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Strategy and innovation for clock services over optical-fibre networks

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Fibre-based time and frequency transfer techniques

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	Contributors:	Anne Amy-Klein, UP13 Eva Bookjans, OBSPARIS Davide Calonico, INRIM Trinidad García, SEVENSOLS Przemysław Krehlik, AGH Jochen Kronjäger, NPL Elisabeth Laier English, NPL Paul-Eric Pottie, OBSPARIS Harald Schnatz, PTB Vladimir Smotlacha, CESNET Anne Tampellini, INRIM Philip Tuckey, OBSPARIS Josef Vojtěch, CESNET Peter Whibberley, NPL
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LIST OF ACRONYMS AND ABBREVIATIONS

ADEV	Allan Deviation
AM	Amplitude Modulation
AOM	Acousto-Optic Modulator
AOS	Astrogeodynamical Observatory in Borowiec near Poznan, Poland
APC	Angled Physical Contact
BEV	Bundesamt für Eich- und Vermessungswesen, Austria
BIPM	Bureau international des poids et mesures
CERN	Conseil Européen pour la Recherche Nucléaire
CLONETS	CLOck NETwork Services: Strategy and innovation for clock services over optical-fibre networks Project
CW	Continuous Wave
DWDM	Dense Wavelength Division Multiplexing
EC	European Commission
EDFA	Erbium Doped Fibre Amplifier
ELSTAB	Electronically Stabilized
FM	Frequency Modulation
GbE	Gigabit Ethernet
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUM	Central Office of Measure in Warsaw, Poland
IPE	Institute of Photonics and Electronics, Czech Republic
ISO	International Organization for Standardization
ITU	International Telecommunication Union
KM3NET	Cubic Kilometre Neutrino Telescope
LDV	Link Design Value
LPF	Low Pass Filter
LPL	Laboratoire de Physique des Lasers, France
MADEV	Modified Allan Deviation
METODE	MEasurement of TOtal DElay
NTP	Network Time Protocol
OADM	Optical Add-Drop Multiplexer
OEO	Opto-Electro-Optical
OPLL	Optical Phase Locked Loop
OSI	Open System Interconnection
OTN	Optical Transport Network
PM	Phase Modulation
PMD	Polarization Mode Dispersion
PPP	Precision Point Positioning
PPS	Pulse per Second
PTP	Precision Time Protocol
RF	Radio Frequency
RLS	Repeater Laser Station
ROADM	Reconfigurable Optical Add Drop Multiplexer
SATRE	Satellite time and ranging equipment
SDH	Synchronous Digital Hierarchy
SFP	Small Form Factor Plugable
SOA	Semiconductor Optical Amplifier
SPBA	Single Pass Bidirectional Amplifier
SyncE	Synchronous Ethernet

SYRTE	Systèmes de Référence Temps-Espace, France
T/F	Time and Frequency
TDEV	Time Deviation
TIC	Time Interval Counter
TRL	Technology Readiness Level
TWOTT	Two Way Optical Time Transfer
TWSTFT	Two Way Satellite time and Frequency Transfer
UTC	Coordinated Universal Time
VLBI	Very Long Baseline Interferometry
WP	Work Package
WR	White Rabbit
WSI	Wavelength Selective Isolator

LIST OF PROJECT PARTNER ACRONYMS

AGH / AGH-UST	Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie, Cracow, Poland
CESNET	CESNET, zájmové sdružení právnických osob, Prague, Czech Republic
CNRS*	Centre National de la Recherche Scientifique, Paris, France
INRIM	Istituto Nazionale di Ricerca Metrologica, Turin, Italy
GARR#	Gruppo per l'Armonizzazione delle Reti della Ricerca, Rome, Italy
Menlo	Menlo Systems GmbH, Martinsried, Germany
Muquans	Muquans, Talence, France
NPL	National Physical Laboratory, Teddington, United Kingdom
OBSPARIS¶	Observatoire de Paris, Paris, France
OPTOKON	OPTOKON a.s., Jihlava, Czech Republic
Piktime Systems	Piktime Systems sp z o.o., Poznan, Poland
PSNC	Instytut Chemii Bioorganicznej Polskiej Akademii Nauk – Poznańskie Centrum Superkomputerowo-Sieciowe, Poznan, Poland
PTB	Physikalsch-Technische Bundesanstalt, Braunschweig, Germany
RENATER	Groupement d’interêt Public pour le Reseau National de Telecommunications pour la Technologie, l’Enseignement et la Recherche, Paris, France
SEVENSOLS	Seven Solutions S.L., Granada, Spain
TOP-IX#	Consorzio TOrino Piemonte Internet eXchange, Turin, Italy
UCL	University College London, London, United Kingdom
UP13	Université Paris 13, Villetaneuse, France
UPT AV CR (ISI)	Ustav Pristrojove Techniky AV, v.v.i., Brno, Czech Republic

* linked third party to OBSPARIS
# third party to INRIM
¶ coordinator

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EXECUTIVE SUMMARY

This document is the result of the work done in Task 1.3 of Work Package 1 of the CLONETS project, and is deliverable 1.5 of that project.

