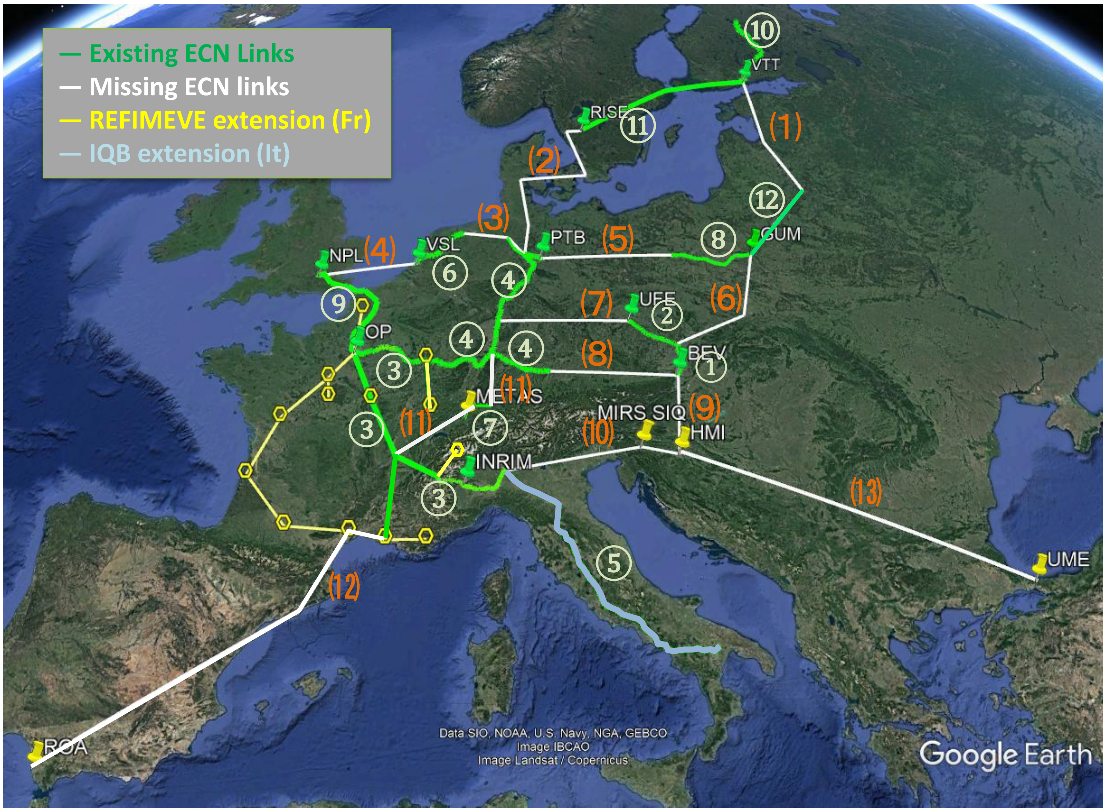


Figure 2.1: Map with already existing (green) and missing (white) ECN links that would enable the envisaged ECN ring topology. The numbers in circles refer to the items in Table 2.2 (existing NIs), whereas the numbers in parenthesis to the items in Table 2.3 (missing links). In addition French REFIMEVE and Italian IQB links are shown.

A map of the existing links detailed in Table 2.2 is shown in Figure 2.1 together with the French REFIMEVE (yellow) and Italian IQB (light blue) extensions (for the most up-to-date details of REFIMEVE and IQB see the respective webpages: for REFIMEVE* and for IQB†). The missing links, also shown in Figure 2.1 using a white colour, are discussed in Section 2.1.2.

2.1.2 Missing Links

The missing links required to complete the overlapping ring topology of the ECN as shown in Figure 1.1 are collected in Table 2.3. These links are also mapped in Figure 2.1 using white colour.

All of the missing fiber links to complete the proposed ECN are intercontinental links. The column "Required connections" of Table 2.3 gives the details of the link route. The priority assigned to the missing links, shown in the last column, is assigned based on a phased implementation of the proposed rings (see section 2.6). The main part of the middle ring should be completed with the highest priority because it is essential for overlapping many fiber links, establishing cross-border links, and providing access to a large percentage of the science users in combination with REFIMEVE and IQB. The priority of the southern link, northern link, and extensions are ranked according to the percentage of science users granted access, from highest to lowest respectively.

	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 (Krakow) – 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 (HR)	Southern	4
10	Croatia – Slovenia – Italy	Zagreb- Milano	Southern	8
11	France – Switzerland	Lyon – CERN –METAS (Bern) – Strasburg	Southern	3
12	France – Spain	Toulouse- Cadiz (ROA)	side branch	11

* https://www.refimeve.fr/index.php/en/the-network/interactive-map-2.html
† https://www.inrim.it/en/research/scientific-sectors/time-and-frequency/italian-quantum-backbone

13	Zagreb – Istanbul	Zagreb - UME	side branch	12

Table 2.3: List of missing fibre links required to provide access to nearly all institutions carrying out research on the identified 5 science cases (based on D2.1)

2.2 Existing National Implementations

Together with task 2.1 we have identified already existing national implementations (NI) for T&F distribution, which were established by NMIs with help from local NRENs, GÉANT or telecom providers. The data were collected during the survey carried out in December 2021 (updated in February and March 2023), mostly among the consortium members, but also other potential beneficiaries of the ECN. The aim of the survey was to assess the legal, technical and geographical conditions of NIs already existing, being under development and future-planned. The results are collected in Table 2.4 and Table 2.5, separately for the optical frequency links and the RF/time links.

The links for the optical carrier transfer exist in some form in most EU countries, although to substantially different extents, varying from single hundred kilometer long stretches to large infrastructures spanning an entire country. The most technologically advanced infrastructures exist in France (ESFRI REFIMEVE research infrastructure), in Italy (Italian Quantum Backbone, formerly known as LIFT) and also in Germany, UK and the Czech Republic (CITAF). In Poland, the currently on-going project NLPQT (National Laboratory of Photonics and Quantum Technologies) is going to enable access to the optical frequency for Polish research laboratories before the end of 2024.

Currently, the cross-borders links exist between France and Italy, France and Germany, France and UK and France and Switzerland. Building the missing cross-border links is certainly the aspect that needs substantial effort and investments, but is necessary for establishing the ECN.

Most of the NIs use proprietary-developed technologies for the optical frequency transfer, which has been commercialised and are currently available from a few companies (see Section 2.3, Table 2.6). They are based on noise-cancelling feedback loops, able to suppress the delay fluctuations occurring in the optical fiber due to temperature and mechanical stress. They require bi-directional operation over the same single-mode fiber and use two closely spaced (tens of MHz), usually un-modulated optical carriers (see D2.1 for more technical details).

The optical bandwidth requirements are in general low and a single ITU channel is sufficient for the optical frequency transfer applications. In almost all European countries, mostly due to historical reasons, the ITU C-band channel C44 (1542.14 nm, 194.400 THz) is used for the optical frequency transfer. The only essential exception, up to now, is Switzerland, where the local infrastructure uses ITU channel C07 (1572.06 nm, 190.700 THz), which is located at the short-wavelength edge of the L-band. Some exceptions exist also in the Czech Republic, but they are, however, limited to the local connections only, and are not essential for the ECN general structure.

For the regeneration of the optical signal, bi-directional erbium-doped optical amplifiers (bi-EDFA) can be used. In long links, however, spanning several hundred kilometers long distances, bi-EDFAs suffer from propagation of unwanted double Rayleigh backscattering (the single backscattering can be removed effectively by band-pass filtering the beat-note signal), residual reflections from optical connectors or other optical components (e.g., filters), which result in generation of a severe fading noise. To overcome this deficiency Regenerative Laser Stations (RLS) can be used after some distance (some 500 km or more, depending on specific conditions along the fiber), offering also convenient means for splitting the signal to external scientific users. Brillouin amplifiers have also been successfully used for regenerating signals along long spans (separated by about 200 km). Usage of Raman bi-directional amplifiers has also been reported, although they do not differ substantially from bi-EDFAs with respect to propagation and amplification of unwanted signals.

Despite different implementations in particular countries and resulting equipment heterogeneity there are good conditions for incorporating NIs (or their parts) into the ECN. The exemption of Switzerland can be handled with help of the optical frequency comb, which can be used to bridge substantially different optical frequencies.

The infrastructure for the time and RF (T&RF) transfer is less developed at the time of writing (concerning the number of operational links) and more heterogeneous than the previously discussed OC infrastructure. The currently existing infrastructures uses substantially different technologies, ranging from uni-directional links exploiting two separate fibres in a standard DWDM telecommunication infrastructure (like WR connections or two-way un-stabilised links for clocks comparison), to fully stabilised solutions using bi-directional transmission in a single fiber, allowing accurate (picoseconds level) determination of link propagation delays (e.g. ELSTAB). The techniques have also been developed for joint dissemination of all metrological signals (i.e., OC, RF and 1 PPS) in a single fiber, exploiting either carrier modulation (amplitude or phase) or wavelength multiplexing in a single ITU channel. The technique with phase modulation is going to be implemented in France within the REFIMEVE network. In Poland a large national infrastructure is currently under development, led by PSNC within the project PIONIERLAB, which by 2024 will connect 21 Polish academic centres using the Polish NREN fiber infrastructure.

The optical bandwidth requirements for T&RF transfer are much larger because of the modulation required to imprint the time tags. It usually requires two ITU channels but can be shrunk into a single ITU channel if really necessary, occupied by substantial increase of costs due to special optical filters requirements.

To regenerate such signals, bi-EDFAs can be used and in some cases the same amplifier can be shared between OC and T&RF signals. Contrary to the OC links, the use of Brillouin amplifiers or RLS is prohibited for transmitting T&RF signals due to their limited bandwidth. Regeneration of signals with opto-electric-optical (OEO) conversion, which from the functional point of view is analogous to the RLS, is possible and has been successfully demonstrated. Problems related to the accumulation of Rayleigh backscattering noise are, in general, similar as in OC links, although, due to much broader optical sources are typically used (telecom-grade DFB lasers or SFP modules) the noise can be regarded as a stationary one and no signal fading is observed. Due to higher bandwidth and to intensity modulation, which is almost exclusively used to imprint the timing information onto the optical carrier, the required signal levels for reliable operation are higher (typically around -30 dBm) compared to the OC links. The OC links gains from coherent detection techniques and much narrower bandwidth, which gives some 20 dB to 30 dB boost when comparing to T&RF links.

Cohabitation of different technologies within the ECN can be challenging, especially due to different calibration methods required for time transfer implementation. There are, however, not any fundamental constraints for such cohabitation. Contrary to the OC links using different wavelengths in various countries to convey the T&RF signal pose not any problems, as no wavelength conversion is required (all processing of the T&RF signals is performed in the electrical domain only).

	Country	connections	signals	Fiber type	Transfer technology	Wavelengths
1	Austria	BEV to Brno	OC	dark channel	OC modems bi-EDFA	1542.14 C 44
2	Czech Republic	from ISI (Brno) to UFE (Prague), from ISI to BEV (Vienna), from ISI to Olomouc – 3 wavelengths, ISI to NPP Temelin	OC	dark channel	OC modems bi-EDFA, bi-SOA	Brno-Prague, Brno-Olomouc 1540.56 C46, Brno-Vienna 1542.14 C C44 and Olomouc C46+1458+1572.06 (ITU C46,C44)
3	France	National fiber network (from Paris to Lille, Strasbourg, Besançon, Modane, Marseille, Bordeaux) + cross-borders (REFIMEVE)	OC	dark channel	OC modems bi-EDFA RLS, MLS	1542.14 nm (ITU C44)
4	Germany	From PTB to Hannover, from PTB to Garching and Strasbourg via Karlsruhe	OC	dark fiber	OC modems bi-EDFA + Brillouin	1542.14 nm (ITU C44)
5	Italy	from INRIM to Sicily and Modane, France	OC	hybrid dark fiber + dark channel	OC modems bi-EDFA + Raman	1542.14 nm (ITU C44)
6	The Netherlands	---	---	---	---	---
7	Switzerland	from METAS to Basel, from Basel to Zurich from Zurich to METAS	OC	dark channel	OC modems bi-EDFA	1572.063 nm ITU C07 (L)
8	Poland	test link Toruń – Poznań NLPQT*	OC	dark fiber	OC modems bi-EDFA & RLS	1542.14 nm (ITU C44)

9	UK	from NPL to Birmingham and Paris, France	OC	dark fiber	OC modems bi-EDFA	1542.14 nm (ITU C44)
10	Finland	---	---	---	---	---
11	Sweden	---	---	---	---	---
12	Lithuania	---	---	---	---	---

Table 2.4: List of the fiber optic links for the optical frequency transfer across Europe. Exceptions from ITU channel 44 marked in red

	Country	connections	signals	Fiber type	Transfer technology	Wavelengths
1	Austria	from BEV to Innsbruck and BEV to Brno	10 MHz 1 PPS	DWDM	uni-EDFA, T&F modems developed with UFE/CESNET	1551.72nm (pluggable)
2	Czech Republic	from UFE to ISI, from ISI to UFE, from UFE to Vienna, Bratislava, Cieszyn, to CMI, ELI, Inst Plasma Physic, Geodetic Observatory, CTU, TUO	10 MHz 1 PPS	DWDM dark channel	WR, proprietary T&F modems uni- and bi-EDFA	pluggable SFPs, C39-C42 on bidi lines
3	France	many links, cross-border planned	1 GHz* 10 MHz 1 PPS*	DWDM for WR dark channel	WR + OC phase modulation	C-band (ITU C44 for OC)
4	Germany	from PTB to Hannover	10 MHz 1 PPS	dark fiber	ELSTAB	ITU C42, C43
5	Italy	from INRIM to Sicily and Modane, France	10 MHz 1 PPS	hybrid dark fiber + dark channel	WR	1542.14 nm (ITU C44)

6	The Netherlands	from VSL to TU Delft, from VSL to ESTEC, (from VSL to Amsterdam, Utrecht, Groningen and Eindhoven under development, scheduled in 2023)	10 MHz 1 PPS	DWDM	WR	1530.33 (ITU C59) 1529.55 (ITU C60)
7	Switzerland	from METAS to Thun METAS-Zurich planned	10 MHz 1 PPS	DWDM	WR	ITU L84, L85 (L-band)
8	Poland	GUM-AOS GUM-FAMO PIONIER-LAB*	10 MHz 1 PPS	dark fiber	ELSTAB bi-EDFA	ITU C35, C36
9	UK	from NPL to Birmingham	10 MHZ 1 PPS	dark fiber	ELSTAB	ITU C39, C42
10	Finland	From VTT to Kajani and RISE, Sweden				
11	Sweden	From RISE to Onsala and Stockholm	10 MHz 1 PPS	DWDM and dark channel	PTP and WR	ITU C44
12	Lithuania	GUM (PL) to Vilnus	10 MHz 1 PPS	DWDM	ELSTAB	ITU C35, C36

Table 2.5: List of the fiber optic links for T&RF transfer across Europe

Figure 2.2 shows the envisaged topology of the ECN divided into the three rings, together with the French REFIMEVE and the Italian IQB (formerly LIFT) extensions. In this figure we marked the parts that are currently available through the NIs, as well the missing links that will need to be built to provide the planned ECN functionality in full.

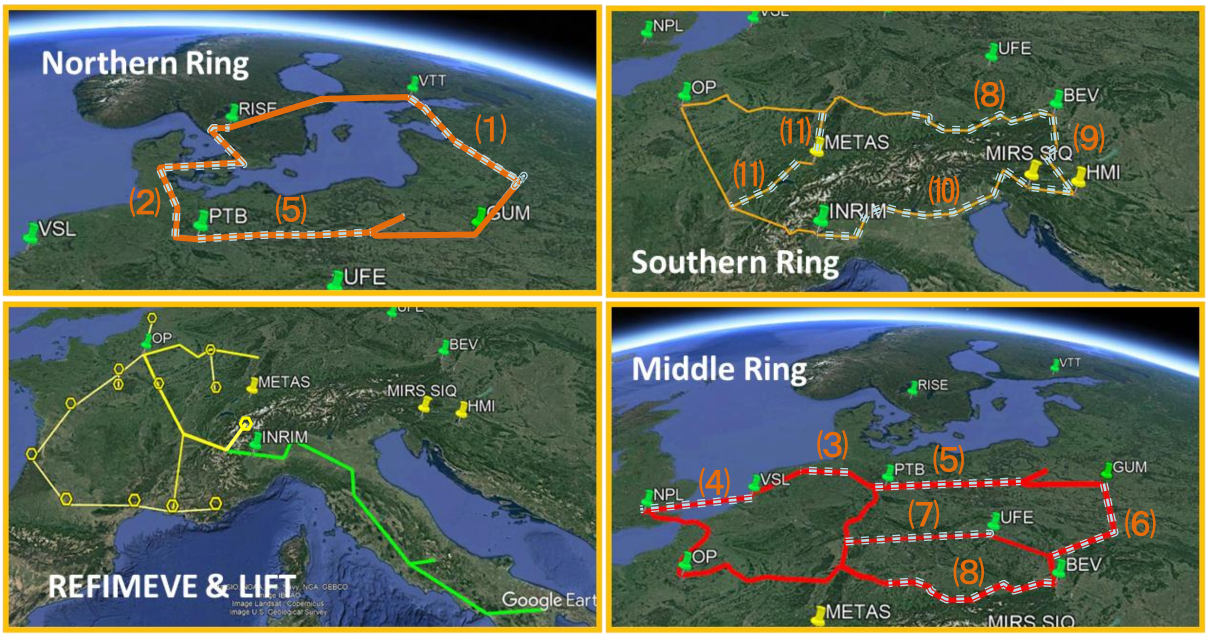
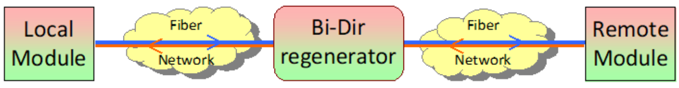
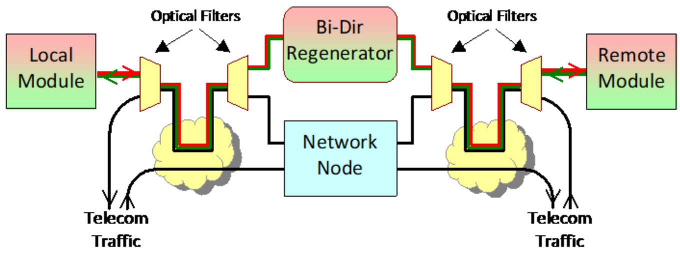


Figure 2.2: The ring topology of the ECN with the missing parts of each ring marked with dashed lines. The number refers to Table 2.3

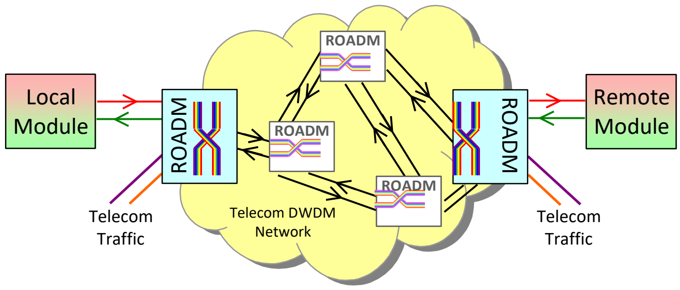
As it has already been mentioned, the NIs are not homogenous and use different technologies, which for now do not support distribution of all the metrological signals (i.e., the optical frequency, the radio frequency and time). That, by itself, is not the biggest problem, as many transfer technologies are compatible to some extent (see section 2.3 about the interoperability) and the links can be upgraded during the consecutive implementation phases (see section 2.6 “Implementation roadmaps”). The important aspect is, however, how the fiber is accessed in particular NI implementations. The most favourable and flexible is the access to so-called dark fiber (Figure 2.3 a), i.e., the fiber that is available solely for the T&F purposes. This allows organising a fully bi-directional transfer system, leaving plenty of optical spectrum for future upgrades and extensions. The other mode of accessing the fiber is the dark channel (Figure 2.3 b), where only a narrow slice of optical spectrum (usually just one ITU channel within a 100 GHz grid) is available in a fiber used simultaneously by a telecommunication operator (in practice such links are available almost exclusively from NRENs). This mode, although much less flexible, still allows for fully bi-directional operation, which is at the cost of bypassing all telecom nodes and in-line amplifiers, and limits future possibilities of adding additional services to the network. The least favourable and limiting approach is to use a standard DWDM telecom network (Figure 2.3 c), where the bi-directional operation is impossible and two separate fibers are used for sending the optical signals in the opposite directions. This approach is, in principle, inadequate for the highest-level applications requiring state-of-the-art stability and accuracy of transfer. As exemplified in Figure 2.4, all these three approaches are currently in use, which we consider as challenging for the ECN implementation.



a).



b).



c).

