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Distributing New Performant Time and Frequency Services over NREN Networks

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Abstract

This document presents the distribution of time and frequency services and existing projects in several European national research and education networks, which are members of the GÉANT 4-3 project.

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Executive Summary

This document presents work carried out by NRENs within the *Network Technologies and Services Development* work package (WP6) in the initial period of the GÉANT GN4-3 project (January 2019 to early 2020) with respect to the distribution of Time and Frequency (T&F) services over European Research and Education (R&E) infrastructures.

T&F as an optical service has become a hot topic for the past ten years, mainly boosted by a dramatic improvement in performance. National Metrology Institutes (NMIs), in collaboration with NRENs, have demonstrated three orders of magnitude higher stability than any existing commercial service over distances of at least 1,500 km, offering tremendous potential for new services in a wide range of scientific, societal and economic domains.

The Technology Readiness Level (TRL) for such T&F services is in some cases now approaching 8 (complete and qualified) or 9 (proven in operational environment), and the growth of metrological links in Europe and the rest of the world has pushed more and more optical vendors to integrate T&F features into their products. However, there is no single agreed 'best' solution for deploying T&F services. Rather, there are multiple T&F setups (monodirectional, bidirectional, quasi-bidirectional) using different parts of the spectrum (S-Band, C-Band, L-Band, or between C and L-band), each having its advantages and disadvantages.

In this document, the *Optical Time and Frequency Network* (OTFN) team of the *Network Technology Evolution* task (Task 1) in GN4-3 WP6 has summarised the different ways in which T&F services might be integrated over optical infrastructures, from the perspective of their National Research and Education Networks (NRENs). It provides basic information on how to qualify T&F service performance, includes considerations that should be taken into account when implementing a national T&F network in an R&E context, and presents overviews of existing implementations of T&F services in the NRENs within the OTFN team.

The guidance in this document aims to be of help to Dense Wavelength Division Multiplexing (DWDM) engineers, scientists working in the T&F domain, or anyone looking at new optical services, or willing to implement, or benefit from T&F links, whatever the size of their organisation and their existing deployed technologies.

1 Introduction

Time and Frequency (T&F) services are critical to many civil and industrial sectors, both directly and indirectly, including telecommunications, geo-positioning (autonomous vehicles), energy, finance, and advanced scientific use cases. Access to precise time and frequency signals is, therefore, of major interest to industry, research and the economy worldwide.

In the past few years, National Metrology Institutes (NMIs) have successfully developed and tested new T&F techniques using optical fibres which have shown a stability performance of at least three orders of magnitude better than the current best commercial services. Moreover, such techniques offer an alternative to Global Navigation Satellite System (GNSS) for end-users who cannot rely on broadcast signals due to, for example, security concerns such as GPS spoofing attacks or reception issues if they are located in an underground laboratory. Further, new T&F services have the potential to respond effectively to the challenges of tomorrow.

These new services generated by NMIs and based on optical fibre transfer (often referred to as metrological T&F services) have emerged in response to a worldwide challenge driven mainly by research institutes that wanted to improve their physical experiments using metrological signals. Early projects and proof of concept deployments were nationally funded, and succeeded in implementing the first optical links, with each country experimenting with its own design. Close collaborations of National Research and Education Networks (NRENs) have succeeded in the development of national and international testbeds and pilot services. Progress towards building an ecosystem, business modelling, regulation, standardisation and exploitation has been studied in projects such as CLONETS [1], but, so far, there is no common standardisation throughout Europe, and as a result many different deployment techniques remain in use.

It is also important to consider how metrological services can co-exist in standard telecommunication networks, one challenge being whether it is possible to run T&F and data services over the same fibres. Such approaches can potentially be valuable to allow distant end-users to be more readily connected to their NMI (or the institution) generating the service.

To this end, the GN4-3 OTFN team members (CESNET, GÉANT, PSNC, RENATER and SWITCH) are working on catalysing the emergence of metrological networks in Europe, and to document their experiences in the early stages of GN4-3. The purpose of this document is to provide a general understanding of T&F services, to present existing and potential solutions with their benefits and challenges (the theory), and to describe the approaches being taken by the NRENs in the team (the practice).

2 Metrological T&F Services and Performance

The new kinds of T&F services that have recently been implemented by NMIs are characterised by the fact that they:

- are generated directly by NMIs which are providing nationally the highest level of standard for the calibration/measurement traceability infrastructure. A list of such NMIs can be found on the BIPM website [3]. Metrological T&F services can, therefore, be related to national reference standards such as UTC(OP), UTC(PL) or UTC(TP).
- use the physical layer 0 (optical fibre) of the Open System Interconnection (OSI) model and therefore differ from purely protocol-based services such as the Network Time Protocol (NTP).

Some of the most common techniques to establish a T&F service are:

- A frequency service over an ultra-stable optical carrier also known as Optical Carrier transfer technique.
- An ultra-stable frequency service over radio frequency modulation also known as radio frequency transfer technique.
- A time transfer service using the White Rabbit system based on the special Precise Time Protocol (PTP) and Synchronous Ethernet (SyncE).

These are further detailed in Section 3.3.

2.1 Performance Indicators

Each of the techniques listed above is based on a particular setup that exhibits different levels of performance.

The performance of time and frequency services is qualified using accuracy, stability and uncertainty, as defined in the International Vocabulary of Metrology [2].

- Accuracy

  Closeness of agreement between a measured quantity value and a true quantity value of a measurand (a quantity intended to be measured). The concept ‘measurement accuracy’ is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error.

- Stability

  Property of a measuring instrument, whereby its metrological properties remain constant in time.

- Uncertainty

  Non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

The metrological traceability property of a measurement is also important. This allows the measurement to be related to a reference through a documented unbroken chain of calibrations, each contributing to the Measurement Uncertainty (MU).

Figure 2.1 depicts an illustration of accuracy and instability measurements.

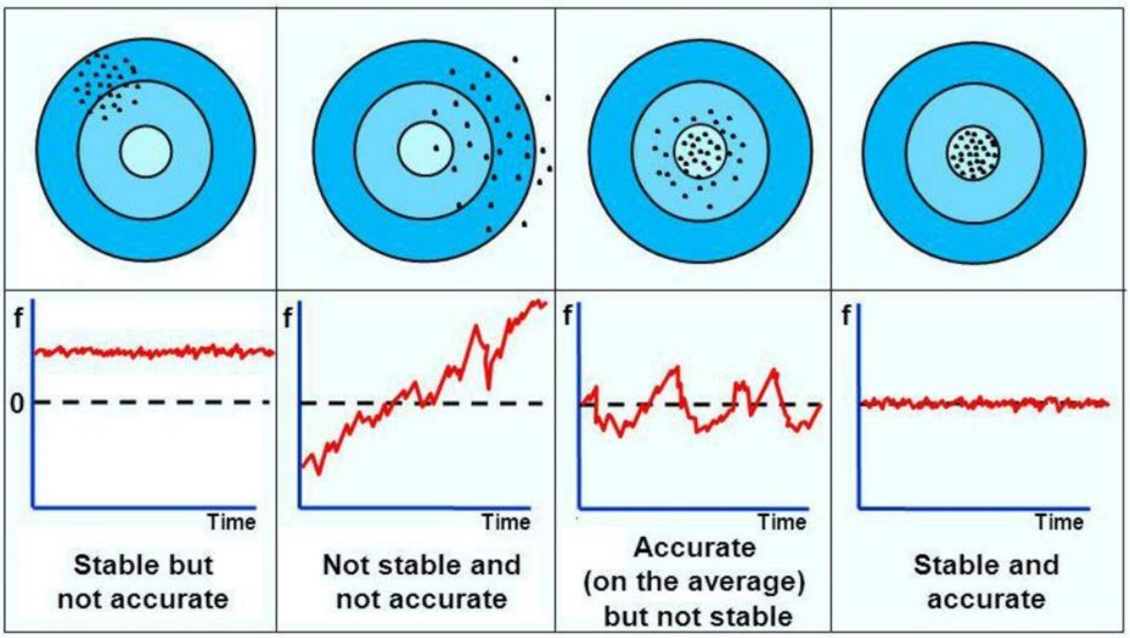

Figure 2.1: Accuracy and stability [4]

2.2 Level of Performance

This section considers how to evaluate performance levels in T&F services.