It provides a comprehensive overview of the state of the art and future prospects of high-performance techniques for time and frequency (T/F) transfer over optical fibre, developed over approximately the past 15 years. It provides a basis for identifying the likely key T/F transfer techniques of the future for various applications. It explains the requirements and constraints associated with these techniques, with the objective of allowing network architects and telecommunications equipment developers to understand the implications of their integration into optical fibre telecommunications networks.

In particular it includes the following material:

- a brief and general discussion of T/F transfer and of the associated optical signal types
- a conceptual, layer-based model of a general optical fibre T/F transfer link
- basic communication link layer concepts:
  - bi-directional (single-fibre), and uni-directional (dual-fibre) links
  - dark fibre, dark channel, DWDM approaches
- the physical origins of delays and distortions in T/F signal transmission
- compensation methods for link delay fluctuations: active, two-way, protocol-based, ...
- T/F signal amplification and regeneration
- multi-point T/F signal delivery
- a survey of the available implementations of these methods, including their characteristics such as performance levels, achievable link lengths, TRL, ...
- the interoperability of different methods
- general approaches to combining techniques to build up networks.

This document demonstrates the existence of a variety of T/F transfer techniques over optical fibre. Some are still in active development while others are already commercially available. Taken together they cover a range of applications, from high-performance signal distribution for a moderate number of users, to extreme performance, point-to-point links, over distances of up to thousands of km. Bi-directional links are needed to reach the highest performance levels, usually using a dark fibre or dark channel implementation, while uni-directional, dual-fibre links can also achieve very good performances. The interactions of these methods with optical fibre telecommunications links are well understood and demonstrated, and implementations are available for a variety of network configurations and conditions. Finally, methods for interoperability among these T/F transfer techniques exist, allowing them to be assembled into extended networks.

1 INTRODUCTION

Over the last two decades optical fibres have not only been employed for high-speed telecommunications, but have also been recognized as a convenient and reliable medium to convey time and/or frequency (T/F) reference signals. Research in this field has sped up substantially with the advent and success of optical clocks, a growing field of research throughout the world with an increasing demand for more stable links. The fractional instability of such clocks has reached the low 10^{-18} ([1]-[4]), requiring adequately "quiet" and stable links for the dissemination of clock signals to distant locations without a significant degradation of the relative frequency stability [5]. Optical fibre links are currently the only viable solution for such applications and the use of optical clocks in modern metrology.

Currently most applications requiring precise timing signals receive them through global navigation and satellite systems (GNSS), like Global Positioning System (GPS) or Galileo. There are, however, numerous applications of T/F transfer within research infrastructures that require a performance beyond the capabilities of GPS disciplined local oscillators, such as very-long-baseline interferometry (VLBI) and geodetic applications. Additionally, the transfer of T/F reference signals over fibre links has been motivated by applications performed in locations outside the range of satellite signals. Prominent examples include large particle accelerators such as CERN, array of detectors such as KM3NeT neutrino telescopes and so called "urban canyons" in densely populated and built-up areas.

The dissemination of T/F reference signals via optical fibres is increasingly considered as a viable alternative to more traditional techniques, based on GNSS, often exploited in the telecom industry. Apart from providing a better stability, signals delivered by optical fibres are practically immune to jamming or spoofing, unlike satellite signals. The role of accurate time transfer is expected to grow in the near future - modern telecom services (5G), smart grids, autonomous cars, time stamping, etc. require it. In all these cases, the security and the reliability of the timing signals are critical issues - optical fibre T/F links can provide this, and in some cases at a reduced cost. The features that justify using optical fibres in T/F metrology are equally relevant to telecommunications. An optical fibre is a transmission medium that is well isolated from any external electromagnetic interference and offers a high bandwidth and a low loss. Therefore it has the capacity to span distances tens of kilometres long without the need of regeneration. Thanks to the guided propagation, the pathways are unambiguous. In consequence, fibre links easily outperform satellite based methods.