Figure 2.3: Illustration of various fiber access methods used in T&F fiber transfer links: dark fiber (a), dark channel (b) and DWDM channel (c)

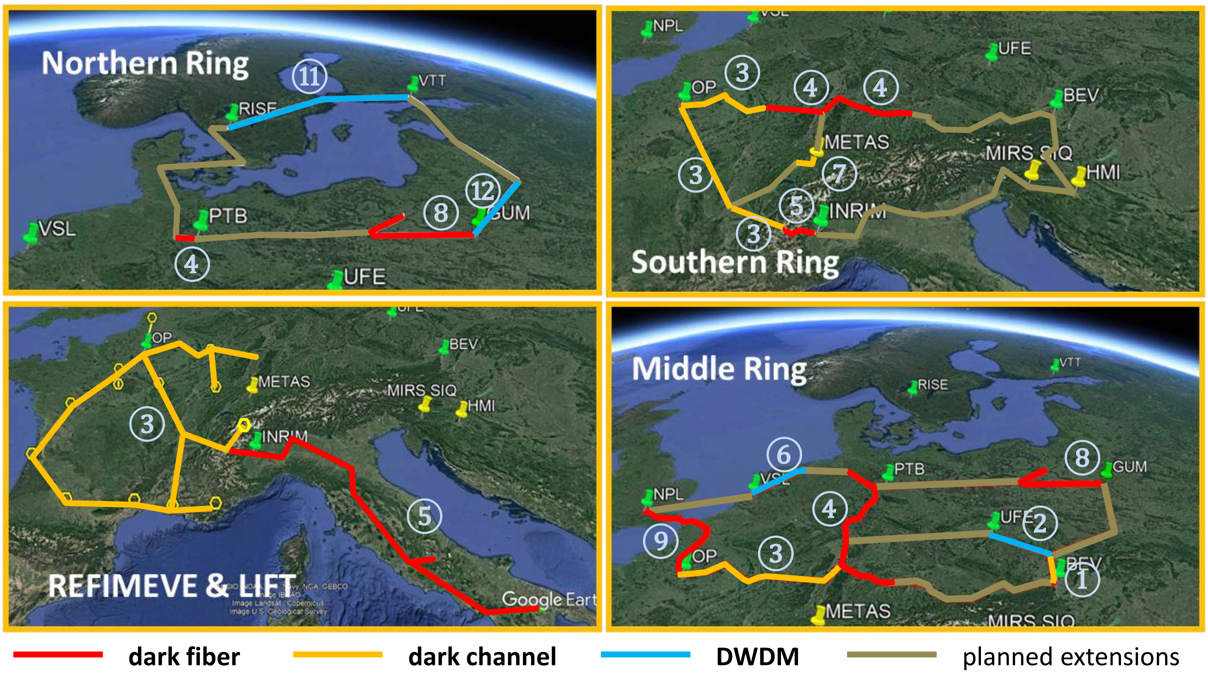


Figure 2.4: The ring topology of the ECN: the links existing within the NMIs with the fiber access method shown. The numbers refers to Table 2.2, Table 2.4 and Table 2.5

2.3 Interoperability of CLONETS with existing European Fiber Networks

It is assumed that construction of the ECN will exploit the NIs, which are present in many EU countries, as outlined in section 2.2. This is a reasonable approach because of cost reduction and also the well-defined responsibility with respect to the infrastructure maintenance and contacts with the scientific users wanting to access the ECN. This is also probably the fastest way to create the pan-European ECN infrastructure.

This approach, however, needs to take into account that each ECN ring spreads across a few countries and that different countries implemented different technologies for realising their NIs. Currently, the largest and the most advanced is the part prepared for the OC transfer, which has been designed and used for pan-European comparison of optical clocks, developed mostly in Germany, France and UK. Adapting these links for the purpose of the ECN, which is also aimed to distribute RF and time, will certainly result in a highly heterogeneous structure network. The design of the ECN must thus consider interoperability aspects to make the vision of the ECN possible and to assure its proper operation in the future.

The interoperability issues can be looked at from different perspectives. In particular, one can distinguish:

- the operation of a single ECN ring in case of different technologies and wavelengths used in different countries;
- the operation of the common paths and branching points;
- the definition of the universal user interface allowing accessing signals and necessary data in a common and known format at each PoP;
- the legal issues, concerning possibility of co-operation with NIs and the ECN;
- the capabilities of the equipment exchange in case of failure.

2.3.1 Single-Ring Operation

In a single ring, different wavelengths can be in principle be used to transfer the optical frequency. As stems from Table 2.4 most of the European countries accepted the wavelength 1542.12 nm (ITU channel C44) for such activities. The task of comparing the optical frequencies within PoPs against the local flywheel can thus be easily handled by beating the signals on a photodiode and counting the resulting beat note directly with a standard frequency counter (see D2.1 for technical details). If, due to some reasons, the beat note appears too high for direct counting (i.e., it exceeds some tens of MHz) it can be divided down with help of a suitable frequency prescaler (assuming a fast enough photodiode). Such techniques can be used up to 50 GHz. In the event that the beat signal is too weak it can be first converted down to an intermediate frequency using a microwave mixer and then amplified, divided and counted[3]. The microwave oscillator in such a scheme appears in a common path so its noise cancels out in the comparison. All the components required to build such setups are available from commercial companies.

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[3] see, e.g.: Ł. Śliwczyński, P. Krehlik, Ł. Buczek, H. Schnatz: „Synchronized Laser Modules With Frequency Offset up to 50 GHz for Ultra-Accurate Long-Distance Fiber Optic Time Transfer Links," Journal of Lightwave Technology, 40, 2022, pp. 2739-2747.

Larger frequency gaps can be handled using an optical frequency comb (see D2.1 for technical details). Such situations will take place in case of interfacing with Swiss NI, where the optical frequency transfer is held at 1572.063 nm (ITU channel C07), resulting in a frequency difference of 3700 GHz. This is the only exception identified till now where application of the optical frequency comb is unavoidable. Similar situations can arise, however, over the missing links (see Figure 2.2).

Using different wavelengths for RF and time transfer does not, in principle, create substantial problems, as each terminal of the transfer system terminates the optical part of the link and entire signal processing is handled fully in the electrical domain.

Substantial problems, however, arise when different parts of the ring use different fiber access methods (i.e., bi-directional dark fiber, bi-directional dark channel or uni-directional DWDM). For the highest possible accuracy and stability of transfer the bi-directional operation over the same fiber is absolutely essential. It is, in principle, possible to establish fully bi-directional transfer of the optical frequency, radio frequency and time in a single ITU channel[4], so a dark channel connection may be considered as capable to transfer all three signals. But this comes at substantial costs of necessary optical multiplexers (expensive 12.5/25 GHz and 25/50 GHz optical interleavers need to be used). In addition, the regeneration systems used for the optical frequency transfer cannot be applied to regenerate RF and time signals due to different principles of operation and bandwidth requirements. Thus at the regeneration points, the optical signals would have to be de-multiplexed, regenerated separately, and then recombined back into the same fiber.

Links based on the DWDM connections are inadequate for the highest level of time and frequency transfer as they use two separate fibres uni-directionally, as well as uni-directional amplifiers. From the point of view of signal quality (i.e., stability and accuracy) they should be considered as backup links only with the recommendation to replace them with dark fibres (the best option) or dark channels in the future. They can be, however, regarded as means to increase the ECN resilience (see Section 3).

2.3.2 Common Paths and Branching Points Issues

In the usual PoPs, two signals are compared against the local flywheel. At the ends of the common-path (i.e., the connections that are shared by two rings, e.g., the middle Ring and the Northern Ring) at least three signals enter the same PoP, so the equipment required to perform the measurements must be proportionally increased, and also the amount of the measurement data that need to be sent to the data repository. A similar situation exists at the PoPs located at the branching points, where a subnet or linear ECN extension is connected to the ECN.

The PoPs located along a common path are still the “usual PoPs” as there is no need to send any additional signals along these common connections and perform any additional measurements.

2.3.3 User Interface at the PoP

The PoP is a point in the structure of the ECN where a user can interact with the signals distributed by the ECN. It is assumed that the signals available at each PoP are:

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[4] see, e.g.: P. Krehlik, Ł. Śliwczyński, Ł. Buczek, H. Schnatz, J. Kronjäger: „Optical Multiplexing of Metrological Time and Frequency Signals in a Single 100-GHz-Grid Optical Channel,” IEEE UFFC 68, 2021, pp. 2303-2310.

- optical frequency generated by the local optical flywheel (i.e., the ultra-stable laser with the optical cavity), working in C-band, preferably around ITU channel C44;
- 10 MHz RF frequency generated by local RF flywheel (H-maser or other ultra-stable RF oscillators);
- locally generated 1 PPS signals.

It is also possible that both 10 MHz and 1 PPS can be locally produced from the optical frequency using an optical frequency comb operating as an optical frequency divider, with necessary additional equipment, like beat generating photodiodes, amplifiers, electrical frequency dividers, electrical signal distributors, etc. Other electrical signals can also be available, like 1 GHz, 100 MHz or 100 PPS. The physical signals available directly from the ECN will be produced by free-running oscillators. Determination of their absolute values (i.e., the optical or RF frequencies and time) is possible by accessing the data collected regularly in the ECN data repository, containing the cross-comparisons of flywheels among themselves, referenced also to the SI units thanks to the contributions from European NMIs.

The definition of the user interface at the PoP is necessary to define how external scientific users can access signals distributed by the ECN. A few variants of such access are considered, depending on the specific user needs and a level of his/her engagement in T&F activities:

- group 1: scientific users operating their own oscillators (either the optical clock, the RF oscillator or their own time scales), require the possibility to refer their oscillators directly to the signals provided by the ECN (see Figure 2.5);
- group 2: scientific users, which, regardless of whether they operate their own oscillators or not, require physically stable and accurate reference signals from the ECN (see Figure 2.6).

The first group can be divided further into the users preferring to carry out the comparison of their

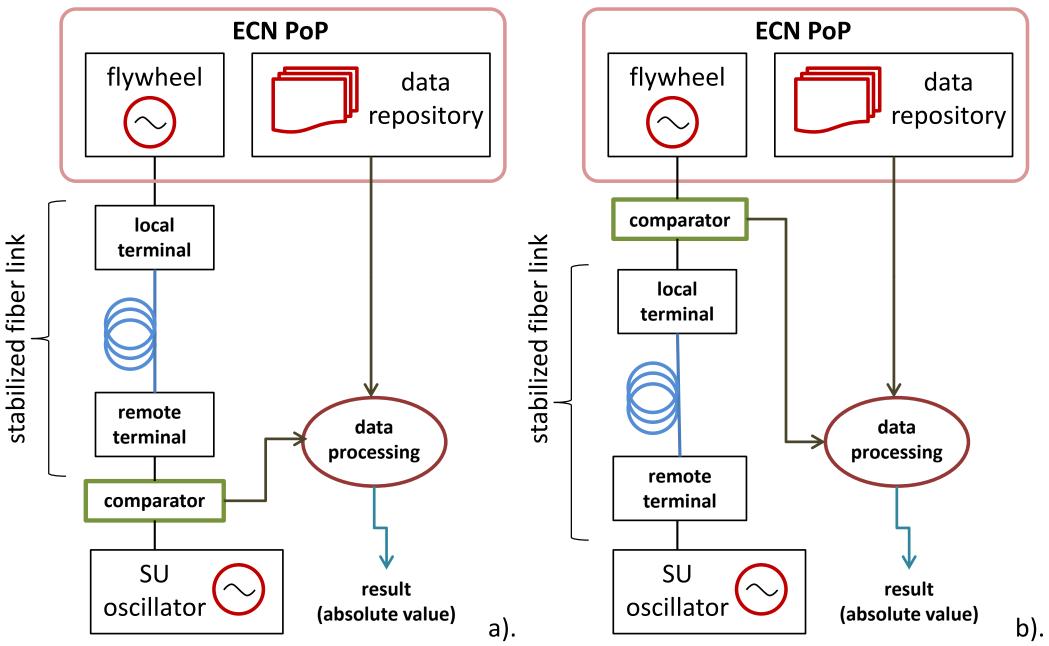

Figure 2.5: Set-up for the determination of the absolute value of the user's oscillator (see Group 1) using the ECN: comparison held at the user's premises (a) and at the ECN premises (b)

own signals with the ECN-provided signals directly at their premises (Figure 2.5 a), or rather at the ECN premises (Figure 2.5 b). To satisfy the needs of this group of users it is necessary to provide the means to compare the user oscillators with the ECN signals and guarantee the on-line access to the data collected in the data repository. The user may then use all these data to determine the absolute value of its oscillator with respect to any absolute standard available within the ECN or correct its own oscillator to follow one of the ECN standards. In any case a fiber link connection is necessary between the PoP and the user premises, in the direction depending on the place where the clocks need to be compared (at PoP or at the user).

The second group of users, which need a physically stable and accurate signal at their premises, require a stabilised link between the PoP and the user, with specified, required equipment (installed directly at the PoP, or at the user's premises) that enable the on-line correction of the ECN signals to reproduce the stability and accuracy of one of the standards available within the ECN (Figure 2.6). To perform the real-time correction an appropriate phase/frequency (φ/f) shifter is required, which can be, depending on the signal type, e.g., an acousto-optic frequency shifter for the optical frequency, a femto-stepper for RF signals or a variable delay line for time. Similarly as in the first group of users (Figure 2.5), the actuator may be located at the user premises (Figure 2.6 a), or at the ENC premises (Figure 2.6 b).

In any case, if the processing of the ECN signals is to be done at the ECN premises a highly-skilled CLONETS technical staff can take care about the equipment configuration and its further operation. In the opposite case it is necessary for the user to guarantee the adequate expertise level in the T&F signal processing and equipment operation.

It is assumed, that independent of the group of users 1 or 2 considered above, the necessary equipment is to be provided by the external scientific user, as well as coverage of all required costs of installation and maintenance. In summary, accessing the signals and data from the ECN by

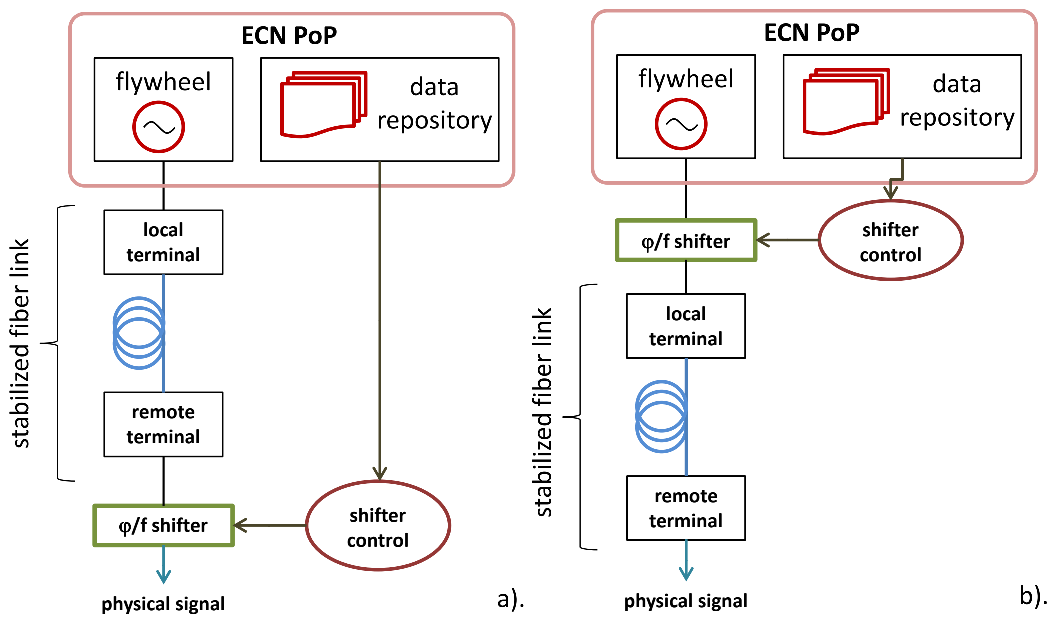

Figure 2.6: Physical signal generation based on the signals and data available from the ECN for Group 2 users: at the user's premises (a) and at the ECN premises (b)

external users requires close co-operation between the interested parties.

2.3.4 Legal Issues

The ECN as considered within the CLONETS-DS will take the form of an association of entities from different European countries. Such a large structure operating complex and advanced infrastructure comprising a specialised fiber network and the associated equipment is difficult to imagine without an adequate legal structure. The legal issues, relevant to the ECN interoperability, understood here as the capability of efficient and structured cooperation of the members of the CLONETS consortium itself on one hand, and the external scientific users on the other, considers:

- the responsibility for the reliable operation of the ECN as a pan-European research infrastructure;
- procedures of notifying about link/equipment failures;
- organisation of co-operation with the external users willing to access the ECN signals;
- defining the rules related to the installation and operation of the scientific user equipment in the ECN premises;
- defining the rules related to covering the costs of the user equipment and required fiber connections between the ECN and the user premises;
- defining the rules related to setting up the user interface enabling accessing the signals from the ECN;
- defining the rules related to granting the access to the ECN data repository to external scientific users.

The questions of the legal structure of the ECN and the solutions to various legal issues have been addressed in details within WP3 - see the deliverable D3.1 "Governance and Sustainability".

2.3.5 Equipment Availability

Table 2.6 collects the names of identified suppliers of the subsystems important for the ECN construction and its further maintenance. The list is certainly not exhaustive, and it might be expected, that in the future the number of manufacturers involved in the T&F market will grow.

Sub system name	EU suppliers
Signal source generation: it consists of lasers, optoelectronic devices, instrumentation.	Ultra-stable lasers : Menlo, Toptica Optical frequency combs: Menlo, Toptica, Menhir Photonics (Switzerland) Laser diodes, laser sources: NKT Photonics, Aerodiodes Photodiodes for the beat note generation: Discovery Semiconductors, Coherent/Finisar, Optilab, Alphalass, II-VI, EPS-Global Photonic components: A&A
Transport system: it consists of stabilisation systems, amplification systems, measurement systems.	Compensation : Exail (ex iXBlue/MuQuans), Menlo, Piktime, Timetech, Orolia (ex SevenSol), OPNT, Creotech Amplification: Lumibird, Menlo, Piktime, Optokon, OPNT
User system: it consists of receiver systems and measurement systems, computers, etc. It might be optical frequency combs and laser source, at some places.	Exail, Piktime, Orolia, OPNT, Creotech
Cross-points: it consists of receiver systems, comparison systems, measurement systems, instrumentation, computers. It might be optical frequency combs and laser source, at some places. GNSS receivers, atomic clock, flywheel oscillators (depending on places) are used.	Optical frequency combs, laser systems: see above. Clocks, flywheel oscillators: Thales, Orolia, T4Science (Switzerland), IQD GNSS receivers : Septentrio Measurement system : Kramer and Klische, Timetech, Orolia, Meinberg, Piktime
Supervision	As a service: Exail, Orolia, OPNT
Maintenance system	As a service: Exail, Orolia

Table 2.6: Overview of European suppliers of specific subsystems

2.4 Gap Analysis of Fiber Connectivity between PoPs and Users

The proposed ring structure of the ECN was planned in a way to assure that a large number of PoPs is localised close to the locations of the scientific users. It is, however, impossible to assure connectivity for all the users identified in the activities of WP1 as their number is large. This burden, similarly as the costs associated with renting the fibres and buying the necessary equipment, must be covered by the users themselves. The role of the ECN, apart from providing the signals and data, will be to provide the expertise and to co-operate with the external scientific users in determining the additional equipment required to connect to the ECN, to access the data generated within the ECN and to monitor and optimise the connection's performance.