2.2.1 Allan Variance and Allan Deviation

To evaluate and quantify stability or accuracy, metrologists commonly refer to several varieties of Allan Variance analysis. The most popular are Allan Deviation (ADEV) and Modified Allan Deviation (MDEV) for measuring frequency instabilities, and Time Deviation (TDEV) for measuring time transfer instabilities. These statistical functions can be represented by tables or, more often, in the form of graphs. More details about Allan Deviation graphs and their variations (overlapping, modified, etc.) are available in [5], [6], and these graphs are very often cited in T&F work.

Figure 2.2 shows an example of a Modified Allan Deviation graph. This highlights the fractional frequency instability versus averaging time of the Villetaneuse-Nancy-Villetaneuse 1100 km compensated optical link (red squares), and of its extension to Strasbourg (blue circles) using the optical carrier technique described in Section 3.3.

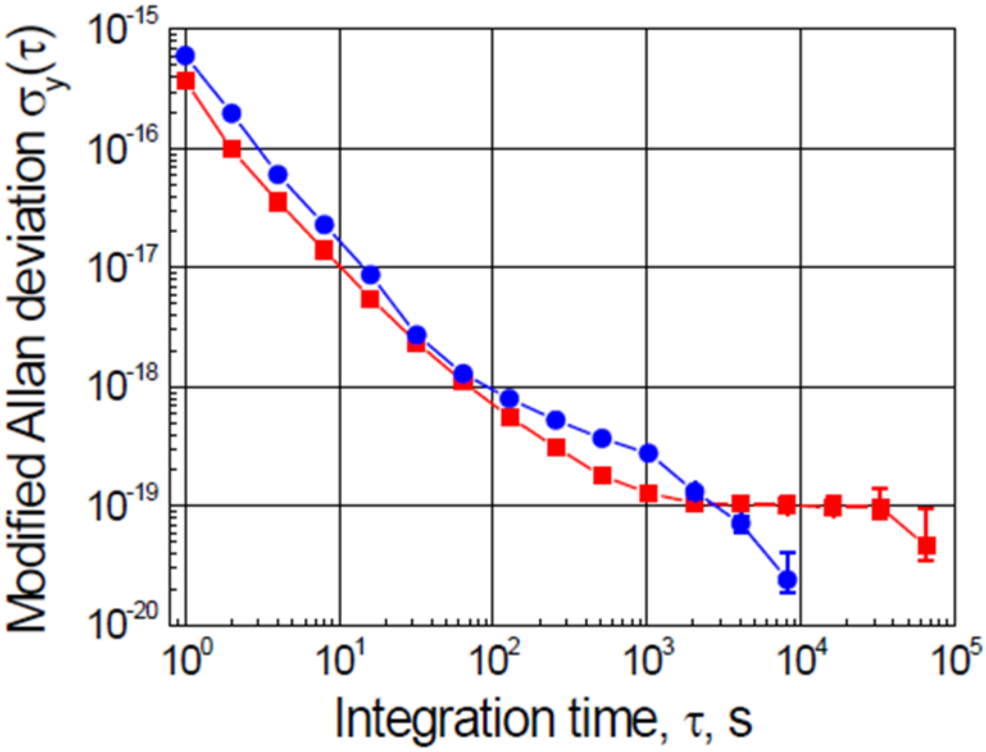

Figure 2.2: Fractional frequency instability versus averaging time of the Villetaneuse-Nancy-Villetaneuse 1100 km compensated optical link (red squares) and of its extension to Strasbourg (blue circles) [7]

2.2.2 How to Read and Interpret the Graphs

In these graphs:

- The X-axis represents the averaging time in seconds.
- The Y-axis shows fractional frequency instability (in ADEV/MDEV without units) and phase instability (TDEV in seconds).

The ADEV/MDEV value shows the instability of the measured signal at a given averaging time. In general, the lower the ADEV/MDEV value and the shorter the averaging time, the better.

To provide proper precision in the comparison of two distant clocks, the instability contributed by the transmission system (optical fibre, GPS, etc.) should be smaller (preferably by at least an order of magnitude) than the instability of the clocks themselves. Because of optical clock improvements, the instability contribution of the transmission system needs to be very low. Satellite-based transfer techniques could not match such requirements when comparing the latest highly advanced clocks, which has led to alternative techniques being deployed through optical fibre.

When using distribution systems in which the reference signal is sent to a distant user who does not have to have their own clock, stability analysis of ADEV/MDEV/TDEV will indicate how much noise will be added to the reference signal.

The rule of thumb here is that the lower the value in the Allan chart, the better. If the instability of the transfer method is more than one order of magnitude lower than the transmitted source, the noise associated with the transfer will be practically negligible, and, at the output, will be a delayed ‘copy’ of the reference signal.

The Allan graphs show that the stability of the transfer techniques is improving, as the averaging period (τ) gets longer. For example, some noise types can be removed by averaging. However, at some point, more averaging no longer improves the results, as can be seen for the red squared line at 2×10^3 s in Figure 2.2.

The slope of the Allan chart can also be used to identify the types of noise that dominate the specific averaging periods. A broad analysis of this topic can be found in [6].

Finally, it should be stressed that while stability analysis is one of the most important parameters, it is not the only one. Apart from this parameter, it is necessary to estimate the uncertainty of a specific link and, in the case of time transfer, to perform its exact calibration [8], which means the necessity of precise determination of the delay between the input and output of the transmission system. All these requirements result in the preferred, and sometimes even necessary, solutions, based on bidirectional transfer (in a single fibre).

3 Ultrastable T&F Service Distribution to Distant Users

This section discusses the theoretical aspects of T&F service distribution over optical infrastructure.

3.1 Typical Characteristics of Fibre-Optic Transfer

Some early T&F transfer techniques designed for use through optical fibres were very limited by external perturbations (external noise, thermic effect, mechanical constraints, etc.) that degraded the metrological signal quality when distributed to a remote end-user.

Fortunately, different solutions (active compensation, phase conjugation, two-way compensation and protocol-based techniques) have been found to compensate for these undesirable interactions and improve the instabilities of this new transfer technique. They all exploit the symmetry of the counter-propagating directions in an optical fibre [9].

In distribution systems, the copy of the signal transmitted in the forward direction is sent back at the far end in the same fibre towards the source, as shown in Figure 3.1. This signal (after a round-trip in the fibre) is compared to the local reference, and the measured difference represents twice the phase noise/error that the signal has accumulated during only one pass.

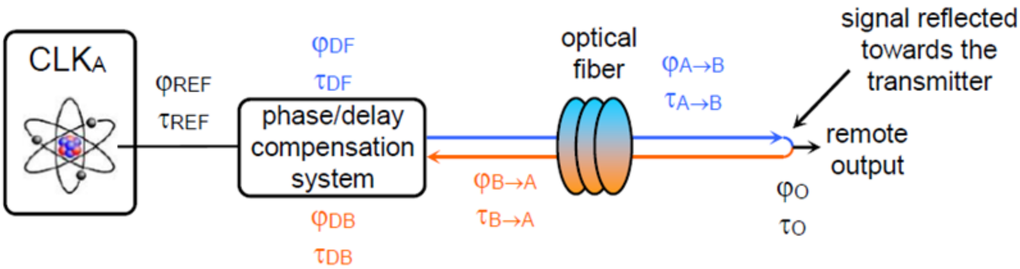

Figure 3.1: distribution of reference signals in a phase/delay stabilised link [9]

Once the noise is known, it is then possible to pre-emptively compensate the input reference signal (frequency and/or time) to get a stable signal at the output, i.e. the T&F service is at almost the same level of performance as the reference signal.

Figure 3.2 shows instabilities when signals are in an open loop system (the 'perturbations' of the fibre line are not corrected – stabilisation is off) and in a closed loop (when most of the perturbations are corrected – stabilisation is on). The Optical Carrier technique is used in this example.