A crucial and important characteristic of optical fibres, nonetheless rarely exploited in the telecom world, is their ability to transmit signals bi-directionally with nearly identical conditions for each of the counter-propagating signals. Thanks to this feature, phase noise, or equivalently propagation delays, caused by varying external conditions, such as temperature fluctuations or mechanical stress, can be compensated for by properly designed fibre links (possible schemes are discussed in Section 2; origins of fibre-related noise are discussed in Section 2.7). If larger distances are required, a number of possible amplification/regeneration schemes exist that are compatible with bi-directional transmission – these are briefly discussed in Section 3. In Section 4, we discuss the equipment necessary to build a multi-user network, network topologies, and practical implementations of T/F transfer techniques. We present a global vision for future T/F transfer networks in Section 5.

This report describes various optical fibre T/F transfer techniques, developed by laboratories and companies, for user-end terminals and for in-field amplification and regeneration. These techniques mainly focus on metrological applications and/or the synchronization of local area networks, although some could possibly also find industrial applications. The purpose of the report is to briefly explain their operational principle and point out possible applications in a network delivering T/F reference signals to various kinds of users. Performance metrics of the described techniques will also be presented. In this report, we distinguish several layers (see

Section 2) within an optical fibre link used for T/F transfer and propose a coherent naming convention.

2 FIBRE OPTIC T/F TRANSFER

A T/F '*transfer'* is a scheme, which allows sharing time or frequency information between different sites. In optical fibre links, the information is encoded in a light signal and transmitted through an optical fibre. The purpose of the transfer may be either to compare two sources (i.e. to determine possible difference of their frequencies or offset of generated timescales) or to deliver T/F from the local to the remote side (i.e. create a 'copy' of the T/F signal there). In this second case of transfer only one T/F source is involved, whereas in the first case two sources are necessary. Both these approaches are not totally exclusive, but in general a system designed for comparison only cannot be used for delivery, whereas the opposite is perfectly possible.

Due to the finite propagation speed of the light traveling inside the optical fibre, the information on the T/F signal reaches the distant end of the link with a delay (about 5 μs/km). At this point one should clearly distinguish between the transfer of frequency and the transfer of time.

A **frequency transfer** through an optical fibre link is usually performed by transmitting a sinusoidal signal. To ensure a *perfect* transfer, the propagation delay fluctuations have to be determined and compensated for, otherwise the transfer will suffer from phase/frequency noise and shifts. This compensation may work either in real time or be performed off-line using further post-processing of measured data.

For **time transfer**, however, this is not sufficient. For a *perfect* transfer the relation between the timescales at both ends of the link has to be known, i.e. it also is necessary to know the absolute value of the propagation delay introduced by the transfer system. Additionally, the time reference signal has to allow for an unambiguous pinning down of the time. For this purpose, typically one pulse per second (1 PPS) is used. Its sharp, leading edge is synchronized with the local realization of UTC (i.e. the delay between 1 PPS and UTC is known). The rule is: the sharper the edge of the 1 PPS signal, the lower the ambiguity of the time instant defined by 1 PPS. Consequently, such signals occupy a substantial bandwidth (about 1-10 GHz). Due to the greater constraints on time transfer, a system specifically designed for optical frequency transfer cannot necessarily serve as a time transfer system, whereas the inverse is possible.

These general concepts related to the transfer of time/frequency are summarized in the table below.

	Frequency transfer	**Time transfer**
Typical signal type	Sinusoidal	Pulse with a sharp edge (e.g. 1 PPS)
Typical bandwidth of the signal	1 Hz to 10 GHz	1 GHz – 10 GHz
Propagation delay	is kept constant (actual value not important)	is kept constant, measured, and compensated for
Propagation delay fluctuations	compensated for	compensated for

Table 1. Summary of the general concepts of T/F transfer.

2.1 Nature of T/F signals

Various fibre T/F transfer techniques employ various different signals to convey the required information on time and/or frequency. These can be:

- light (CW) from an ultra-stable laser, without any kind of modulation. The information is carried by the frequency of the photon itself. The occupation bandwidth is less than 1 Hz; the injected power is typically below 1 mW.
- modulated laser light. The laser light plays the role of the carrier and by modulating the light (using e.g. amplitude, phase or frequency modulation (AM, PM or FM)) the information is imprinted onto the light signal. The occupation bandwidth ranges from 10 MHz to 10 GHz; the injected power is typically below 1 mW.
- a data transfer. The information is formatted into packets. Transmission is in principle independent of the physical layer (copper wire or optical fibre), but some techniques may require specific physical layer attributes to work properly and achieve their full performance.