It is envisaged that the National Implementations, as well as various national-level long-term initiatives (see Table 2.2) and NRENs, will play a major role in providing connectivity to the ECN for the external users. These include REFIMEVE in France, IQB in Italy, NDFF in UK, CITAF in Czech Republic or NLPQT and PIONIERLAB in Poland. In addition, some commercial fiber operators or telecom providers can solve connectivity problems. This can be, for example, a case in Germany, where Deutsche Telecom operates its own network distributing metrological signals for the purpose of telecom synchronisation supervision, connecting their synchronisation centres with PTB. Deutsche Telecom seems interested in providing external customers with high-quality synchronisation signals and certainly has both technical capabilities and expertise to do that.

Other initiatives, like, for example, EuroQCI (see 2.5.3), can also be considered as a means to connect scientific users to the ECN. The QKD community requires synchronisation signals to operate their protocols, which creates potential synergy by sharing quantum fiber links with T&F links.

2.5 Solutions for Missing Connections

In this section the options for the missing connections required to build the ECN rings structure are analysed. Apart from considering GÉANT and NRENs, who are natural choices because of long-lasting service for the scientific community, we consider also other initiatives, like EuroQCI initiative oriented on quantum technologies.

2.5.1 GÉANT and NRENs

Involvement of GÉANT, the collaboration of European NRENs, in building the ECN is desirable because of a few reasons. GÉANT is a large pan-European organisation having substantial level of expertise in maintaining and operating international fiber connections. It has experience in building new fiber links, organising procurements, etc. which will all be necessary to implement the ECN. In addition, GÉANT has already been engaged into the T&F activities through projects GN4-3 and GN5-1, where one of the sub-tasks is related to the Optical Time and Frequency Network (OTFN), being a pilot project to recognize the capabilities of organising the T&F transfer within GÉANT infrastructure. GÉANT is also coordinating the CLONETS-DS project. This certainly allowed GÉANT to gain a level of expertise in T&F activities and understand peculiarities related with distribution of ultra-accurate metrological signals.

Within GÉANT two options have been considered to help building the ECN: using dedicated dark fibres or using ITU channel 07 (1572 nm, the edge of the L-band), which can be operated as a dark channel (similarly to REFIMEVE in France).

The first option relays on procuring new dark fibres by GÉANT. In this option an arbitrary part of optical spectrum can be allocated for T&F applications, and moreover the same fiber may be relatively easily shared with other scientific or experimental services, as quantum communication, earthquake sensing, etc. This option should be considered as preferred one, assuming the costs are acceptable.

In the second option a selected number of connections can be made available within the regular GÉANT network. The connections available using the spectrum of ITU channel 07 are:

- London-Paris,
- Paris-Geneva,
- Geneva-Frankfurt,
- Frankfurt-Amsterdam,
- Geneva-Milano,
- Milano-Vienna,
- Frankfurt-Prague,
- Prague-Vienna,
- Vienna-Bratislava.

The GÉANT network with these available connections marked in red is shown in Figure 2.7.

The solutions proposed by GÉANT may be used to provide cross-border and international connections, whereas National Implementations will be exploited to provide connections within each country.

The estimated costs of the fibres required to build the ECN with help of GÉANT was analysed in D3.1 "Governance and sustainability".

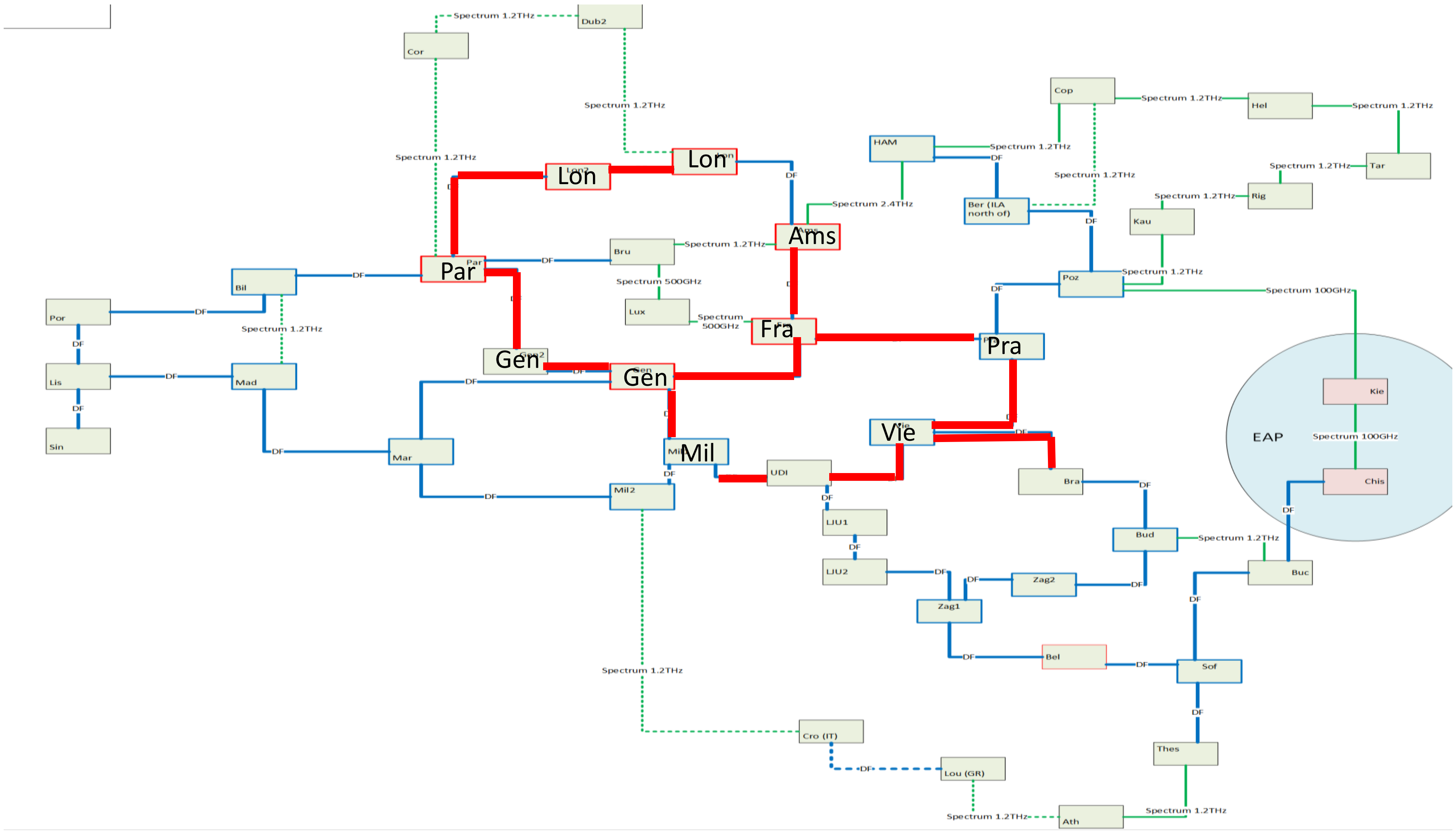

Figure 2.7: The GÉANT network with marked connections available in the L-band

2.5.2 National Implementations

It has been agreed that NIs should be considered as an in-kind contribution of each country. In this sense the NIs are not considered as a tool for providing the means for missing connections. NIs, on the other hand, will certainly evolve and expand within particular countries. The connections created this way may help building the ECN. In a few countries long-term initiatives have been established (listed in Table 2.2, column 4), like, for example, REFIMEVE in France, PIONIERLAB and NLPQT in Poland or CITAF in Czech Republic. In particular, still-expanding REFIMEVE may allow connecting Spain, which is now quite remote, to the ECN.

2.5.3 QKD Networks: EuroQCI

The primary goal of the EuroQCI initiative and program is to build a quantum secure communication infrastructure within the EU that would introduce new ways to protect the data and against cyber threats. At the first stage The QCI's main function will be to implement in a broad way quantum key distribution (QKD), an ultra-secure form of encryption. Within the EuroQCI initiative and its programs a combination of terrestrial and space implementations of quantum-based communication infrastructure is considered and can provide the security of digital services and transmission over short and long distances covering the EU and other continents. Realisation of the EuroQCI program is divided in several stages and will involve different stakeholders. The first stage is to build National QCI infrastructures that will serve as a basis for main and further QCI activities. Each country will implement it in its own way and taking into account national programs and goals. During this stage there will be separate QCI activity that will try to coordinate these national activities. During the second EuroQCI stage it is planned to establish cross border QCI links between national QCI using either terrestrial fiber connections or space segment satellite connections. At the same time, it is planned to run standardisation and certification activities. In terms of applications the early users of the QCI could be government agencies, and authorities of Member States and the EU that require a high level of security to transmit confidential information. The ultimate goal and vision are that the QCI will accommodate additional functionalities alongside quantum key distribution, such as digital signatures, authentication, and secret sharing schemes like e-voting. QCI, given the right technological progress is seen as a path to a Quantum Internet, linking quantum processors and sensors and enabling an EU-wide distributed quantum computing and communication capability. The overall QCI structure is presented in Figure 2.8.

The EuroQCI is composed of three main parts (more information can be found in the document EuroQCI "Concept of Operations (ConOps)"[**]:

- **SpaceQCI**: a space infrastructure and its corresponding ground segment. It provides the capacity for the system to generate key material;
- **TerrQCI**: a terrestrial infrastructure composed of MS-owned and EU-owned infrastructures (NatQCIs) connected to SpaceQCI. MSs may own several NatQCI networks, either interconnected or not;[**]
- **Quantum Hub**: The QH is the QCI orchestrator that manages service requests and allocation of resources based on an established governance scheme. It is the user entry point to the

[**] https://digital-strategy.ec.europa.eu/en/euroqci-conops-concept-operations

QCI system. Its main purpose is to manage service requests, and address service conflicts and service prioritisation.

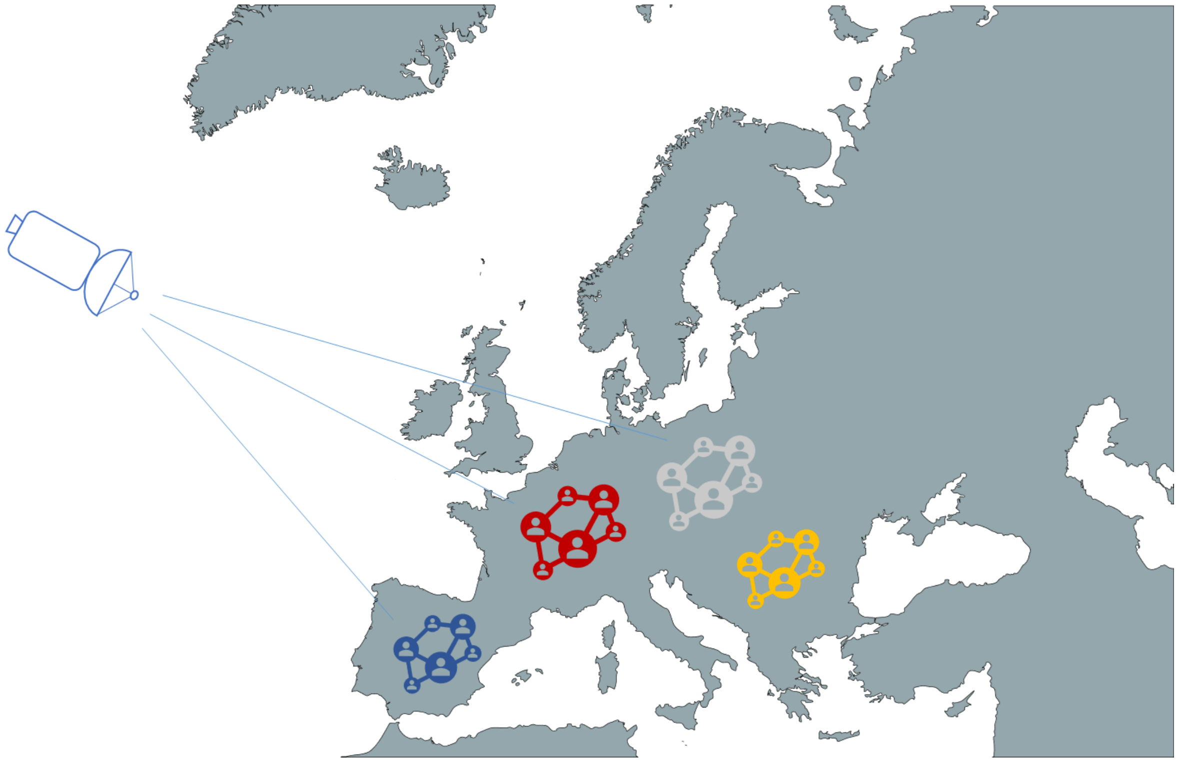

Figure 2.8: EuroQCI structure

Both QKD and T&F transmission are innovative services that could change the image of the Internet in the coming years. Cooperation with the EuroQCI initiative can enable the sharing of fiber optic for the transmission of QKD and T&F signals, both in national and cross border connections.

It should be stressed, however, that initiatives like EuroQCI have their own goals, which are not the same as the goals of the ECN. They thus cannot be regarded as main means or drivers to implement the ECN, but may help to reach specific locations.

2.6 Implementation Roadmap

This section focuses on the proposed timeline for implementing the ECN, taking the current state of the European National Implementations and other available links as a starting point. The ultimate goal of the ECN implementation is to achieve full ECN functionality. Doing this in a single step will require substantial effort, not only financial but also in the sense men power and time. We expect that dividing the implementation process into a few phases will speed it up, giving simultaneously an opportunity of using the capabilities of the ECN by a limited number of scientific users as early as possible.

For the proposed ECN (multi)ring structure the Middle Ring is a central one, required to create the connectivity to the Southern and Northern Rings. Building and testing this ring is a goal of phase 1. The next phase will be focused on implementing the Southern Ring, and the third phase will be focused on the Northern Ring and extensions towards Spain and Turkiye. These phases correspond closely to the priority levels shown in Table 2.3.

2.6.1 Phase 1 Implementation

The first phase assumes achieving reasonable functionality of the main part of the Middle Ring. The required implementation steps are:

1. adoption of the legal structure of the ECN by participating partners,
2. implementing the optical flywheels in the PoPs engaged,
3. implementing the RF flywheels in the PoPs engaged,
4. implementing local time scales in the PoPs engaged,
5. establishing the data repository,
6. implementing at least one interface to the NMI,
7. implementing at least one user interface,
8. implementing and testing the solutions related to collecting the data in the data repository and granting the access to the scientific user community.

The legal structure of the ECN was developed within WP3 and is described in D3.1 “Governance and Sustainability”

Phase 1 is going to be treated as a proof-of-concept phase, resulting in a prototype of the entire ECN. The goal of phase 1 is to implement all the functionalities described in D2.1, i.e.: the relative and absolute services related to all three signals distributed by the ECN, i.e., the optical frequency, the RF frequency and time. This is required for gaining the necessary experience in building and operating such a large infrastructure, and also identifying any potential problems, which will help implementing the full-scale ECN, containing all three rings with extensions towards Spain and Turkiye.

The map shown in Figure 2.9 presents the infrastructure that will exist after the phase 1 implementation – it requires adding only three new stretches to the already existing fiber links. The infrastructure will be also much larger than the Middle Ring alone. The relative frequency service at least for the optical carrier will be available in the entire infrastructure, allowing, for example, the comparison of optical clocks across the Europe (located in Germany, France, Italy, United Kingdom and Poland). The absolute services will be initially available over the limited areas of the Middle Ring only.

The network existing after finishing the Phase 1 will be composed mostly with dark fiber and dark channel connections. The optical frequency transfer uses only ITU channel 44 (1542.14 nm).

Table 2.7 lists all the PoPs that needs to be established and equipped during implementing the Phase 1. It is assumed here that some of the tasks necessary for the Phase 1 can be realised in parallel as they are independent to some extent. This is certainly valid for adoption of the legal structure of the ECN by the participating partners, as well as organising and equipping the data repository and equipping the PoPs.

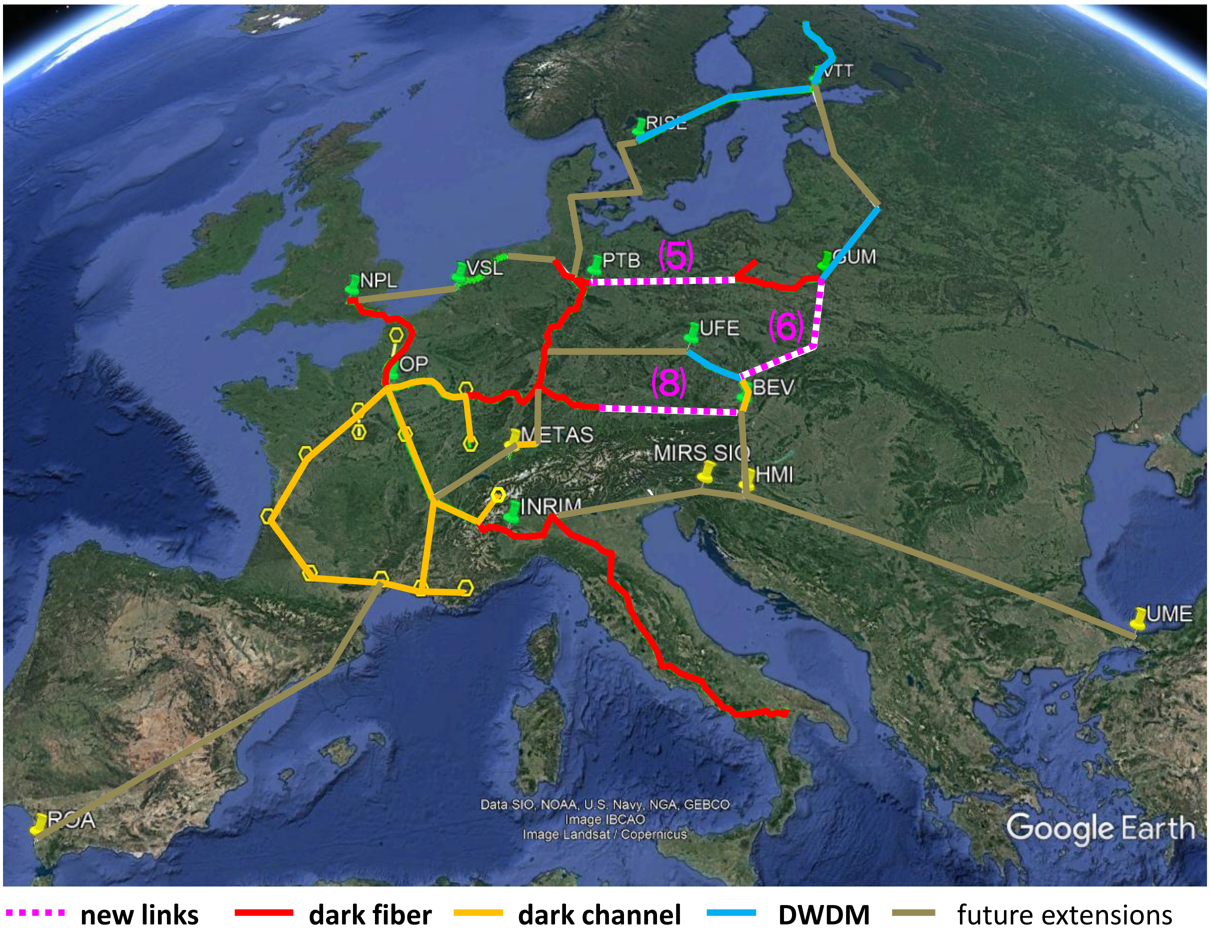

Figure 2.9: A map showing the ECN after finishing implementation of the Phase 1. The new fiber links added in this phase are shown in violet-white line

The type of the equipment required by a PoP depends on its place in the ring. A typical PoP needs to provide its basic flywheel functionality, as defined in D2.1. This requires an ultra-stable laser for the optical frequency transfer and a stable RF oscillator with a femto-stepper for the FR&T transfer, with the additional equipment necessary to compare the signals with respect to those received from the neighbouring PoPs. PoPs interfacing with the NMI requires in addition the interface to local NMI's sources, necessary for the absolute services. This, in principle, requires additional set of the equipment for comparing NMI signals with the PoP flywheel. In some cases the role of the flywheel in the PoP interfacing with the NMI can use the local NMI infrastructure to provide the flywheel functionality instead of operating its own flywheel.