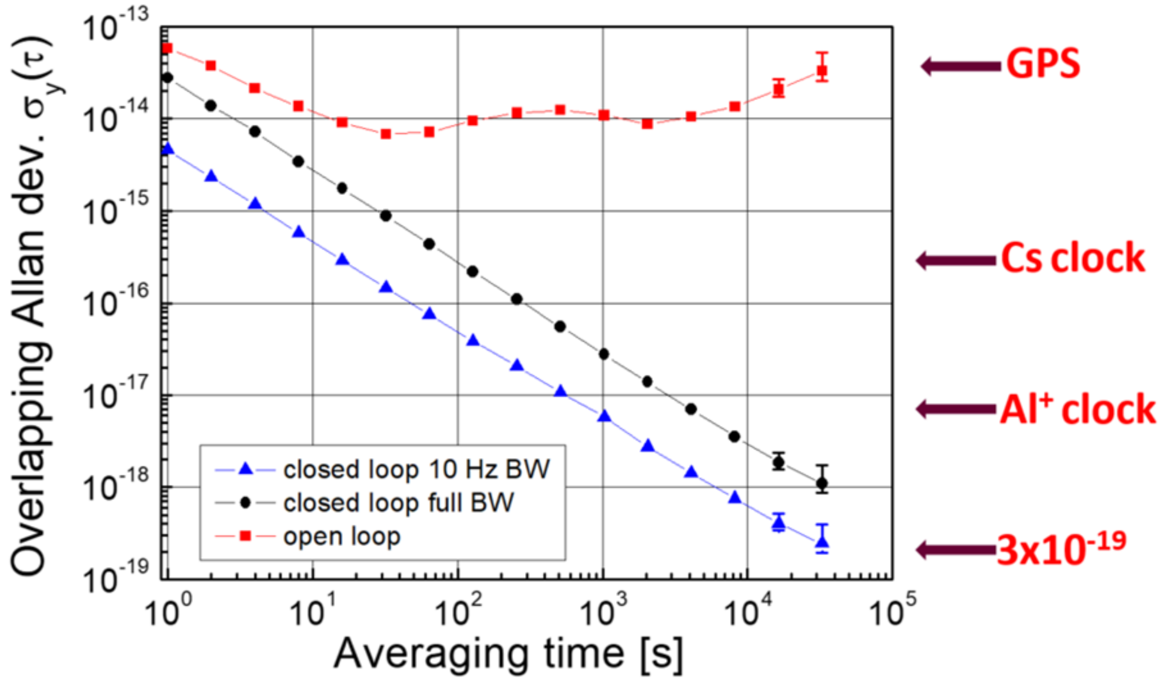

Figure 3.2: Opened and closed loop systems of new optical frequency transfer technique [10]

When the highest performance is required, using two different fibres for the path in and back is simply not good enough because two separate fibres do not respond identically to external interference, even if they are in the same fibre-optic cable [11]. Therefore, bidirectional propagation in the same fibre is required, and should be considered mandatory.

3.2 T&F Transfer Infrastructure Elements

Optical metrological links, i.e., fibre links that are equipped to distribute metrological T&F services from a metrology institute, are at the heart of modern metrology (see Figure 3.3), and require two or three 'typical' types of equipment to provide the signal to a distant end-user:

- A transmitter for the system that is locked (directly or indirectly) to a frequency reference or time and frequency reference (atomic clocks or optical atomic clocks), and that generates the T&F service inserted in the fibre. This role can be performed, for instance, by a WR-PTP switch (White Rabbit with Precise Time Protocol) [12], ELSTAB modules (Electronically Stabilised fibre optic system) [13], a Repeater Laser Station (RLS) [14], etc.
- Amplifiers to compensate the losses of the fibre-induced attenuation. Solutions are mostly based on Erbium Doped Fibre Amplifiers (EDFA) and Brillouin amplifiers (for the Optical Carrier technique).

- Optical Add/Drop Multiplexers (OADMs), which are (mainly) passive components that are implemented in setups where T&F signals are co-propagating with data traffic (i.e., in DWDM networks). OADMs are used to insert and extract metrological signals that need to propagate bidirectionally in the same fibre. This extraction must be done wherever DWDM monodirectional equipment has been installed.

It should be noted that some of these modules are now commercial products.

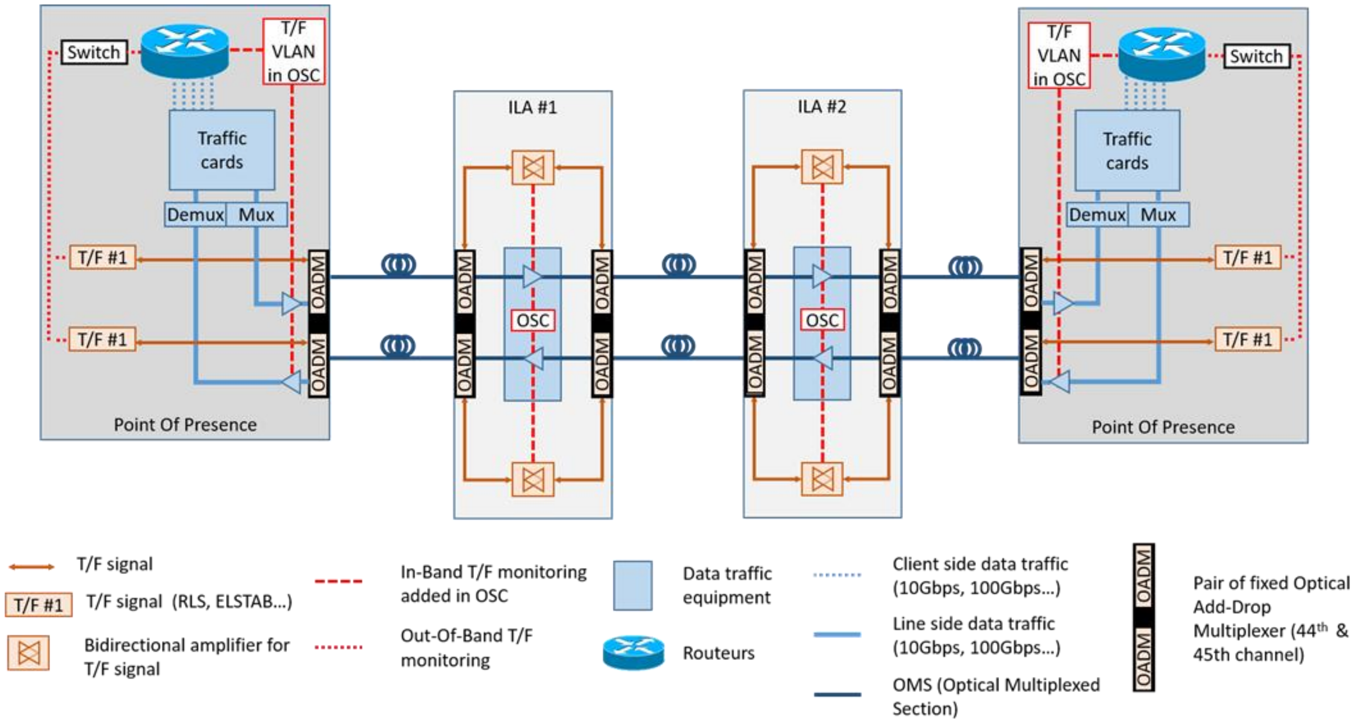

Figure 3.3: Main elements of a T&F distribution setup, co-propagating with data traffic

3.3 T&F Signal Distribution Techniques

A substantial number of T&F techniques have been developed in the past years, as summarised in Table 3.1 below. Some have only been tested in laboratories while others have been working for years in operational networks. Table 1 gives an overview of the existing techniques [9] and their performance at the time of writing this document (early 2020).

Note that research in T&F distribution techniques is still ongoing. New concepts are being tested, and performance is being pushed to its limits. Therefore, the performance and distances given in the table below may change (improve) over time.