Note that both CW and modulated laser light typically conform to ITU recommendations (e.g. ITU-T G.698.2) and should therefore not disrupt data traffic carried in the same fibre. However each operator will have his or her own respective restrictions, which will have to be respected when implementing T/F fibre links within a fibre telecom infrastructure.

2.2 Conceptual model of a fibre T/F link

At some abstraction level a conceptual model of a fibre optic link for T/F transfer may be proposed. The T/F information is shared between two distant places, here referred to as the *'local side'* and the *'remote side'*, and the required metrological functions are conveniently grouped into a few logical layers (see Figure 1).[1]

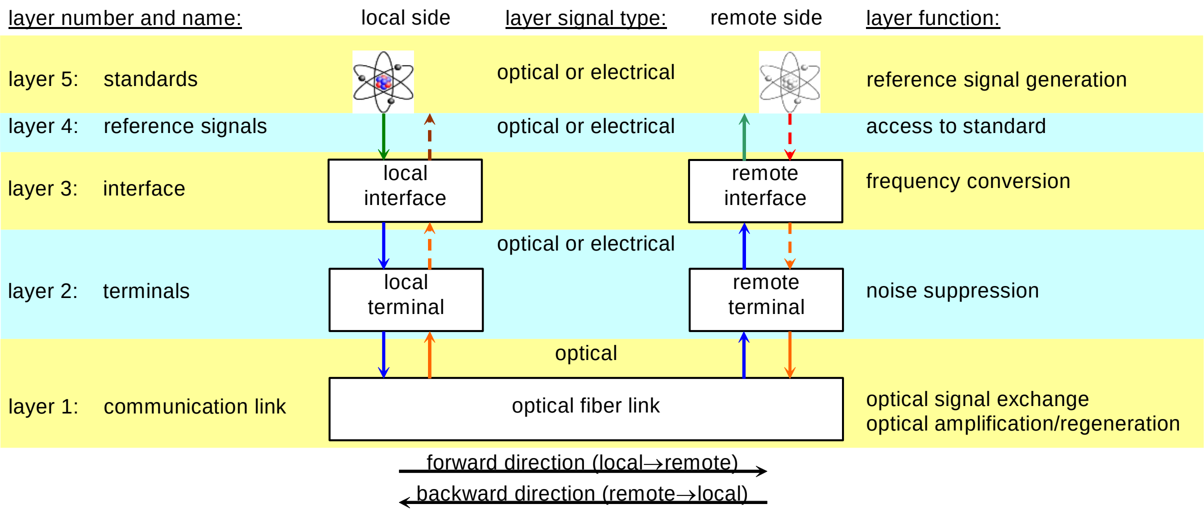


Figure 1. Conceptual model of a fibre optic link for T/F transfer.

Layer 1: *communication link*. The lowest layer of any fibre optic T/F transfer link (named '*communication link layer*') is the medium (i.e. the optical fibre, filters, multiplexers, amplifiers etc.) through which the optical signals are transmitted and exchanged. In this report, we only consider single-mode fibres and optical signals that are located in either the so-called C-band (1530-1565 nm) or the L-band (1565-1610 nm), corresponding to low-loss window of the fibre. For long-haul communication link layers, optical components or systems besides the optical fibre become essential. In particular, amplifiers/regenerators, which we describe in more detail in Section 3. Usually (with exception of the rare cases, for which the user of the T/F transfer link has its own optical fibre infrastructure), an external network operator will provide access

[1] The concept of layers has been borrowed from a well-known ISO-OSI Reference Model (RM), however the model discussed herein is related to the realization of specific metrological functions. As this requires direct access to the physical layer, this model may be regarded as a specific extension of Layer 1 of ISO-OSI RM. The main purpose of this model is to provide clear definitions of various concepts used in fibre optic T/F links.

to the communication link layer, either in form of a dark fibre, a dark channel, or Dense Wavelength Division Multiplexing (DWDM) channel (see Section 2.3.2).

Layer 2: *terminals*. The layer named '*terminals layer*' consists of two pieces of equipment (one piece at each the local and remote side), called 'terminals', which generally include both optical and electronic components. The terminal layer is responsible for supplying the physical fibre optic communication layer with *ad-hoc* signals. It deals with signal emission, reception, and processing, in order to suppress fibre related noise. Depending on the particular application, the input/output signals of these terminals are either optical, electrical, or both. In large T/F transfer networks, a terminal can take on the form of a node, i.e. a piece of equipment that is capable of serving several users from one input signal (see Section 2.5 for details).