Core Site	Function	Ring assignment
Braunschweig	PoP/ NMI	Middle/Northern
Brno	PoP/ NMI	Middle
London	PoP/ NMI	Middle
Paris	PoP/ NMI	Middle/Southern
Prague	PoP/ NMI	Middle
Vienna	PoP/ NMI	Middle/Southern
Warsaw	PoP/ NMI	Middle/Northern
Frankfurt	PoP	Middle

Hannover	PoP	Middle
Poznan	PoP	Middle
Slubice	Cross-border PoP	Middle/Northern
Strasbourg	Cross-border PoP	Middle/Southern
Karslruhe	Branching	Middle
Munich	Branching	Middle/Southern

Table 2.7: List of PoPs planned for implementation in Phase 1

Figure 2.10 shows the implementation timeline of the Phase 1. It is estimated that the time required to perform all the assumed activities will be about three years. This is divided into three shorter periods, each about one year long.

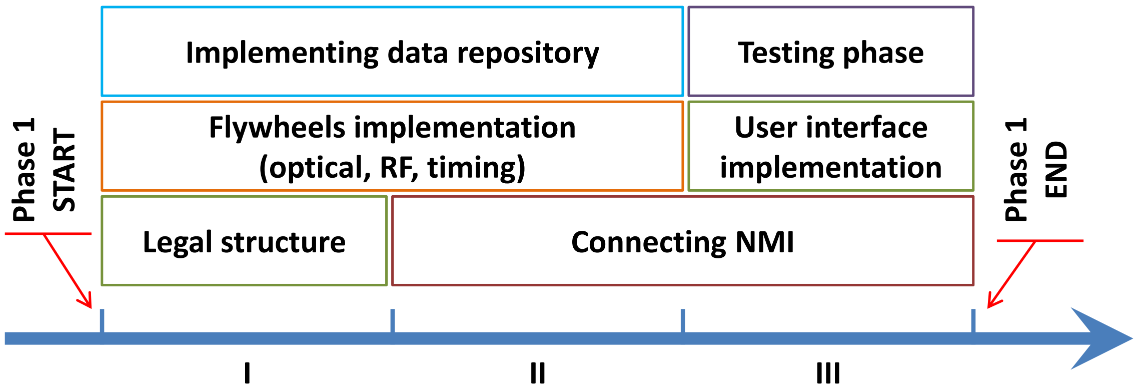

Figure 2.10: Timeline of Phase 1 implementation

2.6.2 Phase 2 Implementation

After finishing the Phase 1, the next step will be to finish the implementation of the remaining parts of the Middle Ring and implementing the Southern Ring. The list of PoPs that need to be equipped during this phase is listed in Table 2.8 and the map showing the shape of the network after finishing the Phase 2 is shown in Figure 2.11. It is necessary to establish 7 new fiber connections. Two of these connections will need to interface with the currently existing link in Switzerland, which uses ITU channel 07 (1572.063 nm). This will require implementing optical combs in corresponding PoPs to cover the large frequency differences that use ITU channel 44.

The following steps are required within Phase 2:

1. adoption of the legal structure by new partners;
2. implementing local time scales, RF and optical flywheels in the PoPs engaged;
3. connecting the newly added PoPs with the data repository;
4. implementing interfaces to the NMIs;
5. installing the equipment enabling implementation of user interfaces;
6. operation and testing phase.

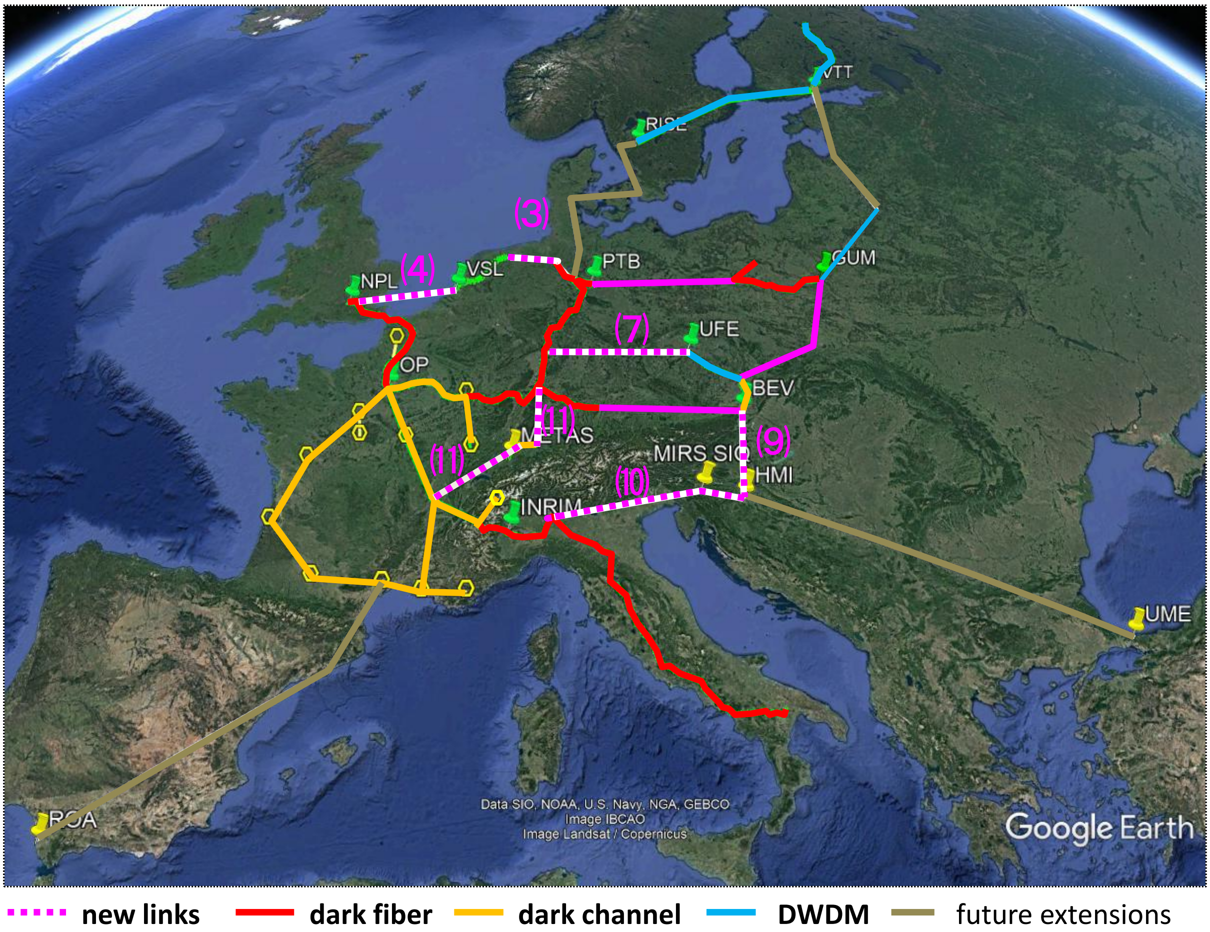

Figure 2.11: A map showing the ECN after finishing implementation of the Phase 2. The new fiber links added in this phase are shown in violet-white line, whereas the links added in the Phase 1 are marked with violet

Core Site	Function	Ring assignment
Bern	PoP/ NMI	Southern
Bruessels	PoP/ NMI	Middle
Delft	PoP/ NMI	Middle
Lublijana	PoP/ NMI	Southern
Torino	PoP/ NMI	Southern
Zagreb	PoP/ NMI	Southern
Amsterdam	PoP	Middle
Basel	Cross-border PoP	Southern
Modane	Cross-border PoP	Southern
Bologna	Branching	IQB (LIFT)
Milano	Branching	Southern

Table 2.8: List of PoPs planned for implementation in Phase 2

The timeline proposed for the Phase 2 is shown in Figure 2.12. It is assumed that it can be shorter than the duration of the Phase 1 thanks to the experience gained. Duration of Phase 2 is estimated to two years.

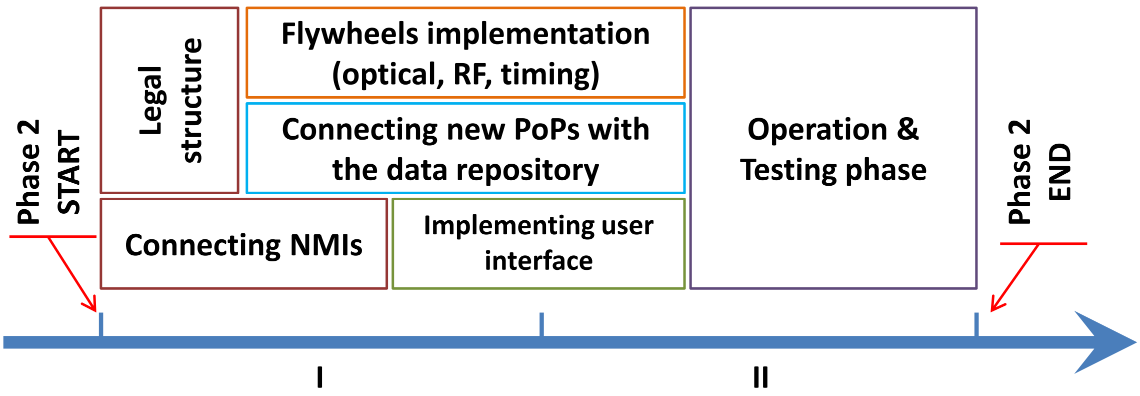

Figure 2.12: Timeline of Phase 2 implementation

2.6.3 Phase 3 Implementation

In the last implementation phase, the Northern Ring is going to be implemented, together with the longest-distance extensions towards Spain, and optionally towards Turkiye. Building the Northern Ring may appear challenging because of the distances between the PoPs and the necessity to cross the Baltic Sea. It may thus be difficult to avoid DWDM connections over this ring. Also the link towards Turkiye may appear especially challenging because of the distance and the necessity to cross at least two international borders between the countries where the T&F infrastructure is not yet developed. Probably GÉANT can provide the fiber infrastructure there thanks to the link from Sophia to Istanbul.

The list of the PoPs that need to be implemented in the Phase 3 is given in Table 2.9 and the map of the entire ECN after finishing the Phase 3 is shown in Figure 2.13. The following steps are required in Phase 3 similar as for Phase 2, except for the additional activities required to implement the extensions:

1. adoption of the legal structure by the new partners;
2. implementing local time scales, RF and optical flywheels in the PoPs engaged;
3. connecting the newly added PoPs with the data repository;
4. implementing the extension towards Spain;
5. implementing the extension towards Turkiye;
6. implementing interfaces to the NMIs;
7. installing the equipment enabling implementation of user interfaces;
8. operation and testing phase.

Core Site	Function	Ring assignment
Boras	PoP/ NMI	Northern
Espoo	PoP/ NMI	Northern
Onsala	PoP	Northern
Stockholm	PoP	Northern

Table 2.9: List of PoPs planned for implementation in Phase 3

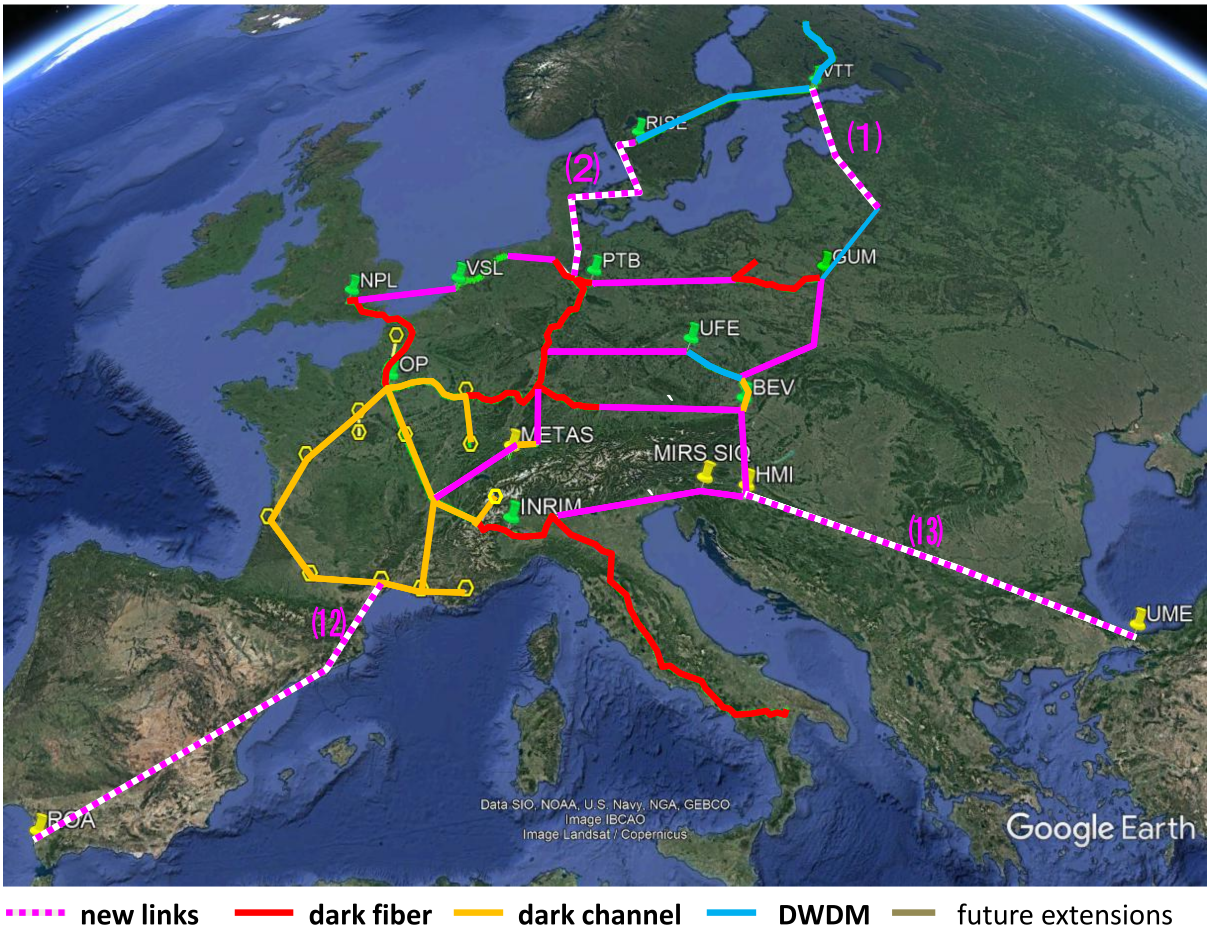

Figure 2.13: A map showing the ECN after finishing implementation of the Phase 3. The new fiber links added in this phase are shown in violet, whereas the links added in Phase 1 and Phase 2 are marked with violet

The timeline of the Phase 3 is shown in. This phase can be the longest one, mainly due to the mentioned challenges with establishing the fiber links to the remote places (like Spain and Turkiye), where no support from local NIs can be expected. It is estimated that Phase 3 can require as much as four years to be completed.

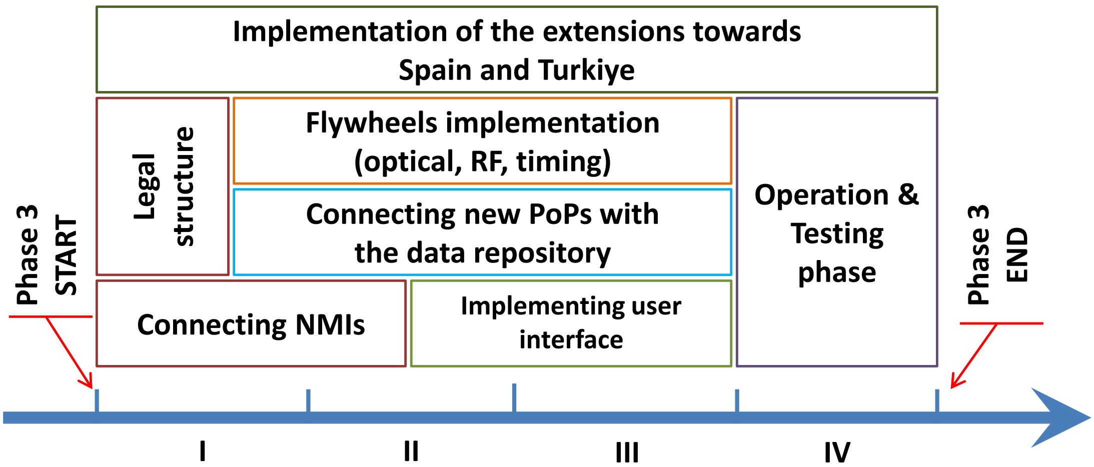

Figure 2.14: The timeline of the implementation Phase 3

2.7 Cost Estimate of the Proposed Network (Phases 1, 2 and 3)

The rings topology covers 17 European countries, the total length geographical length is estimated over 11 500 km, and fiber distance is more than 19 000 km. Cost estimates were based on dark fiber acquisition costs for a period of 10 years. The total cost consists of 4 main elements:

- fiber cost – cost of fiber acquisition (dark fiber);
- equipment cost – cost of acquisition of active elements of T&F dissemination network;
- human cost – cost of specialist responsible for or building, configuring calibrating, and maintaining T&F infrastructure;
- other cost – any other cost, like meeting, promotion, etc.

The cost of Phase 1 – cost of middle Ring – is estimated on 49 450 000 EUR, including fibers – 23 700 000 EUR, equipment 16 150 000 EUR, human 8 400 000 EUR, other 1 200 000 EUR.