Existing advanced techniques			Performances Frequency (instability) Time (precision, Time Deviation TDEV)	TRL	Distances
FREQUENCY	Optical Carrier (Carrier Wavelength)	Active cancellation	10^{-15} @1s ; 10^{-20} @1d	8	>1000 km
	RF Carrier (Modulated Wavelength)	Active cancellation with optical delays	10^{-14} @1s ; 10^{-18} @1d	4	0-100 km
		Active cancellation with electronic delays (ELSTAB)	10^{-13} @1s ; 10^{-17} @1d	8	500-1000 km
			10^{-16} @1d (unidirectional)	8	>1000 km
		White Rabbit PTP	10^{-15} @1d (unidirectional)	8-9	>1000 km
		Phase conjugation	10^{-19} @1d	5-6	0-100 km
TIME	Two-way comparison		TDEV ≈ 2 ps	5-6	100-500 km
			TDEV ≈ 30ps calibration through GPS (unidirectional)	6	100-500 km
	Optical frequency comb		Calibration uncertainty <40 ps TDEV 500 fs @1s	4-5	0-100 km
	Active cancellation with electronic delays (ELSTAB)		TDEV < 1ps calibration uncertainty <40 ps	8	>1000 km
	Protocol based (White Rabbit PTP)		Verified with GPS disagreement ±2 ns	8-9	>1000 km
			Calibration uncertainty <10 ns	8-9	0-100 km

Table 3.1: Summary of performance and capabilities of T&F techniques [9]

Practical approaches to distributing T&F services by the OTFN team members on their own national R&E networks (in France, the Czech Republic, Switzerland and Poland) are discussed in Section 4.2.

The Optical Carrier technique is in production in the French, Czech and (soon) the Swiss NRENs, as well as in other NRENs who are not members of the GN4-3 WP6 OTFN team, but the implementation specifics vary:

- One of the options used by organisations including RENATER is to use channel 44 of the ITU-T DWDM grid (a frequency of 194.4 THz), which has partly been chosen for economic reasons as the components in C-band are cheaper and easier to find than for other bands. Many organisations have also chosen to use channel 44 as it was the only one that allowed them to be directly interoperable with international partners.
- At the time of writing the Swiss T&F project plans to use a frequency (the 7th channel of the ITU-T DWDM grid) at the edge of the C and L-Band to isolate the dark channel at the edge of the C-Band. This choice is intended to prevent potential mutual interference and to facilitate future operating management with data traffic technology including super channels.

- CESNET has been working on utilising a DWDM channel at the edge of the C and L-Band, and even in the S-Band, to keep the C-Band only for data traffic.

It should be noted that optical carriers using different frequencies cannot be directly compared to one another. This is a limitation when comparing optical clocks, and an intermediary ‘gateway’ system is required, whose design is still under investigation. The role of such gateways is usually implemented by an optical comb.

A Radio Frequency (RF) carrier can be used at any optical wavelength in the C-Band, while the L-Band is under investigation but is limited by the availability of optical components and their price. Using this technique, it is possible to transfer time and frequency simultaneously.

White Rabbit can be used at any optical wavelength (S-Band, C-Band, L-Band), depending on the availability of Small Form-factor Pluggable (SFP) transceivers, but it operates at a much lower performance as shown in Table 3.1.

3.4 Component Availability for S, C, C/L and L-band Distribution

Following the description of the different distribution approaches for T&F services in the sections above, Table 3.2 summarises at the time of writing (early 2020) the availability of the hardware components required to implement a service using different spectral options (S-band, C-band, C/L band and L-band).

For NRENs and organisations that are not in the WP6 OTFN team, their statuses are presented based on available information at the time of writing.

Band	OADMs single channel	OADMs band	Transmitter module for Frequency transfer	Transmitter module for Time transfer	Amplification	Operating network
S band	Available on request (custom design)	Available/ on request (CWDM/ custom design)	Commercially available (long lead time)	CWDM only	SOA, Brillouin amplifiers commercially available	SURFNET (WR) CESNET (OC)
C band	Commercially available	Available on request (custom design)	Commercially available	Commercially available for all techniques	Bidirectional EDFA commercially available	RENATER ch.44 (OC) CESNET ch.46 (OC) CESNET-BEV ch.43-46 NPL ch.44 (OC) PTB ch.44 (OC) INRIM/GARR ch.44 (OC)
Between C/L Band	Commercially available	Available on request (custom design)	1572 nm Lasers are available and tested in Lab. Koheras: from stock. RIO: high one-time costs and long distribution time for the production of a dedicated wafer. Lower costs and shorter distribution time is possible by sharing the existing wafer of SWITCH.	Commercially available (longer lead time)	Amplification - EDFA: EDFACL optimised for 1570 installed and successfully tested. Prices and specs available from CzechOS/Optokon.	SWITCH ch.07 (OC) CESNET (RF) (First field tests are promising)
L band	Commercially available (long lead time)	Available on request (custom design + long lead time)	Available on request (custom design + longer lead time) with some limits over 1585 nm	Commercially available (longer lead time)	Bidirectional EDFA commercially available	CESNET (RF)

Legend: OC (Optical Carrier), RF (Radio Frequency Carrier), WR (White Rabbit)

Table 3.2: Availability of main T&F hardware elements for different spectral regions

4 Implementing T&F Services over NREN Networks

As briefly presented in Section 3.3, a multitude of T&F setups are currently deployed in Europe. This section provides more detail of the theoretical considerations involved in designing the distribution of a T&F service over a national NREN infrastructure, and complements that theory by looking at practical approaches to implementing T&F services, taken by the NRENs in the WP6 OTFN team.

This section does not include specific recommendations for deployment, rather it captures the experiences and lessons learnt by the WP6 OTFN partner NRENs during the early period of the GN4-3 project with the aim of informing other NRENs of the approaches.

4.1 Considerations for T&F Service Design and Distribution

4.1.1 Capacity to Integrate Metrological T&F Signal Distribution

The implementation of new optical services, such as Quantum Key Distribution (QKD) or T&F services, requires direct access to the photonic layers in a different way to ‘classic’ alien waves.

Alien waves are wavelengths that are unknown to the network domain, share the spectrum with native wavelengths, and are generally dedicated to carrying data traffic. When distributing metrological T&F services, the mandatory bidirectional propagation in a dark channel forces a spectral sharing setup as defined in [15]. Spectral sharing is a type of architecture where alien wavelengths have their own dedicated transmission equipment as depicted in Figure 3.3. T&F services require at least one or two 50 GHz ITU DWDM channels, so a slice of the spectrum is allocated to carry the service and is, therefore, unavailable to other network elements. Moreover, setting up (and removing) a dark channel has an impact as OADMs need to be inserted at each endpoint site, which requires staff resources to perform.

From an operational point of view, it can be argued that having a dark channel in the middle of the C-Band is the least desirable option, as it may, for example, prevent future use of super channels. A better scenario would be to have it at the edge of the C-Band or even in some other band. A dark fibre could even be dedicated to T&F services, so that standard data traffic and T&F services would be using separate fibres, which avoids the risk of saturating the C-Band. Another advantage is that necessary T&F equipment can be implemented more quickly (once the fibre is delivered) and optimised without fearing to interfere with data traffic.

Table 4.1 summarises the advantages and disadvantages of using dedicated dark fibre for T&F services versus having T&F services running over the same fibre as data traffic (dark channel).

Approach	Advantage	Disadvantage
Dark channel	• Mutualise fibre and housing facilities. • Implementation of the T&F service can start immediately as no extra fibre is required.	• Adds complexity in the network due to the bidirectional signals propagating in a telco architecture. • Setting up the spectra-sharing architecture may be traffic impacting - reduced capacity for data traffic. • Optimising T&F service takes more time in order not to interfere with data traffic. • Each OADM adds up to 0.8dB of extra attenuation which degrades OSNR. • Is not ideal when attenuations/span > 25dB.
Dark fibre	• Data traffic and T&F services are using dedicated fibres and cannot interact (safest option).	• Additional high costs for fibre rent. • More fibres and the two dedicated networks need to be monitored and managed simultaneously (more manpower required).

Table 4.1: Advantage and disadvantage of dark channel versus dark fibre solutions

Table 4.2 summarises the advantages and disadvantages of using different bands when sharing T&F and data traffic over the same fibres.

Band used	Advantage	Disadvantage
C-band	• Band with the most background experience. • Most NMI are using 44th channel of ITU grid when distributing T/F signals.	• The use of a dark channel in the middle of the C-Band may block new DWDM technology such as super channels.
Between C- and L-Band (out of the frequency range currently used by DWDM systems)	• All C-Band channels can be dedicated to carry data traffic.	• Additional equipment (gateways) may be required when interconnecting to networks using another channel for their own T/F service.
L-band	• All C-Band channels are dedicated to data traffic.	• Different channel than used by many other T&F projects (gateways required).