Layer 3: *interfaces*. The layer named '*interface layer*' converts the signal from the reference source to an appropriate T/F reference signal prior to sending it through the transfer link. For example, optical clocks usually operate in the visible part of the optical spectrum. It is therefore necessary to phase coherently shift the wavelength of the optical clock reference signal (the T/F reference source) to the C-band, L-band, or into the RF domain. For this purpose, optical frequency combs are crucial. This layer is not present in all cases depending on the reference source.

Layer 4: *reference signals*. The '*reference signals layer*' corresponds to the physical place where the transfer system accesses signals produced by the T/F reference source. Depending on the particular application, the input/output signals to these terminals are either optical, electrical, or both.

Layer 5: *standards*. The *'standards layer'* is responsible for the physical generation of T/F reference signals, either in the optical, electrical, or both domains. It can include optical clocks, atomic fountain clocks, etc.

These last three layers (i.e. interfaces, reference signals and standards) are part of an effective T/F transfer link, and are therefore mentioned here for sake of completeness only. The operation of combs and clocks are not discussed, as they are out of the scope of this document.

2.3 Communication link layer

In this section, we present the different types of architectures of the communication link layer which are used for T/F transfer. We establish a common naming convention for the different architectures and techniques, point out the important differences between them and highlight their advantages and disadvantages.

2.3.1 Propagation of optical signals

In general, a fibre optic T/F transfer link uses the communication link layer in two directions (forward and backward) in order to optimally suppress fibre related noise. In such a link, a single fibre operates:

- *'bi-directionally'* – both forward and backward signals propagate simultaneously in the same optical fibre; **one fibre is sufficient** for the operation of a T/F link (preferred option);
- *'uni-directionally'* – inside a single fibre only one signal is propagated, either in the forward or the backward direction; **two fibres are required** for the operation of a T/F link, one for each separate propagation of the forward and the backward signal, respectively.

Comments:

The bi-directional propagation is certainly the best possible option for the highest-performance T/F fibre links, because it ensures the greatest possible correlation of the phase fluctuations in both forward and backward directions.

Uni-directional propagation can still ensure a relatively good noise correlation between counter-propagating directions, if the two fibres run in the same fibre cable. In this case, the two fibres are exposed to very similar thermal and mechanical conditions and the correlation remains high, especially in the long term. However, in this approach there is an inherent delay asymmetry between the forward and backward paths that is practically impossible to predict or manage. The difference of propagation delays resulting from the distinct routing that occurs when patching the fibres can easily reach a level of tens of ns or even higher, when it is necessary to pass optical signals through optical components, such as multiplexers, filters, splitters or optical amplifiers. Therefore the best accuracy budgets are achieved with a bi-directional operation.

Bi-directional propagation is essential for the highest stability and accuracy, metrological-level T/F transfer. Uni-directional T/F transfer often is sufficient for modest accuracy requirements. It can be either a more accurate, more reliable, or potentially a cheaper option for applications traditionally relying on GNSS transfer.

2.3.2 Type of communication link layer

For T/F transfer the communication link layer can be classified as:

- a *'dark fibre'* – the entire fibre link, including both the fibre and the optical equipment, is exclusively dedicated to the transfer of a T/F reference signal. The fibre link is not part of any telecom network and therefore is not used for any telecom service (i.e. data transmission). In this case, specific bi-directional optical equipment is installed for the T/F transfer (see Figure 2).
- a *'dark channel'* – a slice of the optical spectrum within a fibre is dedicated to the transfer of a T/F reference signal. The fibre through which the T/F signal travels is usually part of a DWDM telecom network. The fibre is used for both telecom services and for T/F transfer. However, the existing telecom equipment (amplifiers, access points, etc.) is bypassed and specific bi-directional optical equipment is installed, exclusively dedicated to the T/F transfer (see Fig. 3).
- a *'DWDM channel'* – similar to a dark channel, a slice of the optical spectrum within a fibre is dedicated to the transfer of a T/F reference signal with the difference that the (or some) telecom equipment (amplifiers, reconfigurable optical add-drop multiplexers – ROADMs, etc.) is used to carry the signals associated with T/F transfer. As most telecom networks operate fibres uni-directionally, DWDM channels are generally also uni-directional (see Figure 4).