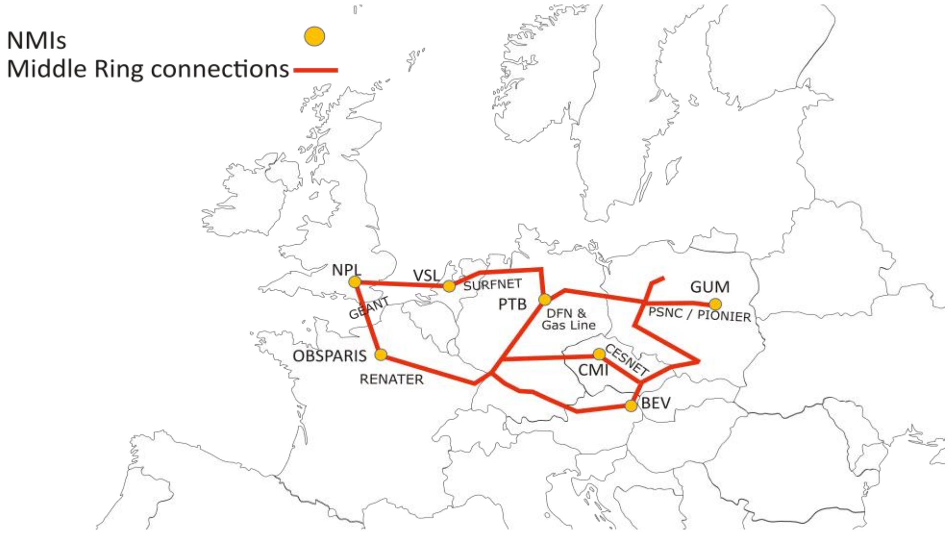

Figure 2.15: Topology of Middle Ring

The cost of Phases 2 and 3 – the costs of the Northern and Southern rings – is estimated on additional 44 350 960 000 EUR including fibres – 19 000 000 EUR, equipment 13 800 000 EUR, human 10 700 000 EUR, other costs 800 000 EUR. The estimated cost of Phase 2 and Phase 3 takes into that parts of the Southern and Northern Rings overlap with the Middle Ring, so these costs are not counted twice.

The three rings topology with all costs included over ten years for installation, maintenance and providing services is estimated at 97 030 000 EUR. More information could be found on D3.1 – “Governance and Sustainability”.

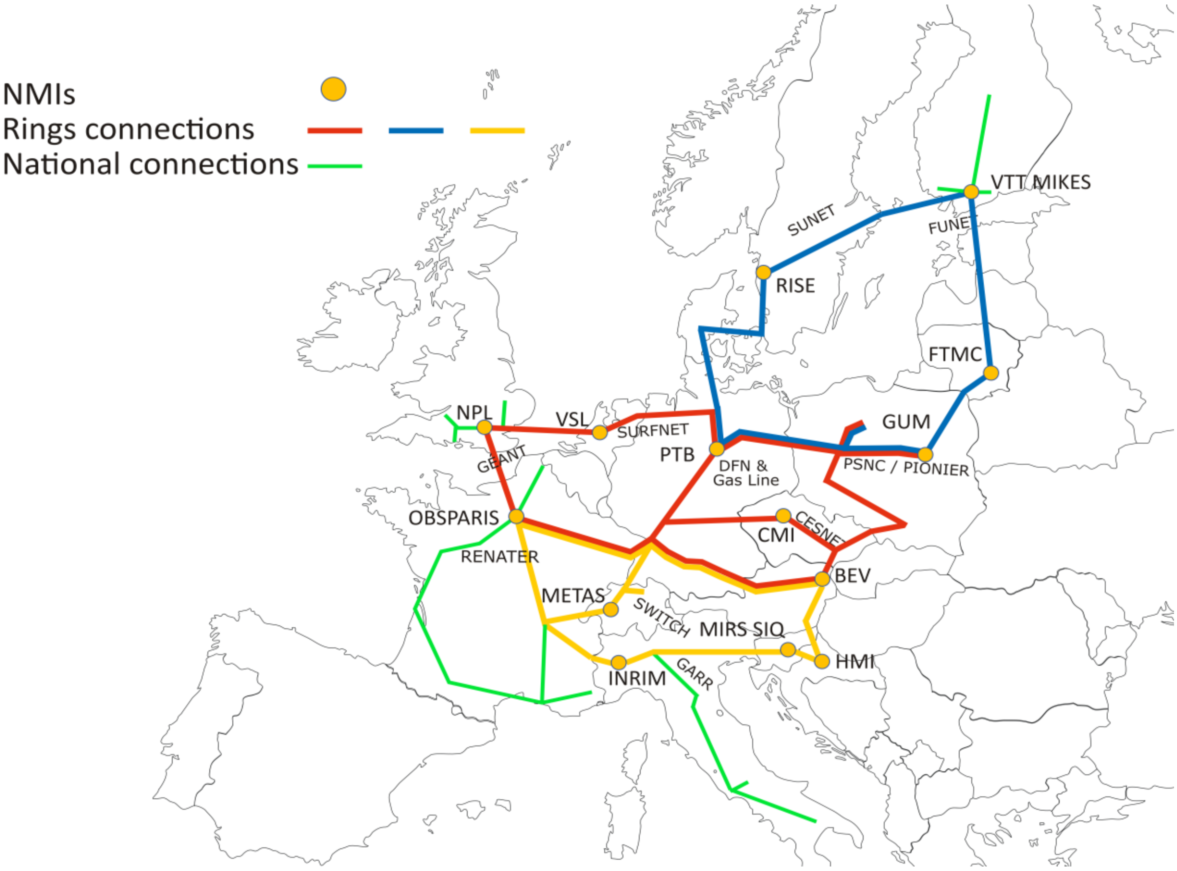

Figure 2.16: The Three-Ring topology

The costs of building a network based on dark fiber are high and without the support of European funds cannot be financed by the project partners alone. Some of the connections can be replaced by dark channels or use in some part the existing national infrastructure, which should reduce the cost of the whole T&F network.

3 Resilience and Redundancy Measures

The following section offers a more detailed exploration of redundancy techniques and how they can be employed to enhance the overall solution's reliability.

3.1 Rings Redundancy

Rings are highly reliable and fault-tolerant network topologies commonly used in telecommunications due to their ability to maintain service continuity in the event of a failure. In addition to their performance capabilities, ring topologies are often cost-effective compared to other network topologies. By leveraging the redundancy inherent in ring topologies, businesses can reduce the need for expensive backup equipment and can often achieve the same level of reliability with fewer link deployments. This cost-effectiveness, combined with their resilience, makes ring topologies an attractive choice for telecom network operators and is the usual solution deployed for medium/long distances.

As detailed in D2.1, the ECN is intended to be deployed though multiple rings. ECN distribution is based on the flywheel concept where a local high-end oscillator (ultrastable laser, H-maser, caesium clock, etc.) is placed to compare to the frequencies received (ν_{N-1} & ν_{N+1}) from its two connected peers. Figure 3.1 shows the representation of a PoP node as defined in D2.1 (top) and its simplified representation (bottom) utilised in the subsequent figures to demonstrate the implication of ring architecture to provide redundancy.

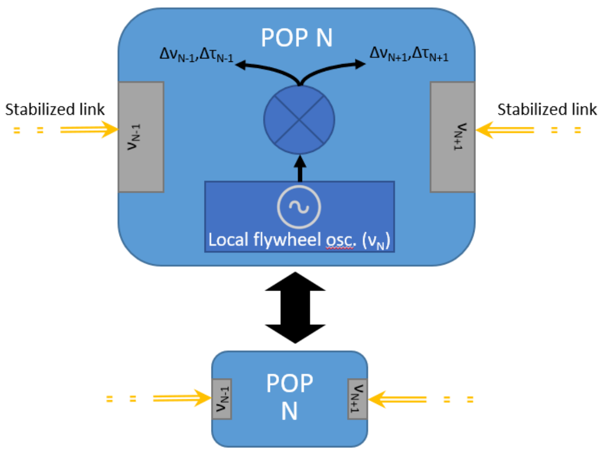

Figure 3.1: Schematic representation of PoP node with its flywheel oscillator needed to perform comparison (top) and a simplified equivalent representation of PoP node (bottom)

The flywheel approach, as opposed to the typical master-slave hierarchy needed in well-established phase distribution architecture (i.e., Sync-E, PTP-HA/WR), has the advantage to avoid any link re-configuration in case of failure.

Figure 3.2 provides a simplified view of the elements in the ECN ring showing that:

- at least two NMIs are connected to the ring;
- share the same data repository for all the PoP within the ring.

Each PoP node:

- is connected to two peers through bidirectional links (double line with double arrows);
- has its own flywheel oscillator that transmits its frequency (ν_N) to two PoP peers;
- receives frequency ν_{N-1} & ν_{N+1} from two PoP peers;
- report the comparison between the peer frequencies (ν_{N-1} & ν_{N+1}) and its local one (ν_N) to a data repository;
- can provide a user synthetised solution (e.g., 10MHz/PPS, WR) retrieving the corrections to perform from the data repository. (For clarity only UserA & UserB have been drawn but one or more users could be connected to each PoP).

If a fiber break occurs as shown in Figure 3.3, the node N will fail receiving the frequency (ν_{N+1}) and thus will not be able to perform the comparison of its own flywheel with respect to this frequency. However, it will still be able to properly compare its local frequency (ν_N) to the one from (ν_{N-1}).

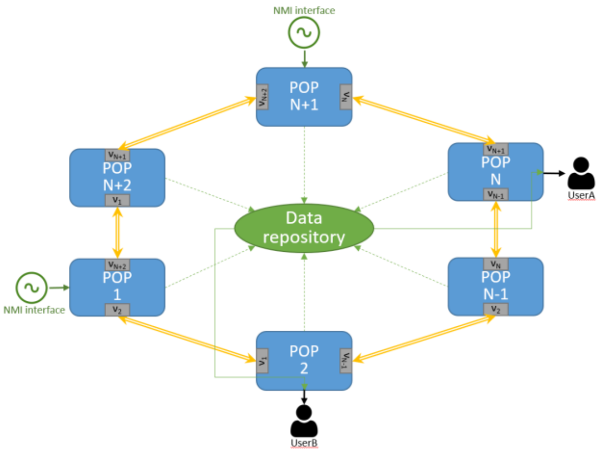

Figure 3.2: ECN POPs ring under normal operation

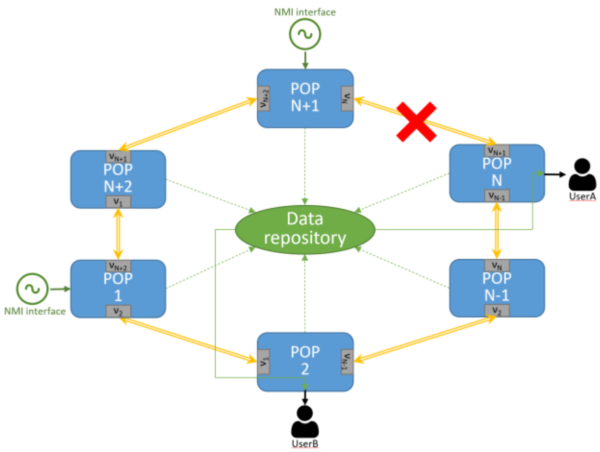

Figure 3.3: ECN POPs ring with broken fibre link

It is worth mentioning that the data repository is a key element in the flywheel approach as it enables to synthesise the final user signal at the user interface by applying the corrections to the local frequency (ν_N) according to global comparisons retrieved from the data repository. This is particularly relevant in case if one of the local oscillators (e.g., ν_N) is malfunctioning or failing as shown in Figure 3.4. In this situation the synthesised user signal can be only based on the data received from one of its peers (ν_{N-1} or ν_{N+1}) and the frequency (ν_N) will be marked as faulty in the data stored in the data repository and the results of its comparison will not be available globally. In case of a failure of the local flywheel, the stability of the signal at the user interface will, however, degrade, as it can be only done using the noisy signals obtained from the neighbouring peer PoPs. In normal situation the local flywheel is used to for strip off the high frequency noise accumulated along the fiber, but under its failure it will be no longer possible. This, however, does not mean leaving the user without the signal at all, although he has to be warned about degraded performance of the service received.

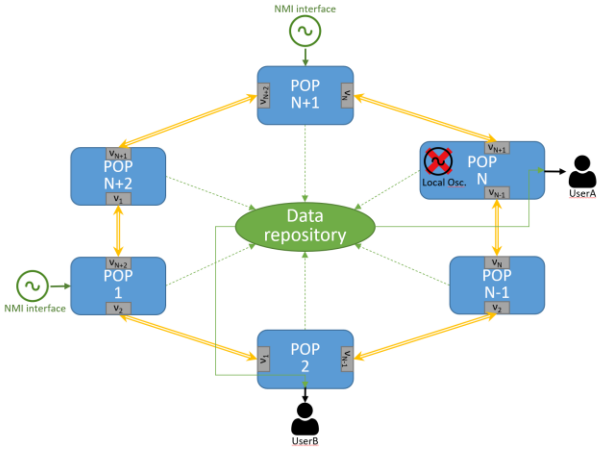

Figure 3.4: ECN POPs ring with faulty local oscillator

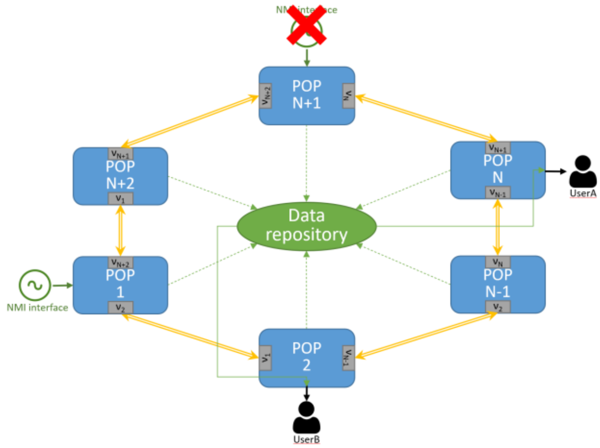

Figure 3.5: ECN POPs ring with defective interface from NMI

In case if the interface to the NMI clock is malfunctioning, as shown in Figure 3.5, only the comparison data with respect to the second NMI in the ring can be considered to get traceability for absolute time and frequency services. It is why each ring should be connected to at least two NMIs.

To summarise, the ECN architecture is redundant by design and does not require additional backup links to tolerate failures. However, to reach a resilient solution the final design should integrate different types of technologies to ensure a proper behaviour under multiple kinds of threats.

It is difficult to assure the resilience of the ECN without degrading the quality of the services provided as the T&F transfer technologies used within the rings are of the highest possible performance and cannot be substituted with other comparable technologies. The only available approach would be to increase further the number of the fiber connections using dark fiber or dark channel for T&F transfer, and use them to provide redundant cross-ring connections (this case already exists to some extent within the Middle Ring thanks to the connection between Frankfurt via Prague to Vienna – see Figure 2.1). This will, however, substantially increase the cost of the ECN. A possible resilience solution that should be considered can be based on assuring in each ring a few backup connections using standard DWDM telecommunication infrastructure (based on two parallel fibres, as shown in Figure 2.3 c). Such links can be used to transfer the optical frequency and RF with some degradation (expected relative accuracy at the order of 10^{-16} to 10^{-17}, depending on the link length and route[6]), and also traceable time assuming that the links can be calibrated using external means (e.g., satellite techniques). The cost of this solution will not be high because only renting of a small fraction of bandwidth is required (one or two ITU channels), without any additional costs of amplifiers and regenerators.

The solution to achieve resilience adequate for lower-level applications may rely, for example, on the WR technique, which, however, can provide only limited resiliency for time transfer (i.e., the accuracy will be degraded with respect to the ECN target values), and cannot provide resiliency at all for the optical frequency. Figure 3.6 shows how optical transfer and WR could be mixed in the same

[6] see, e.g.: K. Turza, P. Krehlik, Ł. Śliwczyński: "Stability Limitations of optical Frequency Transfer in Telecommunication DWDM Networks," IEEE UFFC 67, 2020, pp. 1066-1073 and K. Turza, P. Krehlik, Ł. Śliwczyński: " Long Haul Time and Frequency Distribution in Different DWDM Systems," IEEE UFFC 65, 2018, pp. 1287- 1293.

ring together with the standard ECN services to increase the resiliency of the architecture. It is important to notice that WR links have the direction indicating the master-slave hierarchy and that some of the links (dashed) are used in survey mode only to offset monitoring without disciplining any clocks. The next chapter about resiliency is going to explain in greater details the different level of resiliency and how the architectures should be designed to offer the optimal approach.

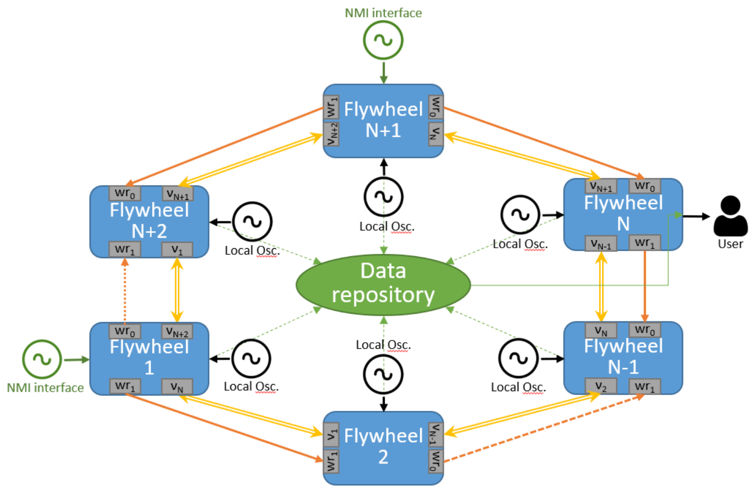

Figure 3.6: Resilient ECN design mixing standard ECN services with WR

3.2 Resiliency

After discussing the intrinsic redundancy of ECN, it is crucial to understand the different levels of resiliency and how they work in conjunction with redundancy. While having multiple input sources is a significant factor in enhancing resiliency, it is not the sole factor.

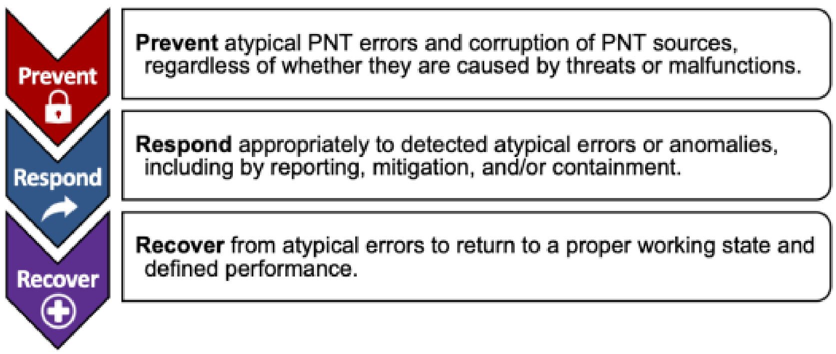

Figure 3.7: Core functions of resilience from the "Resilient PNT Conformance Framework" (Department of Homeland Security (DHS))

The first key to increase the resiliency is the identification of a threat (intentional or unintentional). Each node/device should be able to detect different type of failure/threat such as:

- link failure;
- device not responding;

- local oscillator damaged;
- device not properly updating;
- flappy link (micro-cuts);
- calibration errors along the path (inaccuracy);
- intentional spoofing shifting offset at the external reference.

Once the detection has been detected it needs to properly synthesise the user solution sources or to slowly drift by putting itself in holdover mode. Finally, after the threat has disappeared, the device should return to its previous state or potentially stay in its current state.