Table 4.2: Pros and cons of different frequency bands when using dark channel

4.1.2 User-Oriented Services and Performance

Time and frequency services are critical to many infrastructures, including telecommunications, energy, research institutes and the finance sector, but not all require the state-of-the-art performance which is the most demanding in terms of network architecture.

It is important to engage with the end users regarding any potential service to understand their requirements, especially the precision required, before proceeding with a service design.

It should also be noted that the frequency and time transfer techniques presented in Table 3.1 are distributing different types of signals. Some can be easily used (standard 1/10/100 MHz outputs) and do not require expensive equipment to be bought by end-users, while others, for example, the optical carrier technique, are distributing an ultrastable non-modulated optical signal which can only be useful when connected to a frequency comb.

It is, therefore, important not to focus only on the performances mentioned in Table 3.1 but also on signal usage. White Rabbit for instance shows lower performance but is a cheaper solution that can be more easily implemented and used, and may meet many users' requirements.

Table 4.3 presents the advantages and disadvantages of different T&F service distribution techniques for existing TRL 8-9 services.

Different techniques	Advantages	Disadvantages
Optical Carrier [10] [16]	• Best ultrastable frequency service performances. • Has been operated in different setups (dark channel and dark fibre).	• Limited number (but more demanding) of end-users because frequency combs are required to use the distributed signal. • Industrialised equipment is designed to work @ 194.4THz in C-Band. • Alternative systems using other frequencies are being deployed and are to be tested in the real field. • Requires highly trained personnel.
ELSTAB Active cancellation with electronic delays [17]	• Distributions Time and Frequency services. • Wavelength is fixed but can be chosen all over C-Band to fit any ITU channel.	• Even greater performances might be required for the most demanding end-users (optical clock comparisons).
White Rabbit PTP [18] [19]	• Easy to use. • A wide range of potential end-users. • Time and Frequency service. • Affordable prices.	• Performances only slightly better than GPS.

Table 4.3: Pro and cons of metrological T&F service

4.1.3 Lead Time to Service Deployment

Implementing a T&F sub-network based on dark channels can potentially be a long process as it may force an operator/NREN to re-think their optical layer. The increased attenuation induced by the additional OADM may also potentially require deployment of Raman pumps to maintain the required OSNR. An analysis of the optical layer would, therefore, be prudent to determine whether such modifications (and the associated costs and time) are required.

However, implementing T&F services over dark fibres can potentially be even more time consuming (it will likely depend at least on existing dark fibre availability) and it is, therefore, important to understand which of the two solutions is most appropriate depending on the time frame available or required.

Different techniques	Advantages
Short term (less than 2 years)	• Using existing fibre network 'should' be quicker than purchasing new fibre dedicated for T&F services (if no spare fibre capacity exists).
Long term (4/5 years)	• T&F could be deployed when the optical layer is renewed so that potential T&F problems can be anticipated and resolved in the layer 0 design.

Table 4.4: Lead time considerations

These considerations should be treated cautiously as administrative procedures and easy access to fibres can vary a lot from one country to another.

Agreeing a common technique and channel over which to run T&F services is challenging. Not every telecommunication network shares the same situation regarding their current utilisation of bandwidth or access to dark fibres. A dark fibre-based architecture dedicated to carrying T&F services is undoubtedly the easiest and safest option from an operational point of view, but this solution, in general, is likely to be more expensive because of the additional fibre and housing costs. Again, this needs to be evaluated in each scenario.

On a qualitative point, T&F and data signals have been run on the same fibre on the RENATER network for more than 10 years without any incident occurring. With appropriate planning and testing, this should, therefore, not prevent any institution to start implementing metrological T&F services.

4.2 T&F Service Distribution: NREN Examples

There are many T&F service setups currently in operation or under investigation. This subsection provides an overview of the T&F service implementations in the WP6 OTFN team member NRENs. The table below summarises these networks.

Country	Type of architecture	T&F service implemented	First T&F implementation	Scope
France	Dark channel @194,4 THz co-propagating with data traffic	Frequency service	2012	More than 2,000 km in operation
Switzerland	Dark channel @190,7 THz	Frequency service	2019	More than 200km
Czech Republic	Dark band Incl. 194.4 and 194.6 THz C-Band L-Band	Time and Frequency service	Time transfer project started in 2009	More than 900 km of bidirectional channels and 1000+ km in DWDM km
Poland	Dark fibre / DWDM	Time and Frequency service	2012	More than 800 km in dark fibre and about 1600 km in DWDM

Table 4.5: Main information regarding some metrological T&F networks

4.2.1 RENATER - Co-Propagation with Data Traffic in the Middle of C-Band

The work on the propagation of time and frequency services in RENATER started through a collaboration with Observatoire de Paris and Laboratoire de Physique des Lasers (LPL) as a part of the REFIMEVE+ project in 2009. The REFIMEVE+ project aimed to distribute a metrological ultrastable frequency to French scientific laboratories and perform comparisons with European NMIs through the RENATER DWDM network and cross-border fibres (CBFs). With its commitment to provide more than 10,000 km of dark channel infrastructure with the T&F services in the middle of the C-Band, RENATER is not just a member of the REFIMEVE+ consortium, but a key partner.

To make the transport of an ultrastable frequency possible, RENATER was required to adapt its network so that the REFIMEVE+ signal can propagate bidirectionally in a standard monodirectional telecommunication infrastructure

This technique was first demonstrated in 2009 on a short 11 km fibre link using CWDM propagation. It was then implemented on longer spans with simultaneous data traffic on the neighbouring channels of the 100 GHz DWDM grid.

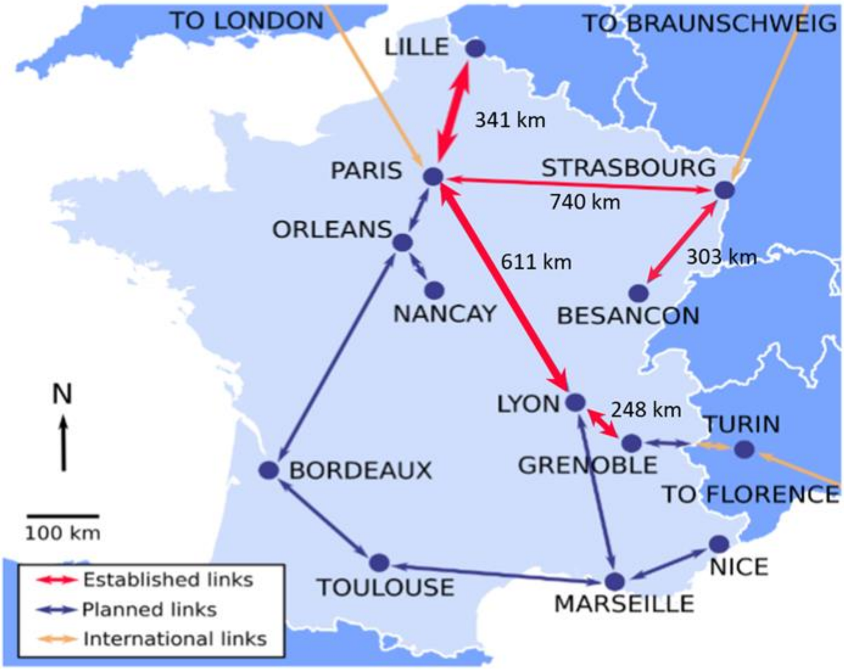

Figure 4.1: REFIMEVE+ network

A typical optical link in the RENATER network is depicted in Figure 4.1, and is based on Repeater Laser Stations (RLS), bidirectional amplifiers and OADMs (Optical carrier technique @194.4 THz).Dedicated OADMs are installed at each Point of Presence (PoP) and In-Line Amplifier (ILA) site so that the metrological signal (in brown) bypasses the DWDM equipment. Once extracted the signal is re-amplified separately from the remaining data signals. The insertion of an OADM pair causes an extra attenuation of 1.6 dB on each span.