Comments:

The dark fibre (see Figure 2) approach has the advantage that the fibre link is solely dedicated to the T/F transfer and consequently, does not pose a risk to data traffic. The T/F transfer can be implemented quickly and can be specifically optimized for the T/F application without having to consider whether any data traffic is perturbed. Therefore a high stability and/or accuracy of the T/F transfer can readily be achieved. To fully exploit its potential, dark fibres are operated bi-directionally. It is important to note, that this approach is generally the most expensive option and, in practice, is not always possible because the fibres are not always made available by the network operators. For links longer than about 100 km, the attenuation in the fibre becomes large enough to require the implementation of bi-directional amplifiers and/or regenerators (see Section 3). Additionally, a supervision/monitoring channel has to be set-up for the remote management of the employed optical equipment, further increasing the complexity, set-up time, and cost of the fibre link.

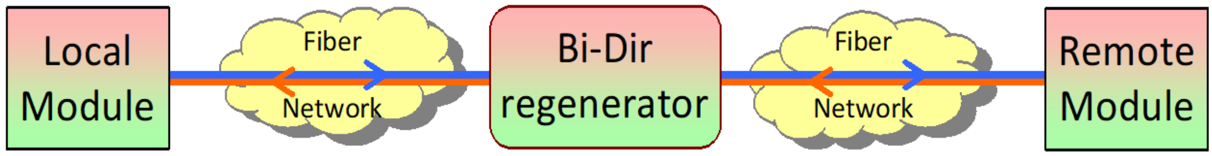


Figure 2. T/F transfer link using a dark fibre approach.

The dark channel approach (see Figure 2) is more difficult to implement, but is more cost effective, as it requires only a slice of spectrum in a fibre already loaded with regular telecom traffic. The mutualisation of the fibre leads to a drastic cost reduction. As of today, dark channels are mostly used bi-directionally. This creates a very untypical situation for telecom networks, where fibres are used almost exclusively in pairs, with separate fibres designated for each propagation direction. In principle there is no specific contradiction in using a dark channel bi-directionally, proven by successful implementations, which have been operating without trouble for almost ten years in France [6]. However, a close active partnership with the network operator is mandatory when implementing dark channel T/F links.

Implementation of dark channels requires a modification of the existing telecom network through the insertion of additional optical filters (optical add-and-drop multiplexers - OADM). For links longer than 100 km, these filters have to be added not only at the local and remote sides, but also in all points along the link where any telecom access/regeneration equipment is installed, as this telecom equipment is not compatible with a bi-directional propagation. For long-haul links, bi-directional amplifiers and/or regenerators must be implemented. In contrast to the dark fibre approach, the bi-directional equipment must satisfy the requirements specified by the network operator. It is important to stress that the bi-directional dark channel approach can provide the same, highest stability/accuracy of T/F transfer the dark fibre approach, although its implementation is more complex.

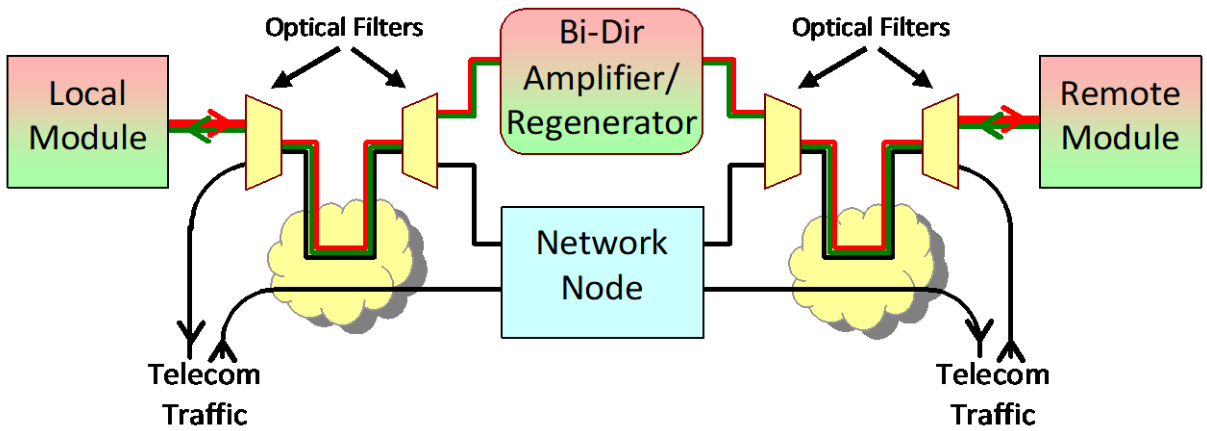


Figure 3. T/F transfer link using a dark channel approach.