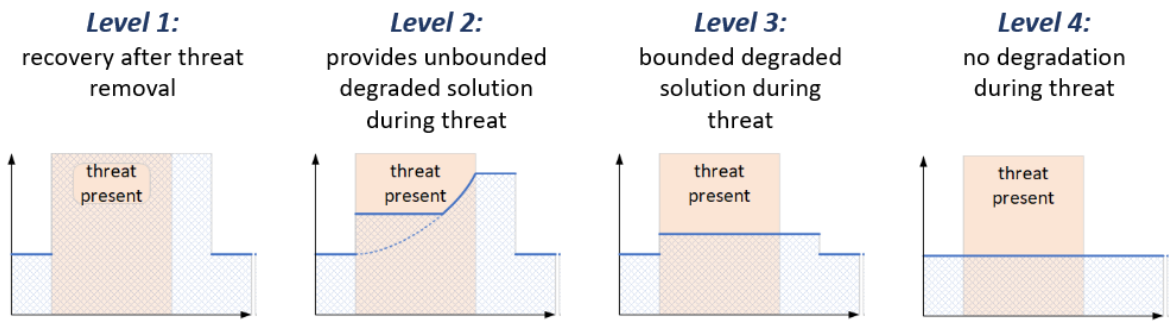

Figure 3.8: Level of resiliency as defined by the IEEE-P1952 group

Figure 3.8 shows the different levels or resiliency as defined by the IEEE-P1952 group where:

- the 1st level only states that the device should recover itself after a threat removal;
- the 2nd level mention that the device should provide unbounded degraded solution during the threat - his is typically done by placing the device in holdover while a threat has been detected;
- the 3rd level specify that the degraded solution should be bounded during the threat. For example, by using a backup timing source with worst but bounded capabilities (i.e., WR as a backup of optical transfer) or by following a holdover reference with bounded performance during several hours/days;
- the 4th level is that no degradations are perceived during the threat meaning that:
  - the threat must be detected quickly before impacting the final solution;
  - the transition while updating the corrections of the final solution must be performed seaming-less;
  - the backup solution must be as good as the original one;
  - when the threat recovers the device might decide if it should return to its previous state or maybe stay in the current one.

The last level is also perceived as a system of system by combining multiple inputs and comparing/weighting them together to provide the final decision to the user.

In 2022, the USA Department of Homeland Security (DHS) has published reference architecture for resilient PNT systems. To reach a Level 3 or 4 of resiliency the generic blocks (as shown in Figure 3.9) must:

- limit their external inputs to protect the solution;
- must use diverse technology types to avoid being vulnerable to the same kind of attack;
- must verify the state of each input (by performing cross-verification and/or combining them);
- provide automatic recovery of compromised components;
- protect internal state by isolating local clock;
- allow a manual system recovery.

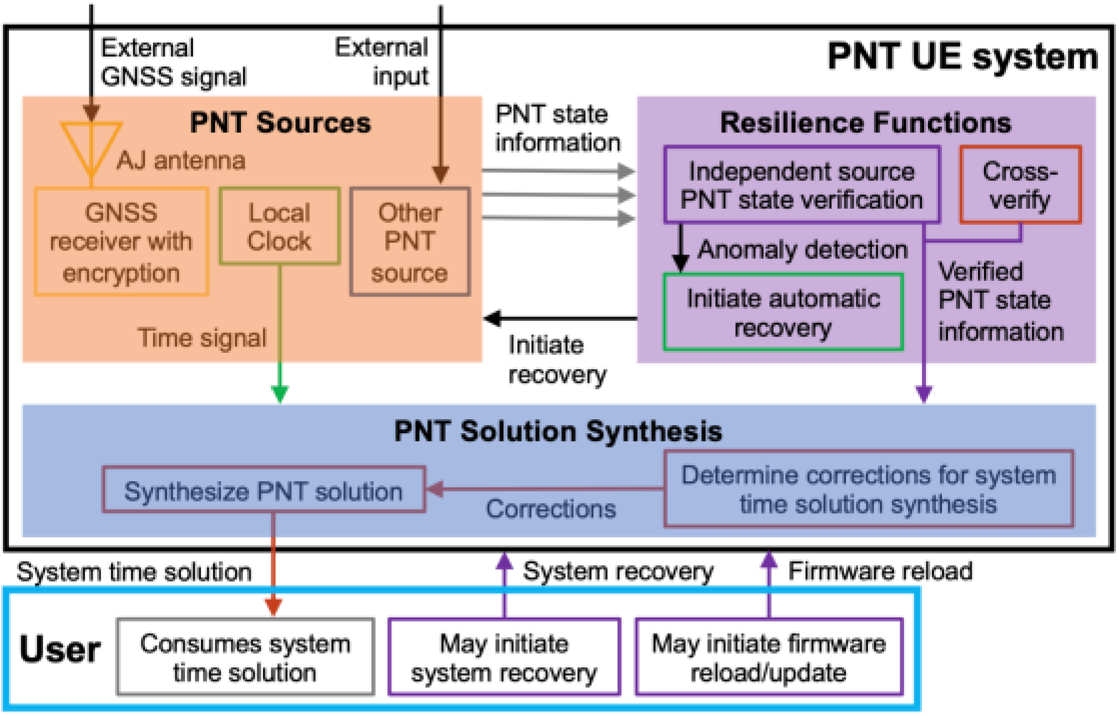

Figure 3.9: Types of components in a resilient PNT UE system from "DHS Resilient PNT Reference Architecture"

By doing the exercise to fit those blocks within the already defined ECN network, a possible node architecture to reach level 3 or 4 of resiliency is depicted in Figure 3.10 with the following implications:

- each node is connected to two other PoP peers using at least two types of technology;
  - stabilised links providing standard ECN services;
  - White-Rabbit (PTP-HA) as backup solution;
- an external GNSS receiver with PPP time transfer could be combined with the high-end local oscillator (H-maser, caesium) to reach accurate absolute time transfer (~1ns uncertainty);
- each input evaluates its own states independently;
- a cross-comparison stage between the different sources against the local oscillator is performed and the results are sent to the data repository to compute for the global solution;
- considering the data retrieved from the data repository and the cross-comparison of multiple inputs, a module performs the selection/fusion of them and provides the corrections to apply for the sub-system in charge to synthesise the user solution;
- the same module should also be in charge to quickly alert the system (through data repository or other mean) that a threat has been detected while doing the cross-comparison

so that the other node in the network can quickly react taking into account this new information;

- finally, the user solution is based on applying corrections to the phase/frequency retrieved from the local high-end oscillator. To apply those corrections different solution might be considered depending on the final implementation (e.g., frequency stepper, phase delay, tuning a VCXO oscillator, etc.). Once this new end-user clock is properly tuned it will be used by other protocol such as WR or PTP to distribute time to end-user application as detailed in section 0.

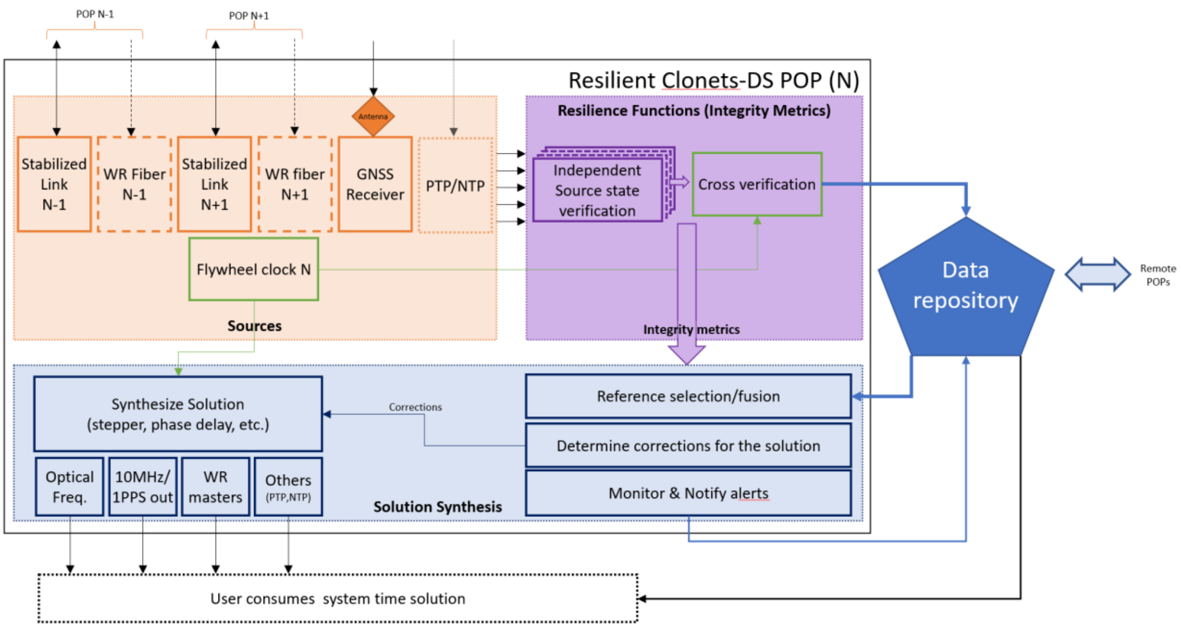

Figure 3.10: Proposal of resilient node architecture within ECN network

4 Future Integration of Lower-Level Applications

After deployment of the different ECN rings, it is important to trace a plan on how to distribute time from any POP node to lower-level applications.

The technology used to perform the distribution might vary depending on the accuracy and precision requirements on the user end. Several protocols are typically used including White Rabbit (the precursor of PTP High Accuracy profile), IEEE-1588-v2019 (PTP) or even NTP.

Most of the low-level use-cases that could benefit from timing distribution from the ECN have been already discussed within D1.1 however we provide a short resume of the most relevant ones:

- radio-telescope interferometry between distributed antennas;
- ground stations synchronisation (e.g., ESA Galileo ground stations);
- High Frequency Trading between multiple stock-exchange;
- backup ePRTC (Core Grandmaster) for regional telecom network;
- distributed data centres synchronisation for coherent database;
- critical infrastructure such a power plants / smart grid;
- fintech applications needing to fulfil MiFIDII requirements.

4.1 Interoperability with White Rabbit, IEEE-1588v2 and NTP

For the purpose of this section the time-transfer techniques between two points (A & B) can be modelled as illustrated in Figure 4.1, where:

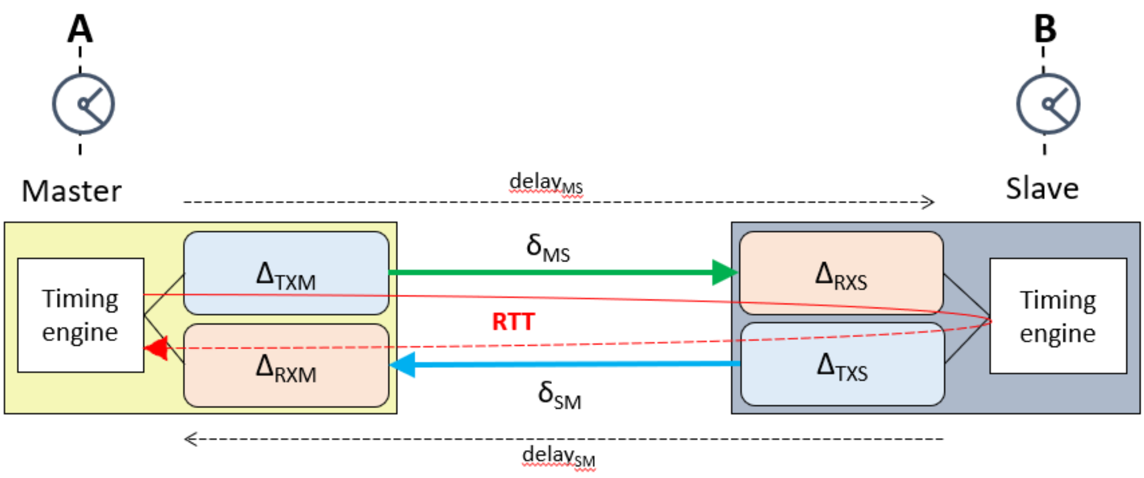

Figure 4.1: Simple model of time-transfer

- the slave clock (B) is synchronising to a distant master clock (A) though their time engines;
- the round-trip time (RTT) is the only real measured that can be obtained;
- the delay between Master and slave is the one needed to properly set the clock at B. This can be written as $t_B = t_A + delay_{MS}$. However, the value of $delay_{MS}$ must be inferred from the RTT and other contributions: $\Delta_{TXM}, \Delta_{RXS}, \Delta_{TXS}, \Delta_{RXM}$ & δ_{MS}, δ_{SM};
- the precision of RTT will depend on the timestamping mechanism. This will impact on the accuracy of the final time transfer.

To understand the difference between considered protocols their main features are resumed in Table 4.1.

	WR / PTP-HA	PTP G8275.1	PTP Default	NTP
Accuracy	<1ns	10-100ns	50-10us	1us-10ms
Precision	15ps RMS	10ns RMS	~50-500ns (network dependent)	-
Phase tracking	Yes	No	No	No
Sync-e (syntonisation)	Yes	Yes	No	No
Semi-static delays	Yes	No	No	No
Asymmetry	Plug-n-play with bidir. Semi-automatic with DWDM	Manual calibration	Partial support	No
Only optical fiber	Yes	Yes	No	No
Transparent clock (TC)	No	No	Supported but not required	Not supported
Dependency on Network load.	No	Yes	Partial (if TC used) or Strong	Strong
HW timestamping	Needed	Needed	Recommended	Optional (typically only on master)

Table 4.1: Characterisation of time transfer protocols

WR/PTP-HA is clearly the only protocol that can reach a sub-nanoseconds accuracy thanks to its phase detector and its advanced calibration features. Thus, the PTP profile for telecom network using Sync-e feature (ITU-T 8275.1) enables decent accuracy but also needs a specific optical network fully compatible with sync-e to reach those performance levels. To continue, the default PTP (or similarly the ITU-T 8265.1 profile) allows for time distribution on a more generic network but with degradation of the final accuracy. For example, if switches on the path support the transparent clock feature, one can expect to reach around 50ns of accuracy whereas if the network is non-timing aware the accuracy can easily reach several microseconds under heavy traffic. Finally, the NTP protocol provides the worst accuracy and precision but has the advantage to be well established in the industry and thus to be deployable at almost no cost.

4.2 Deployment of T&F Protocols on Commercial Optical Networks

As explained above, the selection of the proper protocol depends on the user requirement but this decision is also impacted by the commercial network deployed between the user-end and the nearest PoP node.

This section debriefs the different type of optical link typically deployed in the industry and how WR or PTP ITU-T 8275.1 behaves on each one of them. (The deployment of 8265.1 and/or NTP has not been considered for this deliverable as it can be easily set-up on any kind of network).

As illustrated in Figure 4.2 a, the simplest (and cost-effective) way to connect two devices is using a duplex fibre with two unidirectional communications. However, from a timing distribution perspective having a duplex fibre introduce different delays as the length of those two fibres might be slightly different and can quickly provide an offset (i.e., 30cm of difference in the length will introduce around one nanosecond of delay).

Therefore, in WR, most connections rely on bidirectional communication (as shown in Figure 4.2 b), where the link occurs on the same physical medium but utilises two distinct wavelengths: λ_A & λ_B (one for each direction). Once the RTT is obtained and all the fixed delays have been properly calibrated ($\Delta_{TXM}, \Delta_{RXS}, \Delta_{TXS}, \Delta_{RXM}$) at factory, the $delay_{MS}$ can be easily retrieved using the asymmetry coefficient which is calibrated as the ratio (α) between the two wavelengths λ_A & λ_B on a given type of fibre.

$$\alpha = \frac{\delta_{MS} - \delta_{SM}}{\delta_{MS}}$$

NOTE: As PTP 8275.1 only provides a manual value to adjust the asymmetry between the back-and-forth paths, it requires a manual calibration procedure for both duplex or simplex fibre deployment.

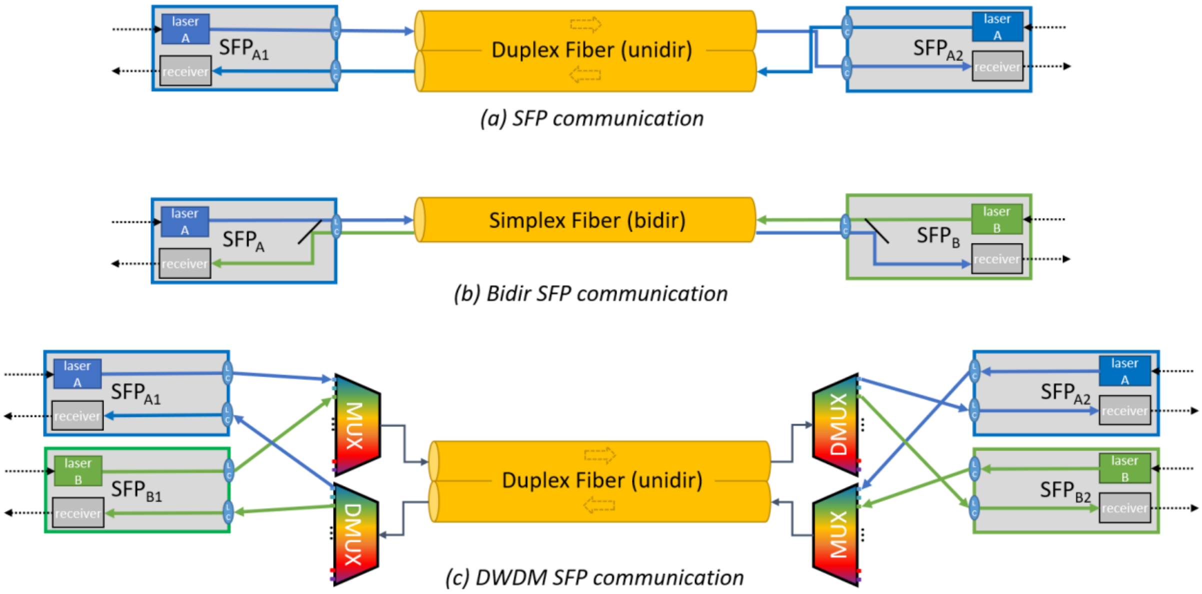

Figure 4.2: Simplex/Duplex fibers and Standard/Bidir/DWDM SFPs

However, in the telecom industry, most of the communication and especially the long-distance links (>10km) are based on DWDM techniques (Figure 4.2 c) where multiple wavelengths are multiplexed on the same fibre. Those fibres are usually unidirectional, and the different wavelengths travel in the same direction. This is due to the integration of EDFAs, which in telecom DWDM networks operate unidirectionally to cover long distance links (>150km). This means that in this case we have also the same problem as in (a) where small differences in the fibre length on the two paths can introduce sdelays that need to be calibrated.

Finally, the preferred way to accurately distribute timing on metro-area distances is using DWDM SFPs as bidir SFPs. This combination allows to get a very stable transmission wavelength compared to one given by bidir SFP. For distance below 1km this difference is not appreciated, however it starts to become a real concern for distances above 10km.

$$\sigma_{\lambda(DWDM)} \sim 1e^{-10} < \sigma_{\lambda(BiDir)} \sim 3e^{-8}$$

DWDM SFPs provide two (RX and TX) connectors that need to be plugged on a single fibre. This combination can be achieved through the use of filters (as illustrated in Figure 4.3 d) or DWDM mux/demux (as depicted in Figure 4.3 e) due to the SFP receiver's capability to accept all wavelengths on the C-band.

If available, the use of DWDM mux/demux is the preferred option has it allows to add a layer of redundancy using the duplexity of the fibre. It also permits to apply enhanced calibration technique by allowing a redundant connection on an additional physical medium.