The ultrastable frequency transfer from Paris to Reims and back (540 km) has been in operation since 2012, the first extension to Strasbourg since 2014 [20] and the second extension to Besançon since 2018. The Paris-Strasbourg branch of the network is connected to the German infrastructure of Physikalisch-Technische Bundesanstalt (PTB) in Strasbourg, where both OBSPARIS and PTB perform atomic clock comparisons.

The deployment of the first fully outsourced industrial implementation was done in 2017 by the industrial Muquans (Paris-Lille link).

In parallel to these extensions, the RENATER and REFIMEVE+ teams are working on the development of a dedicated Data Communication Network (DCN) and its integration within the RENATER supervision including:

- the creation of a Network Management System (NMS)
- the implementation of a Simple Network Management Protocol (SNMP) polled by the NOC of RENATER's hypervisor
- the training of RENATER's NOC on REFIMEVE+ architecture specificities
- the coordination between RENATER's NOC and REFIMEVE+ vendors

4.2.2 The Swiss T&F Network at Edge of the C- and the L-Band

In the context of a project founded by the Swiss national science foundation, SWITCH committed to support the transfer of a high precision frequency (<10^{-15}) from the Swiss National Metrology Institute (METAS) to the University of Basel, and from there to ETH in Zürich. The frequency, which is traceable to the Swiss primary frequency standard, will be used to improve the accuracy in molecular ion spectroscopy and to develop ultra-narrow-band THz lasers. The project committee decided to go for a bidirectional transfer on a single fibre with optically stabilised links, the same technique which is used by INRIM, RENATER and others. This technique would make it possible to increase the precision of future applications like the comparison of optical clocks.

The project started in January 2019 and will end in 2022. The frequency should be available to researchers by the end of 2020.

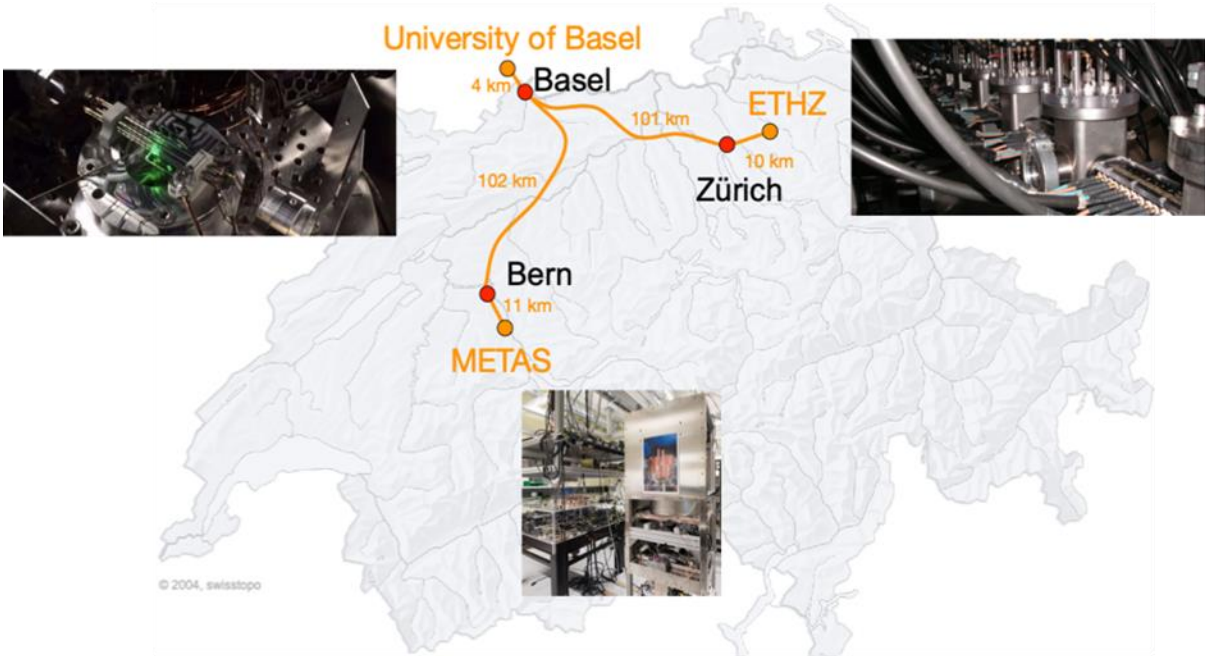

Figure 4.2: The Swiss metrology project

From the beginning of the project it was clear that it would not be possible to rent dark fibres given the estimated costs of more than CHF 100’000- per year. Especially not if the application would need to be available after the end of the project, and if the frequency would be made available to additional research institutes in Switzerland. To circumvent the high renting costs, SWITCH offered to use an optical channel on its existing network infrastructure. Besides saving on the high fibre renting cost, SWITCH’s existing housing and network operation infrastructure could also be used.

The most likely channel to use would have been ITU channel 44 (1542.14 nm), which is used by many other major projects in Europe. However, ITU channel 44 is in the middle of C-band which is used by all DWDM equipment. While it has been proven by RENATER and CESNET that it is possible to use channel 44 for frequency transfer in parallel to the DWDM data channels, SWITCH considered the impact on the data transport infrastructure to be high, the rationale being:

- A significant part of the available spectrum is already being used for data transport.
- The need for bandwidth is still growing. It is expected that dynamically allocated super channels will soon be deployed, which is possible with the existing DWDM system with ROADM supporting flexgrid already.
- It is not clear if the next generation of optical equipment and its management system will support channel 44, and what the implications on the functionality and the cost will be.
- This application should be supported longer than just during the lifetime of the currently used equipment.

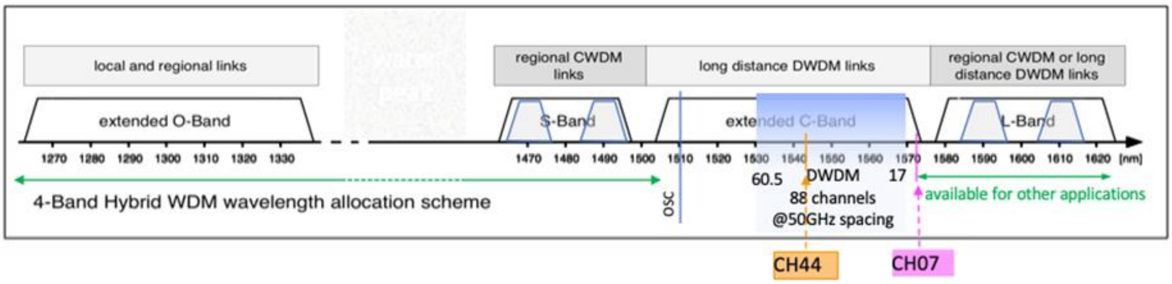

Figure 4.3: Use of the optical spectrum

After spending some time with the evaluation of an alternative channel, it was decided to use ITU channel 07 (1572.06 nm) at the edge of C-band with the following advantages:

- Low risk of a conflict with DWDM equipment using C-band (or L-band in the future).
- Equipment (laser, filter, and amplifier) is available.
- There is free spectrum for additional channels in the vicinity of channel 07 available for other applications like time or White Rabbit based transmissions.

The optical layout is shown in Figure 4.4.