The dark channel approach can be implemented in DWDM networks using "old" technologies, which convert optical signals to electrical ones and vice versa (i.e. opto-electro-optical (OEO) conversion) at each network node (e.g. synchronous digital hierarchy (SDH) or optical transport network (OTN)), as well as in modern optical DWDM networks, where an all optical signal path can be established between the sender and the recipient. Private telecom operators may perceive this approach as inconvenient and undesirable out of fear of potential interruptions of, or interference with, live telecom data traffic. They can remain hesitant to allow an 'alien' signal, which they do not directly control, to pass through the telecom network.

The *'DWDM channel'* approach[2] uses a slice of the optical spectrum in an optical DWDM network while passing the T/F signals through all (or part of in some cases) the optical telecom equipment (see Figure 4). In comparison to the dark channel approach, the constraints are higher here as the power of the T/F signal has to be kept constant and is not independent of the gain settings of the telecom equipment used to pass the data traffic. This approach is possible in modern DWDM networks only, where no OEO conversion takes place.

The advantage of this approach is that the burden of optical amplification is shifted to the network operator as both the fibre and the amplifiers/regenerators are mutualised. Due to the shared infrastructure, the cost of a DWDM channel is highly reduced. The price to pay is an unknown and unpredictable asymmetry in the delays, because the DWDM channel cannot be operated bi-directionally. An unquestionable advantage of the DWDM channel approach is its availability and the highly reduced costs – in practice it might often be the only option possible. This approach is also very flexible – a connection between any two points of the network can be arranged and changed dynamically i.e. "on demand". Additionally, a DWDM channel is optically transparent, so that the same optical path can be used to convey T/F signals, i.e. an optical carrier and RF signals without requiring changes to the network.

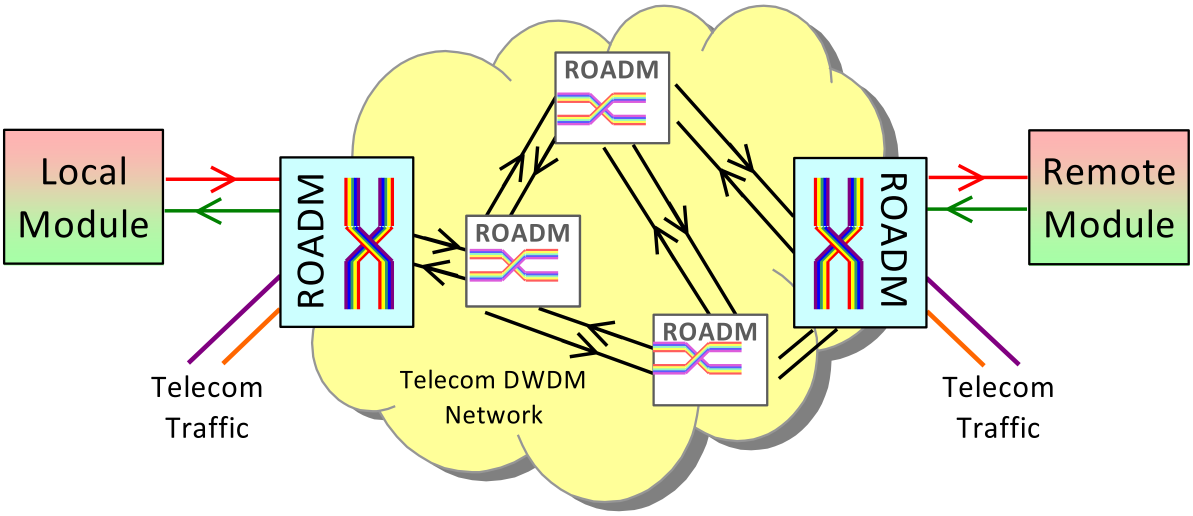


Figure 4. T/F transfer link using a DWDM channel approach.