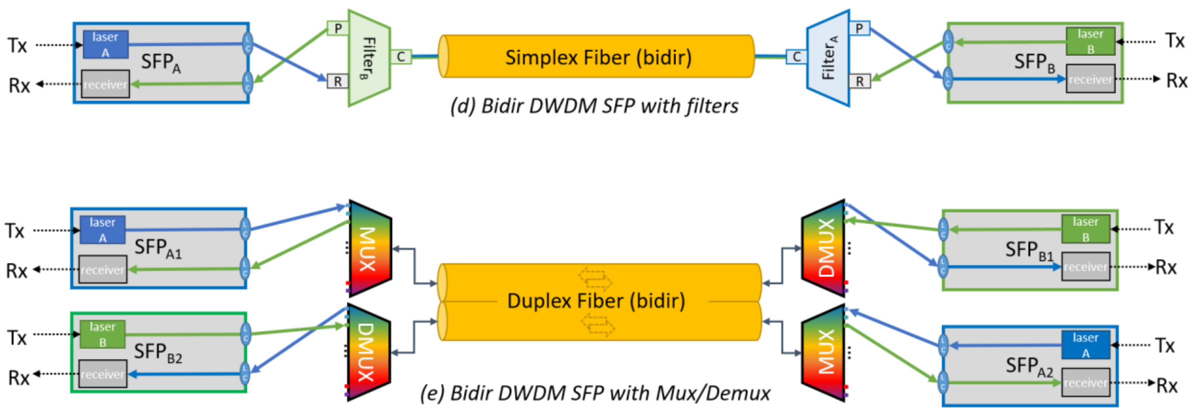

Figure 4.3: Bidir DWDM SFP with filters (d) or Mux/Demux (e)

4.2.1 Deployment with Filters

The benefits of using optical filters embedded in the equipment can be summarised as follows:

- it allows direct test and calibration at manufacturer site before shipping the equipment to the customer;
- it reduces the risk of unauthorised manipulation before installation;
- it improves cabling management by using shorter (≤50cm) duplex single mode fibres;
- it allows to swap device without recalibration (useful in case of RMA and temporal replacement by a spare device);
- it allows to control temperature of filter box by reading the internal temperature sensors;
- it reduces the required rack-space;
- it avoids using an external box which reduces manufacturing, shipping, and installation costs and environmental waste.

Those filters allow simple deployment from one (or two) PoP nodes to two BC devices at user location when a dark fibre can be provided to connect those two locations. Figure 4.4 shows an example of the redundant connections to be performed using those fibres. It is worth to mention that typically a duplex dark fibre is provided which means that the two links from PoP_N to BC_A and BC_B travel on the same duplex-fibre but using different physical medium.

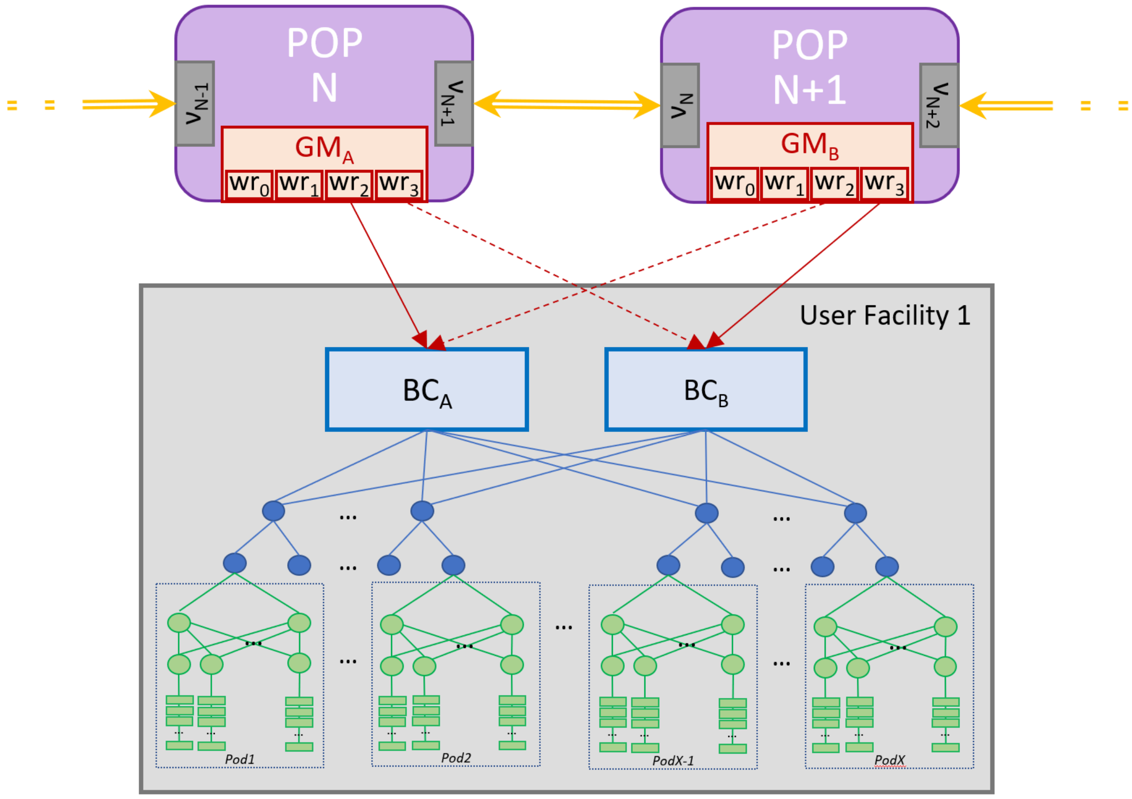

Figure 4.4: Redundant timing distribution from flywheel nodes to user facilities

4.2.2 Deployment on a Standard Optical Network

It is probable that most of the links between a PoP node and the user facility are standard DWDM links with only some channels available for deployment. In this case, the DWDM SFPs are typically connected to a mux/demux on each side and the communication is done unidirectionally.

It some cases, even if the standard way to connect is through a different fibre for TX and RX paths, the DWDM mux/demux will allow to connect them in as bidirectional links (Figure 4.3 e). This kind of connection will greatly improve the calibration of asymmetry allowing to perform fibre-swap techniques or similar.

In case a unidirectional amplifier (EDFA) is deployed between the PoP location and the user facility, one can use a WR repeater together with OADM (see Figure 4.5) in order to bypass the EDFA and allows bidirectional links on DWDM technology[7].

This means that at each site where an EDFA is used, a WR repeater device must be placed to regenerate the signal and thus adding a new hop on the WR distribution chain. In 2016, the University of Granada has characterized the stability of WR through multiple hops showing that sub-nanosecond accuracy could be kept even after 15-hops. After that a new WR rabbit Grandmaster should be created by taking advantages of the flywheel concept. Worth mentioning, that in case a

[7] Torres-González, J. Díaz, E. Marín-López, R. Rodriguez-Gómez: “Scalability analysis of the white-rabbit technology for cascade-chain networks,” 2016 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS), Stockholm, 2016, pp. 1-6, doi: 10.1109/ISPCS.2016.7579515.

dedicated management network is not easily available for those WR repeaters, the in-band management feature should be enabled to monitor the states of those devices using the timing network.

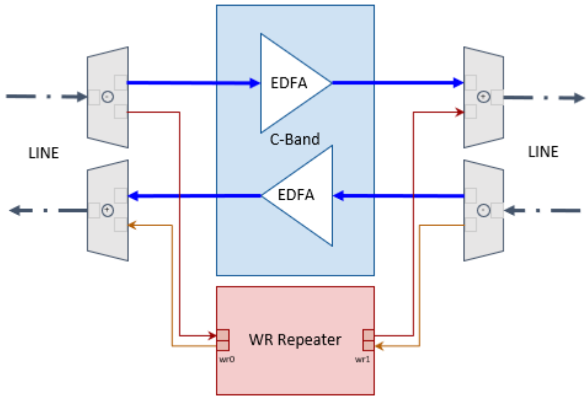

Figure 4.5: Bypassing unidir EDFA with OADM and WR repeater

4.3 WR as a Sub-Ring of an ECN Ring

Finally, a user can deploy a local WR ring as sub-ring of the core ring (ECN) as described in Figure 4.6. By doing this it will offers redundancy at multiple user location while optimising the cost of links to deploy. This kind of topology is also interesting as it also offers a backup path for the ECN ring itself. More information about how to deploy redundant WR network using ring or tree topology can be found in the Appendix A.

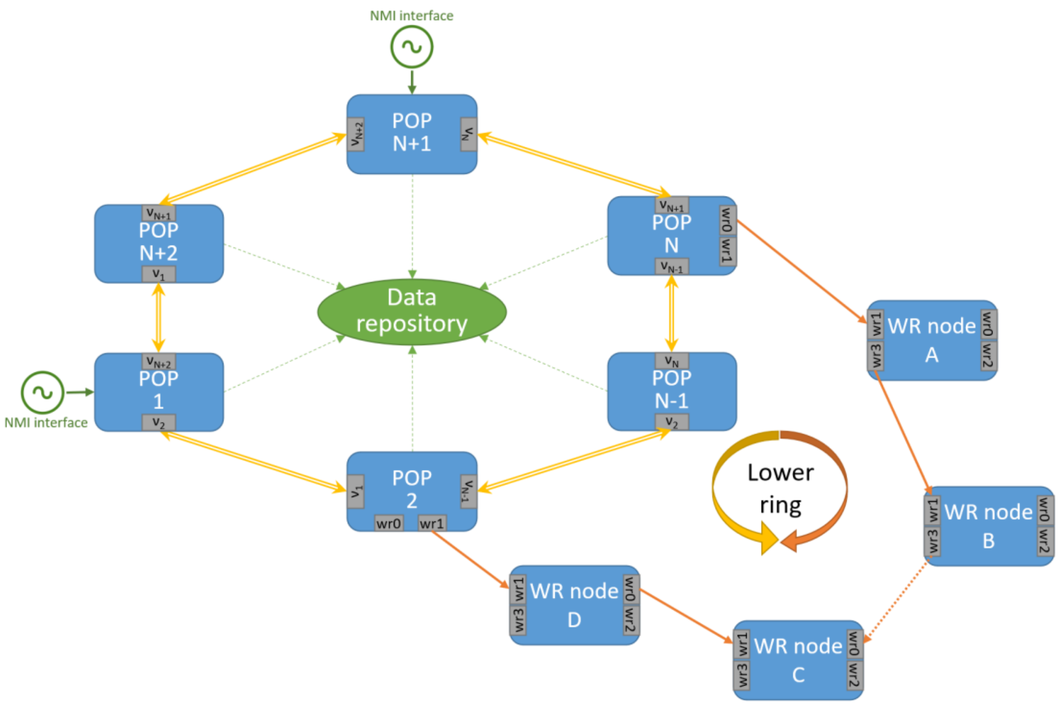

Figure 4.6: WR as a subring of ECN ring

4.4 Scalable Layered Approach

As explained above the used of different protocols (WR, PTP, NTP) depends on the final user requirements but also on the cost-scalability relationship. A layered approach is thus recommended using extremely accurate and resilient deployment on the upper layer to consumes as little as possible of the final timing budget.

A reference description of the multiple layers is provided below:

- Layer 0 (violet): Represents the European Core Network with the different PoPs. It uses standard ECN services to distribute highly accurate time & frequency.
- Layer 1 (red): Corresponds to the long-distance WR links, typically using standard DWDM infrastructure. It is also used to connect the nearest PoPs to the top level (regional ring) of the user facility.
- Layer 2 (blue): Corresponds to the medium distance links (<100km) within user network. WR is the recommended technology, but PTP ITU-T 8275.1 could be used depending on the type of links deployed and the final accuracy to reach. For instance, in a telecom infrastructure this layer corresponds to the zonal link.
- Layer 3 (green): This layer is known as the last-miles and typically contains a very high number of devices (hundreds to thousands). The technology deployed to distribute time is therefore very cost-sensitive and typically use standard PTP profiles. It is important to note that if a few nanoseconds of the timing budget have been consumed by the previous layers (Layer0 toLayer 2), the final layer alone can exhaust the remaining budget entirely.

Figure 4.7 depicts the above-mentioned approach[8] showing how the ECN ring could provide time to the regional ring (using, e.g., WR), which is then distributed to the local one where it is finally transmitted using standard ITU-T 8275.1 to the end-node 5G Radio-Units (antennas).

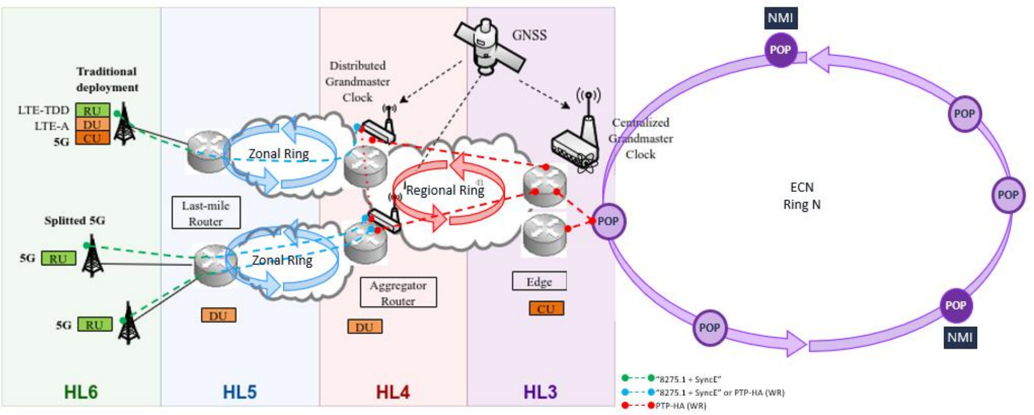

Figure 4.7: Cascaded rings mixing multiple types of technologies.

[8] based on A. Minetto, B. Rat, M. Pini, B. Polidori, I. De Francesca, Ivan, Luis M. Contreras, F. Dovis: "Nanosecond-level Resilient GNSS-based Time Synchronization in Telecommunication Networks through WR-PTP HA," 2023, TechRxiv. Preprint. doi: 10.36227/techrxiv.22032446.v1

5 Summary

In this document we discuss the aspects of the technical implementation of the European Core Network T&F reference system. The architecture of the ECN, composed of three rings covering large part of Europe, with a possible extensions towards Spain and Turkiye, was proposed as a result of in-depth analysis and discussion within task 2.1 of WP2, taking the findings of WP1 as the starting point.

The ECN proposed in the project will result in a large-scale, European-wide infrastructure and it will be certainly challenging to implement it. This implementation must include the following aspects:

- finding the possible solutions to assure the fiber connections between the PoPs;
- assuring interoperability of the resulting network, especially across the boarders;
- proposing the roadmap of equipping the PoPs with the required transmission equipment and installing appropriate regenerators along the long fiber lines;
- estimating the costs of fibers and required equipment;
- assuring resiliency and redundancy of the resulting network.

The above-mentioned aspects are considered in sections 2 and 3 of this document.

In sections 2.1 and 2.2 the aspects related to required fiber connections are analysed. In particular, we recognised the currently existing national implementations present in some European countries to transfer time and frequency. These implementations have been motivated mostly by the needs of time and frequency metrology and driven by NMIs, but also by academia and high-end industry. The capabilities of GÉANT and NRENs have been investigated with respect to providing fibers on the routes defined in WP2.1 and further described in deliverable 2.1 “Technical Design Report”. These aspects are further discussed in section 2.5 dealing with identified missing connections. Potential opportunity of co-operation with the EuroQCI initiative, focused on quantum technologies was analysed in section 2.5.3.

The aspects related to the interoperability are covered in section 2.3, where we described and proposed solutions to a number of identified issues, like providing the ECN services within a single ring, between the rings and on the branching points. The structure and equipment required to interface with the external users was also discussed. We also shortly address the question of the legal structure of the ECN important for its interoperability, referring to the in depth discussed in WP3, summarized in deliverable 3.1 “Governance and Sustainability”.

The implementation phases and roadmaps are discussed in section 2.6. We assumed three phases of the ECN implementation, starting from the currently most advanced Middle Ring, through the Southern Ring and ending at the Northern Ring, which we expect to be the most challenging one due to large distances and lack of well-developed T&F infrastructure until now.

The problems of redundancy and resilience are discussed in section 3, where we investigate the level of internal redundancy of the ECN itself and considering the methods and possible extensions to its further increase. It was identified that the only possibility to improve the redundancy and resiliency of the ECN can be obtained with increasing of the number of high-quality (dark fiber or dark channel) connections, which, however, may be difficult to obtain. This is the result of highly specialised and cutting-edge technology required to implement the ECN, which cannot be substituted with any other currently existing technology. Some level of resilience is possible only for lower-level applications that can gain from DWDM links or technologies, like e.g. WR.

The last problem discussed in this document is related to the integration of the ECN with lower-level applications, where the highest accuracy and stability of standard ECN services is not required, but the benefit of interfacing with the ECN may come from its large area covered. The possible approaches based on WR are covered in section 5. The document is supplemented with an appendix, describing the redundancy of the WR

Appendix A Redundancy for WR network

Redundancy on the ECN ring has been already discussed in the Section 3.1 however to help possible users understanding how time from an ECN POP could be distribute until their final application it is important to explain how redundancy must be handled. This appendix is therefore focused on how to implement redundancy with commercial equipment and specifically using the WR technology even if many concepts can be applied to standard PTP.

A.1 Redundancy Rings

As explained before, ring topologies are a very cost-effective way to handle redundancy for long distance links.

In contrast to optical frequency transfer, disciplining clocks using WR or PTP sync-e network requires following a master-slave hierarchy. It is also important to highlight that only two ports in all the nodes are needed to provide redundancy and thus the master/slave hierarchy must be decided automatically. In PTP (and also PTP-HA/WR), this can be performed through the alternate Best Master Clock Algorithm (aBMCA) as defined in ITU-T 8275 and it can also be combined with the stepsRemoved (number of hops) from the Grandmaster (GM) node in order to improve the performance.

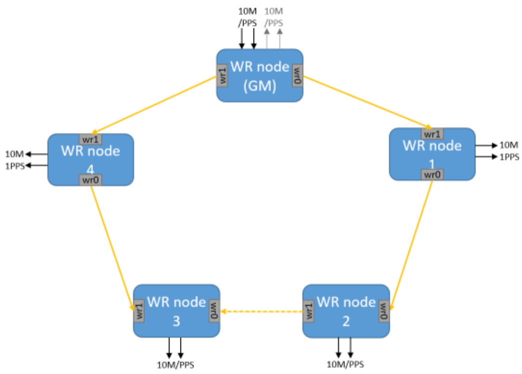

Figure A.1: Simple ring topology

Figure A.1 shows how WR is distributed within ring is normal condition where:

- each link is represented by an arrow where the end of the arrow represents a slave port disciplined by its peer master port (start of the arrow);
- the dash links shows that there is a passive master-slave connection: this means that all the PTP timestamps are computed but not used to discipline the local oscillator. This is also known as a slave port in survey mode;
- the GrandMaster (GM) node receives 10MHz & 1PPS from an external reference and distributes this reference to all other nodes in the rings. The GM node thus only provide timing and its ports are configure as master.

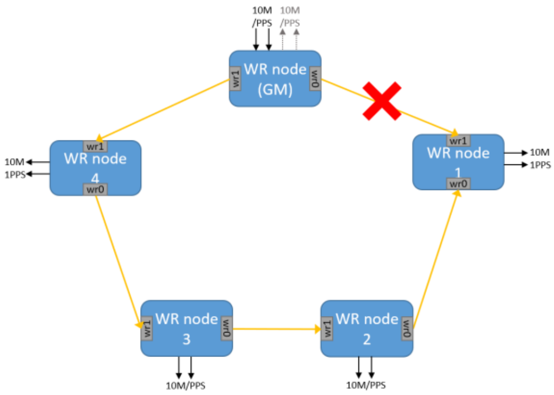

Figure A.2: Simple ring topology with link failure

In Figure A.2 a failure has been simulated (red cross) by cutting the link between the GM and WR node 1. When doing this, the network automatically restructure itself by performing several actions in the following order:

1. WRnode1 detects the failure and change its clock class to announce that it is not locked anymore to the GM. It goes temporarily in Free-Running/Holdover mode.
2. When, WRnode2 receives the degradation of WR node1 source from the updated announce message send by WR node1. Therefore, WRnode2 checks if he has received a better clock quality from another port. In this case, the port connected to WRnode3 states that its ClockQuality is better and thus automatically reconfigure itself as the new slave port.
3. WRnode2 try to lock to WRnode3. This operation might last tens of seconds.
4. Once the locking state is reach, WRnode2 announced to all its over port that he is now following the GM coming from WRnode3.
5. WRnode1 receives the new announce message from WRnode2, and thus swap its configuration so that its wr0 is now the new slave port.
6. After another tens of seconds, the WRnode1 is locked again to the same GM but this time through WRnode2.