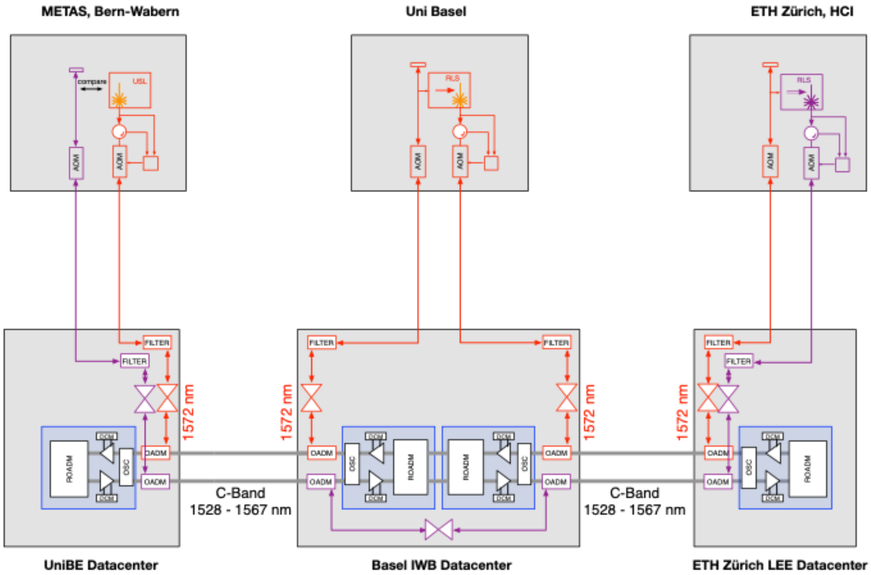

Figure 4.4: Optical layout

The main disadvantage of the choice of Channel 07 is the incompatibility with other European projects. To be able to perform comparisons with signals based on channel 44, an expensive optical comb is needed to perform the gateway function described in Section 3.3.

In summary, sharing the data network infrastructure with applications for T&F transfer saves costs for fibre renting, housing and operation. Using channels between C- and L-band allows a clear separation of time and frequency applications from network data transfer, and simplifies deployment and integration. This could be a strong argument to facilitate the proliferation of frequency transfer in other networks.

4.2.3 The Czech T&F Network in the Middle of C-Band and Planned Move to Edge of C- and L-Band

CESNET has been developing its Time and Frequency infrastructure since 2011. At present, more than 1200 km of fibre lines are used for T&F transmission, as shown in Figure 4.5.

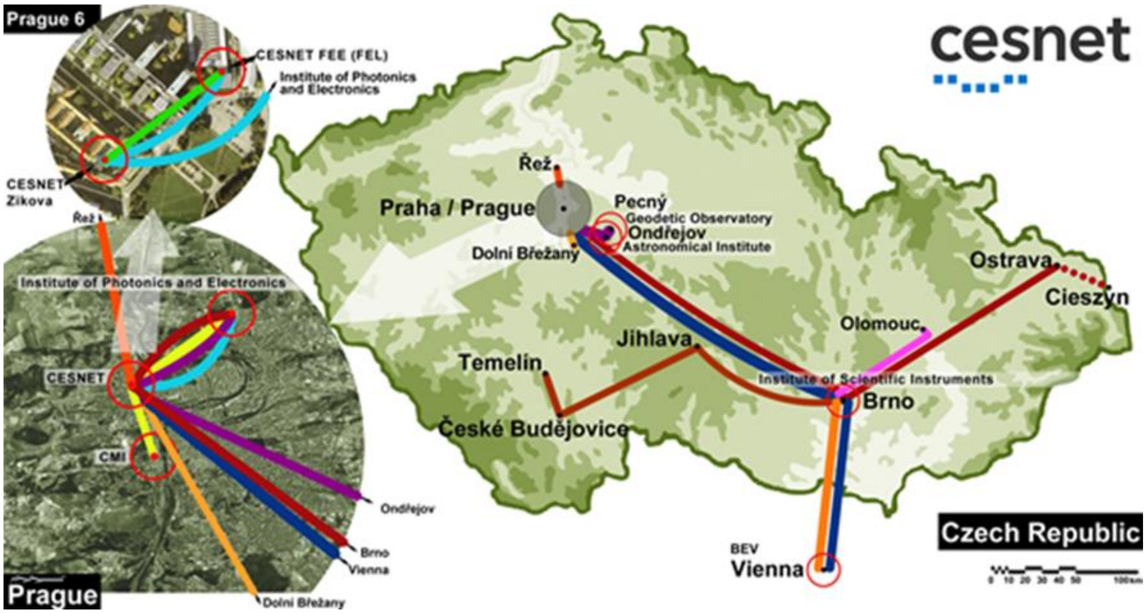

Figure 4.5: CESNET Time and Frequency infrastructure

The T&F infrastructure shares fibre with the regular data transmission network, to reduce T&F infrastructure operational expenditure. The presented T&F infrastructure enables parallel distribution of accurate time and ultra-stable frequency based on Wavelength Division Multiplexing (WDM).

The bidirectional transmission channel is provided in the C-band between 1540-1546 nm, or alternatively 1540-1543 nm [21]. This approach allows simultaneous transmissions of optical frequency (in the CESNET network both 1542.1 nm Ch. 44 and 1540.6 nm Ch. 46 transmissions are present) and time, and tends to be more versatile compared to a joint T&F transmission [22] using time modulated onto the frequency signal.

The T&F infrastructure CESNET connects:

- CESNET in Prague
- Czech Metrology Institute, national time laboratory operated by Institute of Photonics of the Czech Academy of Sciences providing UTC(TP), in Prague
- Institute of Scientific Instruments, Czech Academy of Sciences in Brno
- Czech Technical University, Faculty of Electrical Engineering in Prague
- Czech Metrology Institute, length laboratory in Prague
- Geodesy and Cartography Observatory in Pecny
- Institute of Nuclear Research in Rez
- Institute of Nuclear Research in Temelin
- Palacky University in Olomouc
- Bundesamt für Eich- und Vermessungswesen, Austrian NMI in Vienna UTC(BEV)

Cross-border fibre between Brno and Vienna is used for optical transfer of time and coherent optical frequency.

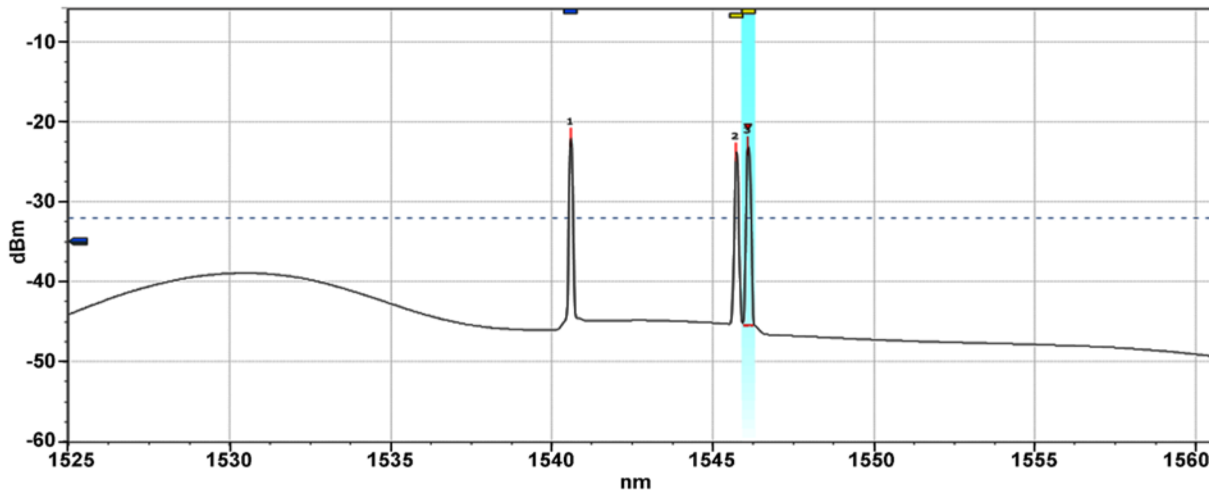

Figure 4.6: Simultaneous transmission of coherent frequency (left) and time (on right) within single bidirectional channel

The two-way time transfer is based on Time Transfer Adapters (TTAs) [23] developed by CESNET and on White Rabbit technology [19].

It was noted that bidirectional transmission of ultra-stable quantities in the 'legacy' C-band 1540-1543 nm or even 1540-1546 nm windows may present a complication for future DWDM network planning with broadband spectral channels. Therefore, space directly after the C-band (1570 nm) or L-band window has been verified as the space to use for future T&F transmission service migration.

4.2.4 The Polish T&F Network, Time and Frequency Services in Dark Fibre Infrastructure

Another solution which allows time and frequency transfer in optical fibre links is a dark fibre approach. This approach requires that the entire fibre link and the optical equipment must be exclusively dedicated to the transfer of the time and frequency reference signal, with no data traffic present. Moreover, specific bi-directional optical equipment is installed for the time and frequency transfer, as shown in Figure 4.7.