By looking in more details this operation can be quite slow to performs (between 10-30 for each hop swapping their configuration). In this example, it should last less than 1 minute to fully recover all the nodes in the ring however this might be more problematic with larger rings containing more nodes (i.e., a typical regional ring in telecom contains around 100 nodes).

Until a node is still not connected to the GM from the new backup path, it is typically leaved in holdover mode and is slowly drifting from the reference depending on the quality of its oscillator (few minutes with DOCXO or few hours for micro-rubidium).

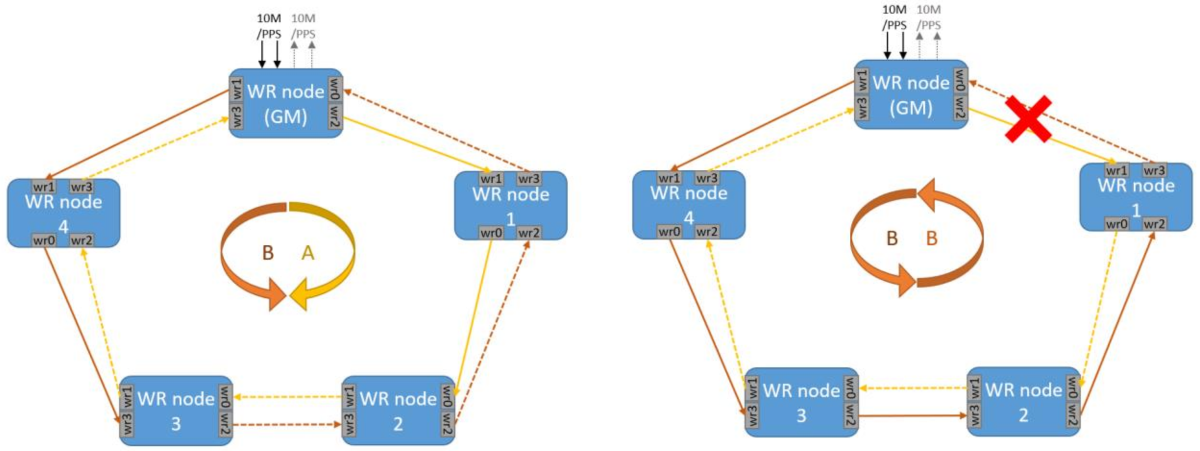

Figure A.3: WR distribution on dual ring in normal condition (left) or under failure (right)

To reduce the time to fully reconfigure a single ring a cost-effective approach is the dual ring solution that only requires to use 4 ports per devices instead of 2. Then for each connection between two nodes a duplex link must be provided. As explained in the section 4.2 about distribution on commercial optical network a connection can be with:

- dark fibres: this is typically offered as provider typically provide duplex dark fibre;
- bidir DWDM: DWDM are always provided on duplex fibre. Thus, when using a bidir DWDM this mean that we are using two channels on one fibre, this let us use two other channels on the second fiber;
- standard DWDM: In this case, the cost to run this solution is more expansive as two channels must be provided instead on a single one. However, it is recommended to get at least two DWDM channels in order to ease the calibration procedure.

As shows in Figure A.4, the two rings (A & B) are always running in parallel even if for each node only one of its receiving ports is configured as slave (disciplining its oscillator from the master) whereas the other one is configured in survey mode (computing all the delays but not disciplining the oscillator). Having one port in slave and another one in survey allows an almost instantaneous swapping between the two ports without needing to wait for announce messages to propagate all other the ring. The benefits of using the double ring are:

- Faster (and almost seamless recovery) when a failure occurs.
- Additional information about the links useful to enhance the calibration at each node.

Then, to increase the robustness of the solution, one must consider adding two (collocated) nodes at each hop of the ring as illustrated in Figure A.5. This solution allows to handle multiple failures in the ring without compromising the solution:

- Failure of one link.
- Failure (or programmed maintenance) of a device.

- Failure of Grandmaster node (or its corresponding external reference)

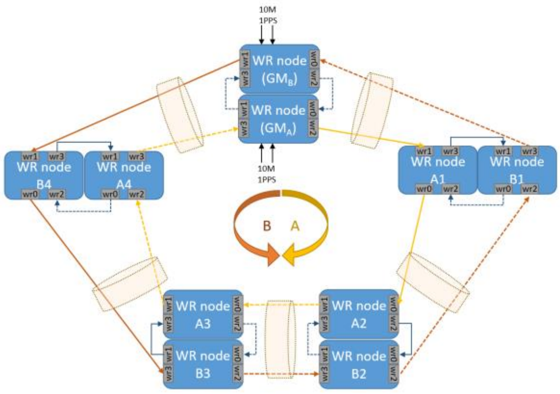

Figure A.4: Redundant nodes in double ring topology

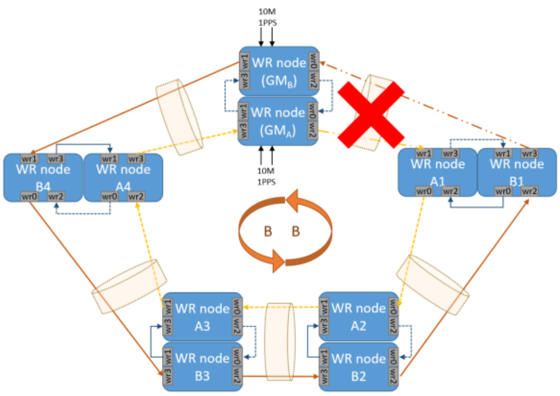

Figure A.5: Redundant nodes in double ring topology with a link failure

A.2 Redundant Tree Topologies

For shorter distances (<1km) the tree model is the recommended one as it allows a stronger resiliency as one device failure does not disturb the full network, however it needs more cabling.

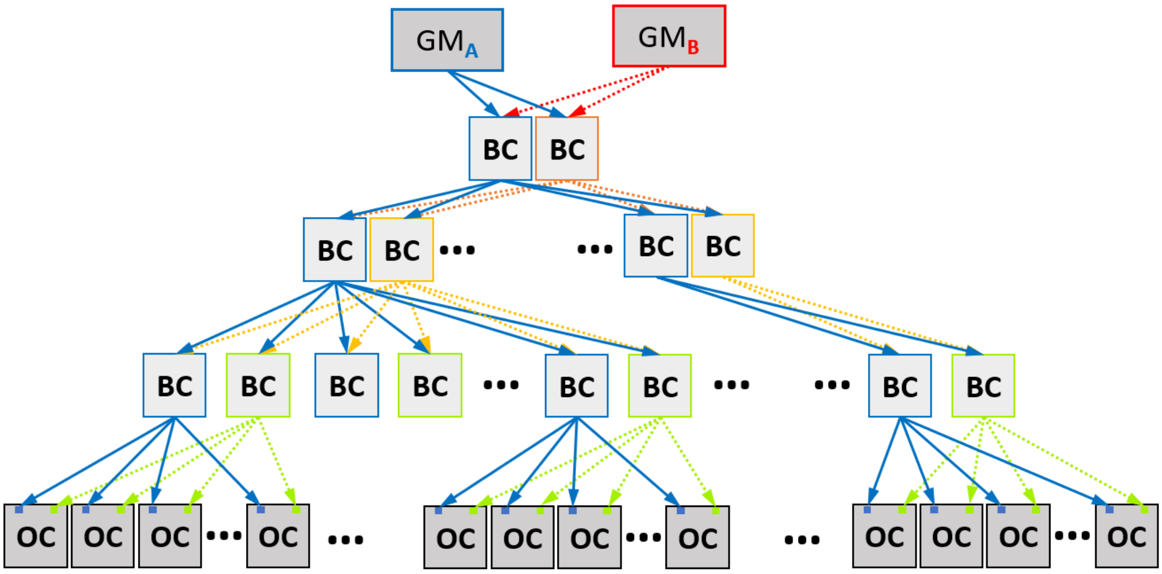

Figure A.6: Double-link redundant tree topology

Figure A.6 illustrates a complete double-links tree topology, which is a highly dependable method of creating a redundant tree topology. However, the numerous cables required, and the number of ports consumed may be too high for certain applications.

By doing some simple mathematics one can obtain that with:

- P : *the number of ports for each device* (e.g., 16)
- L : *the number of levels in the tree* (e.g., 5)

The total number of OC that can be used is given by:

$$N_{OC} = \frac{P}{2} \times \left(\frac{P-2}{2}\right)^{L-2} \times 2$$

and the total number of BC to create the structure is given by:

$$N_{BC} = \sum_{i=2}^{L-1} P\left(\frac{P-2}{2}\right)^{i-2}$$

In the case of 5 layers (as in Figure 2.12) with 16 ports per device we have:

$$N_{OC} = 8 \times 7^3 \times 2 = 5488$$

$$N_{BC} = 16 \times (7^0 + 7^1 + 7^2) = 16 + 112 + 784 = 912$$

$$N_{LINK} = 2 \times (N_{BC} + N_{OC}) = 2 \times (912 + 5488) = 12800$$

Another inconvenient of using the typical double-link tree topology with the BMCA algorithm is that the end-node (OC) can only monitor the information coming from the same GM. This is due that each level is following the same device as current master and thus have no knowledge of passive master until the switching is done.

To optimise the number of links & devices while maintaining a great level of reliability one of the typical proposals is the use of dual path topology. Figure A.7 illustrates how this topology is built and shows that each OC is connected to both GM (A & B) through two different paths (blue & red). In case one of the devices along one path has an issue (or a link is broken) all the devices below this failure will stop getting properly the synchronisation however the end node devices will be able to select the backup path (in red) to continue working.

It is worth mentioning that we recommend keeping a double links for the first level to avoid that a failure of one GM itself could totally make unusable one of the paths.

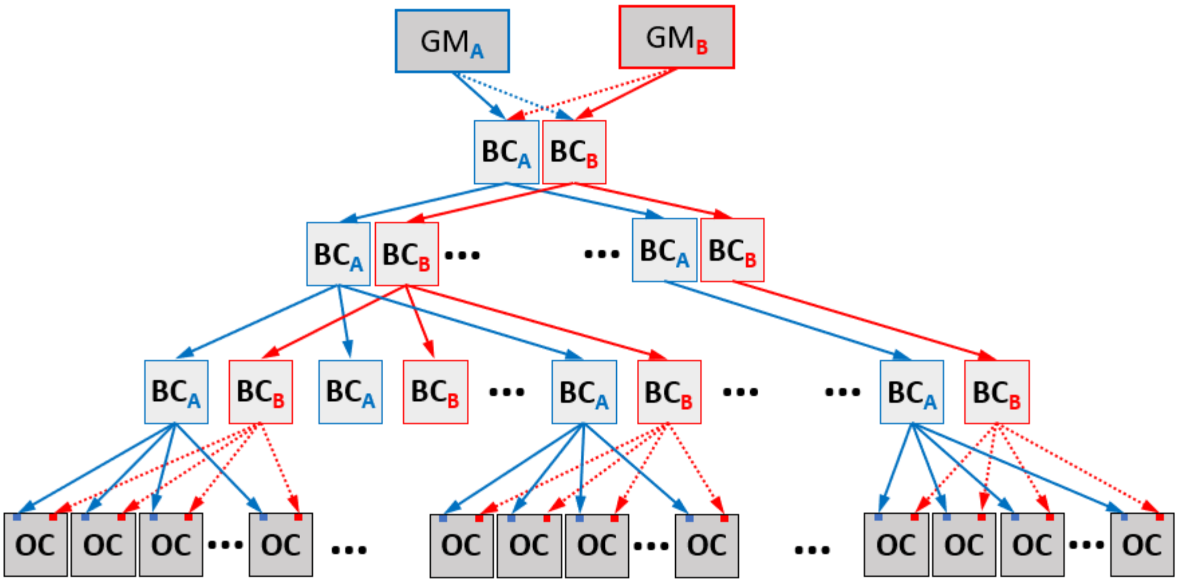

Figure A.7: Dual path redundancy topology

By using similar mathematical notation as above we can compute the number of end-nodes and the total number of boundary clocks for any kind of depth in the tree topology.

$$N_{OC} = \frac{P}{2} \times (P-1)^{L-2}$$

$$N_{BC} = 2 \times \left(\sum_{i=2}^{L-1} \frac{P}{2} \times (P-1)^{i-2} \right)$$

In the case of 5 layers) with 16 ports per device this will give us:

$$N_{OC} = 8 \times 15^3 = 27000$$

$$N_{BC} = 2 \times (8 \times 15^0 + 8 \times 15^1 + 8 \times 15^2) = 2 \times (8 + 120 + 1800) = 3856$$

However, for ease of comparison with the previous topology we have decide to use only two pairs of BC on the first levels (and leave one ports available at each BC):

$$N_{OC} = 2 \times 14^3 = 5488$$

$$N_{BC} = 2 \times (2 + 2 \times 13 + 2 \times 13^2) = 4 \times (1 + 14 + 169) = 844$$

$$N_{LINKS} = 2 \times N_{OC} + N_{BC} = 11820$$

This results that, for the same number of end-nodes, deploying less BC devices and a lower quantity of links especially on the top layers of the network where the links are usually more costly to deploy.

To resume, the dual path deployment has the advantages of providing reference from the two GMs (A & B) at the OC to allow to compare both references and decide which one is the best one by running the BMCA only at the end-nodes levels.

A.3 Mixed Redundant Topologies

Finally, to increase the resiliency of the dual path tree topology in a cost-effective way is to combine it with a ring topology as backup on the penultimate level as shown in Figure A.8.

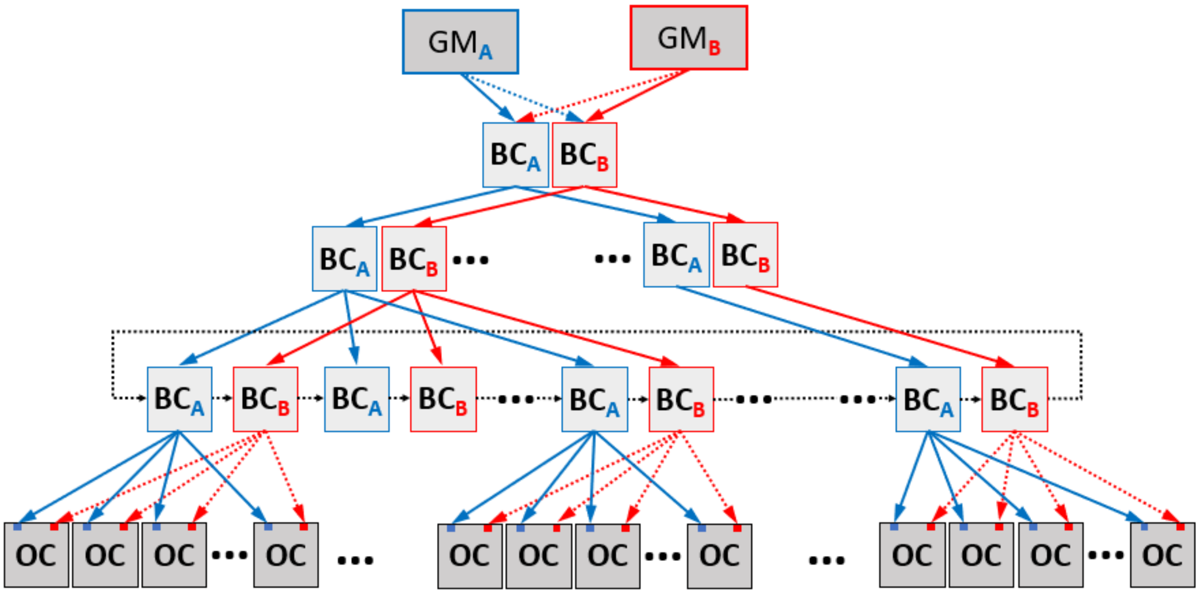

Figure A.8: Mixed redundant topology with dual path & ring

By doing so, it allows to still provide a redundant solution even when some devices/links in level 2 and 3 are not working properly. This is also very useful to perform maintenance operations (i.e., firmware upgrade) while still providing redundant capabilities. For example, an error could occurs on GMa while some nodes on red path are being updated.

For comparison with the previous model, the following numbers can be obtained by keeping two ports for the ring on the last level:

$$N_{OC} = 2 \times 15 \times 14 \times 13 = 5460$$

$$N_{BC} = 2 \times (2 + 2 \times 15 + 2 \times 15^2) = 4 \times (1 + 15 + 210) = 904$$

$$N_{LINKS} = 2 \times N_{OC} + N_{BC} + 210 = 12034$$

Then one can deploy only a single ring connecting all the BC at the last levels (shown in Figure A.8) or it can be split in subrings depending on how the deployment of the links must be handle at each location. It is worth highlighting that the ring will mostly be used as backup directly from the peer device: if the device from B path is not getting proper synchronisation from its master it will ask its peer device (the blue BC connected next to it) to be its new master. In the case that both master of BCA & BCB are not working, then the new timing will come from another BC (at the last BC level) but synchronised by other masters.

A.4 Automatic Recovery: Selecting the Proper Timing Reference

As mentioned in the previous section, in the PTP community the Best Master Clock Algorithm is the common algorithm used to select which source to follow to discipline the local oscillator of the device. This algorithm has the advantage to be very generic and thus works in most of the use cases however this also introduces several drawbacks that need to be highlighted:

- BMCA does not work properly in rings has if the timing is coming from the same GM but from two different ports (sides of the ring) it will always select the from the lowest clockID defined as a combination of MAC address and port number at the GM.
- BMCA does not consider the number of hops.
- BMCA only decides based on the information provided in the announce messages, if those value are incorrect or intentionally fake it might decide wrongly.
- BMCA will always try to switch back to the supposedly “best” timing source even if the current one is totally working fine and the switching might introduce errors/drifts.

To improve BMCA focusing on telecom network and most specifically on ring the ITU-T has developed an algorithm called alternate BMCA (a.k.a aBMCA) that considers a localPriority to improve how loops are managed in a ring.

Glossary

ACES	Atomic Clock Ensemble in Space
AOS	Astrogeodynamic Observatory of Polish Space Research Center
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 over optical-fibre networks
DEMETRA	H2020 project for EGNSS Timing/Synchronisation
DFN	Deutsches Forschungsnetz
DHS	Department of Homeland Security
DOI	Digital object identifier
DMP	Data Management Plan
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DWDM	Dense Wavelength Division Multiplexing
ECN	European Core Network
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 comb	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
IFCS	International Frequency Control Symposium
IQB	Italian Quantum Backbone (formerly LIFT)
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 (former name for IQB)
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
NI	National Implementation
NIR	Near-InfraRed
NMI	National Metrology Institute
NREN	National Research and Education Network
NRO	Nançay Radio Observatory
OADM	Optical Add-Drop Multiplexer
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 Center
PTB	Physikalisch-Technische Bundesanstalt
REFIMEVE+	Réseau FIbré Métrologique à Vocation Européenne (The french link project)

RENATER	French National Research and Education Network
RF	radio frequency
RI	Research Infrastructure
RLS	Regeneration Laser Station
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
T&F	Time & Frequency
T&RF	Time and Radio 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 Frequency Transfer Techniques
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
WR	White Rabbit