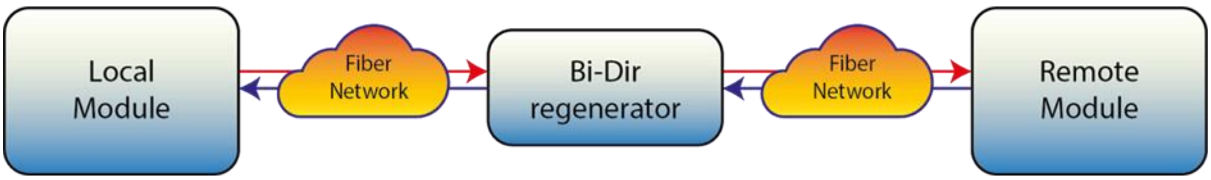

Figure 4.7: Time and frequency transfer – dark fibre approach

The advantage of using dark fibre links is that they are dedicated to T&F signal transmission and, therefore, there is no risk to data traffic, so the T&F transfer can be specifically optimised for T&F applications without having to analyse whether the T&F transfer affects the data transfer.

It should be noted that exploiting the maximum potential of dark fibre is only possible with bi-directional transmission in a single fibre. In the case of transmission over more than 100 km, the attenuation of the fibres is large enough to require the implementation of bi-directional amplifiers and/or regenerators.

The disadvantage of the dedicated dark fibre solution is of course the cost of obtaining dark fibre from telecommunication operators.

The service provider can access a local and a remote module and bi-directional regenerators in the same way as with other network equipment.

This transmission model has been successfully used in the OPTIME [24] T&F distribution network, as shown in Figure 4.8. The system covers more than 2400 km of fibres in Poland and Lithuania. All connections are based on the ELSTAB [25] system provided by the AGH University of Science and Technology in Krakow. The red link uses dark fibres, the blue link uses a unidirectional DWDM system [26].

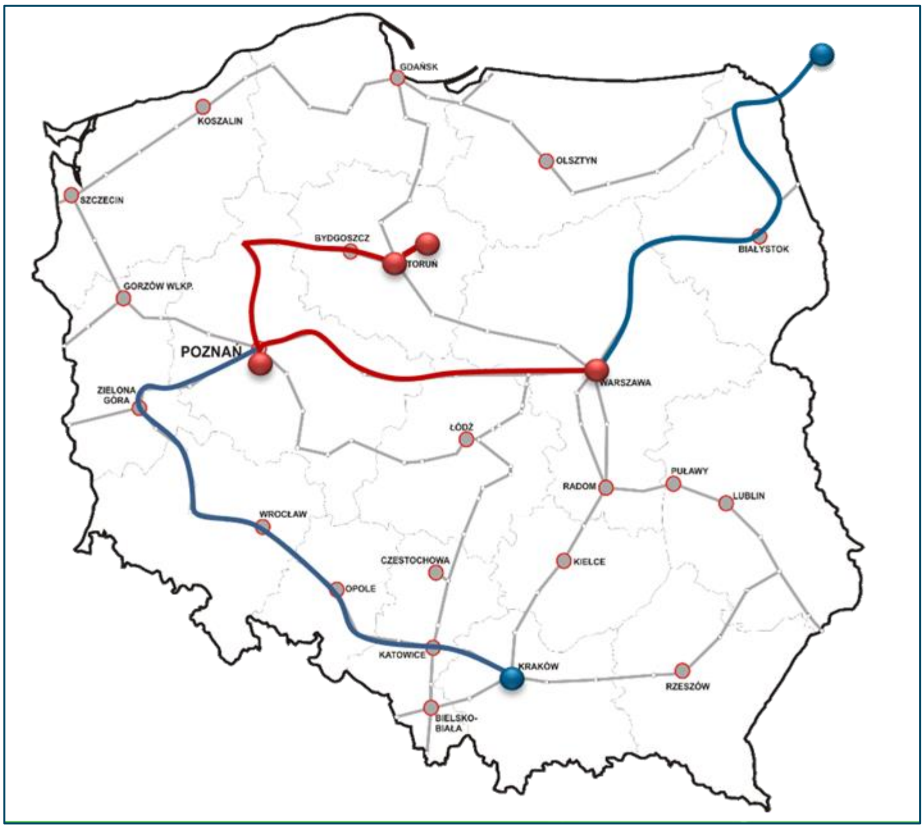

Figure 4.8: OPTIME - Time and Frequency distribution network in Poland

The OPTIME network connects:

- Poznan Supercomputing and Networking Center (PSNC) in Poznan
- Central Office of Measures (GUM) - polish NMI located in Warsaw provides UTC (PL)
- Astrogeodynamic Observatory (AOS) located in Borowiec near Poznan provides UTC (AOS)

- Orange PL located in Anin near Warsaw
- National Laboratory of Atomic, Molecular and Optical (KL FAMO) in Torun
- Torun Center for Astronomy Nicolaus Copernicus University located in Piwnice
- Center for Physical Sciences and Technology (FTMC) - Lithuanian NMI located in Vilnius provides UTC (LT)
- AGH University of Science and Technology in Krakow
- Jagiellonian University in Krakow

5 Conclusions

T&F service distribution is at a turning point as the early successes of the first optical link deployments have brought this new service under the spotlight, and have aroused great interest in T&F distribution, especially from European NMIs, but also to a wide range of potential end users connected to the GÉANT and NREN network infrastructures.

This white paper aims to provide key understandings of the distribution of these new T&F services and, through reviewing the experiences and lessons learnt by the GN4-3 OTFN team, is meant to help network and DWDM engineers in the GÉANT community in determining their approach to setting up T&F service distribution in close collaboration with their local NMI.

While network operators are likely to be looking for ways to exploit their fibre infrastructure more efficiently (and especially their optical spectrum) with new offers (bandwidth capacity, alien waves, and new applications such as Quantum Key Distribution, QKD), implementing T&F services is likely to be an important part of that process, resulting in a win-win scenario.

This document has provided an overview of the different approaches available to distributing T&F services on NREN infrastructures, covering the metrology requirements, hardware building blocks and the different architecture options for distribution over dedicated dark fibre or using shared fibre for data. It highlighted the fact that a close collaboration with local NMIs and an end-user driven approach are essential. It concluded by showing examples of four T&F deployments on the NREN networks of participants in the GN4-3 project WP6 OTFN team.

In practice, it should be kept in mind that a chosen solution is usually a balance between performance (which transfer technique to use), the desired architecture (dark channel, dark fibre, frequency), and the available budget to implement a suitable T&F service for an organisation and its end-users.

One takeaway of this document is that there is as yet no single approach to T&F service distribution that is favoured by all NRENs, including GÉANT, and, therefore, more discussion and dialogue is needed to both raise the level of knowledge and understanding of the related technologies, and to consider how differently implemented T&F services may be interconnected at appropriate locations.

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Glossary

ADEV	Allan Deviation
DCN	Data Circuit Network
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fibre Amplifiers
ELSTAB	Electronically Stabilised
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ILA	In-Line Amplifier
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union, Telecommunication Standardisation Sector
km	kilometre
LPL	Laboratoire de Physique des Lasers
MDEV	Modified Allan Deviation
METAS	Swiss National Metrology Institute
MU	Measurement Uncertainty
NMI	National Metrology Institute
NMS	Network Management System
NOC	Network Operations Centre
NREN	National Research and Education Network
NTP	Network Time Protocol
OADM	Optical Add/Drop Multiplexer
OSi	Open System Interconnection
OTFN	Optical Time and Frequency Network
PoP	Point of Presence
PTB	Physikalisch-Technische Bundesanstalt
PTP	Precise Time Protocol
QKD	Quantum-Key Distribution
R&E	Research and Education
RF	Radio Frequency
RLS	Repeater Laser Station
SFP	Small Form-factor Pluggable
SNMP	Simple Network Management Protocol
SyncE	Synchronous Ethernet
T&F	Time and Frequency
TDEV	Time Deviation
TRL	Technology Readiness Level
TTA	Time Transfer Adapter
WDM	Wavelength Division Multiplexing

WP	Work Package
WR-PTP	White Rabbit with Precise Time Protocol