2.4 Terminals layer

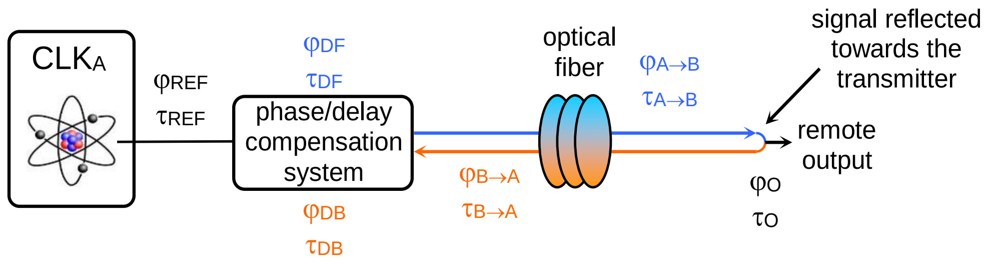
The terminals layer receives the signals from atomic standards and is responsible for their conversion to the optical domain (if necessary, as it is the case for signals from caesium clocks) and providing means to compensate fibre-related noise. For the compensation there are four general schemes which will briefly be presented here. All of them are based on exploiting the symmetry of the counter-propagating directions in an optical fibre.

2.4.1 Active compensation

'Active compensation', as its name implies, relies on correcting fibre-introduced fluctuations by inserting an appropriate correction (in either optical or electrical domain) into the signal path. The correction is based on a feedback loop, which drives a phase error between the signal from the reference and the round-trip signal (i.e. the signal reflected from the remote terminal) to zero. Depending on the realization, an actively compensated system can stabilize either the

[2] The term *'DWDM channel'* may sometimes be identified with *'alien lambda', 'alien wavelength' and 'photonic service'*. All these terms have a similar meaning, although their usage and definitions have not been fully agreed on, yet. In our context the term '*DWDM channel'* is used to describe the transmission of specific T/F signals, that are in general different from standard telecom signals (i.e. they do not form digital data contained in packets), through a single channel of a DWDM telecom network. Other CLONETS documents may use different naming conventions.

phase or the group delay at the output of the transfer link relative to its input (see Figure 5 for details). Such a system can thus be used to deliver ('distribute' or 'disseminate', as it is also called) a local clock signal to some distant location.



<u>*phase stabilization:*</u>

$\varphi_O = \varphi_{REF} + \varphi_{DF} + \varphi_{A\to B}$

$\varphi_{RT} = \varphi_{DF} + \varphi_{A\to B} + \varphi_{B\to A} + \varphi_{DB}$

if $\varphi_{RT} = 0$ (kept by feedback) then

$$\varphi_O = \varphi_{REF} + \left.\begin{array}{l} + (\varphi_{DF} - \varphi_{DB})/2 + \\ + (\varphi_{A\to B} - \varphi_{B\to A})/2 \end{array}\right\} \cong 0$$

<u>*delay stabilization:*</u>

$\tau_O = \tau_{REF} + \tau_{DF} + \tau_{A\to B}$

$\tau_{RT} = \tau_{DF} + \tau_{A\to B} + \tau_{B\to A} + \tau_{DB}$

if $\tau_{RT} =$ *const.* (kept by feedback) then

$$\tau_O = \tau_{REF} + \tau_{RT}/2 + \left.\begin{array}{l} + (\tau_{DF} - \tau_{DB})/2 + \\ + (\tau_{A\to B} - \tau_{B\to A})/2 \end{array}\right\} \cong 0$$

Figure 5. Dissemination of reference signals in a phase/delay stabilized link.

Active compensation is an on-line, real time service, not requiring any post-processing. Thus this technique can be interesting for users requiring access to stable signals from atomic standards, but simultaneously prefer not to operate their own clocks and bother with synchronizing them with other clocks around the world. A fibre link with a known, stabilized propagation delay can be used for time and frequency transfer, whereas a link with a stabilized phase can be applied for frequency transfer only.

2.4.2 Phase conjugation

A *'phase conjugation'* is a feed-forward technique (sometimes described as passive) that can be exploited for an RF frequency transfer over an optical fibre. The idea (see Figure 6) is to use a probe signal (derived from the main transmitted signal) to sense the phase fluctuations introduced by fibre and then use this phase to pre-distort the main signal transmitted over the same fibre. This pre-distortion signal (φ_{COR} in Figure 6) is obtained by frequency mixing the probe signal after its round-trip inside the fibre with the main signal. As the frequency mixing results in a subtraction of phases it is possible to obtain φ_{COR} opposite to φ_F by making the main frequency twice the probe frequency. As the accumulated phase noise is directly proportional to the frequency of the signal, the phase accumulated by the round-trip signal will be exactly equal to the phase accumulated by the main signal propagating in one direction only. There are many variations of this technique that differ in the number of signals propagating in the fibre (in some implementations only two signals are required instead of three) and the particular approach to generate the compensation signal.

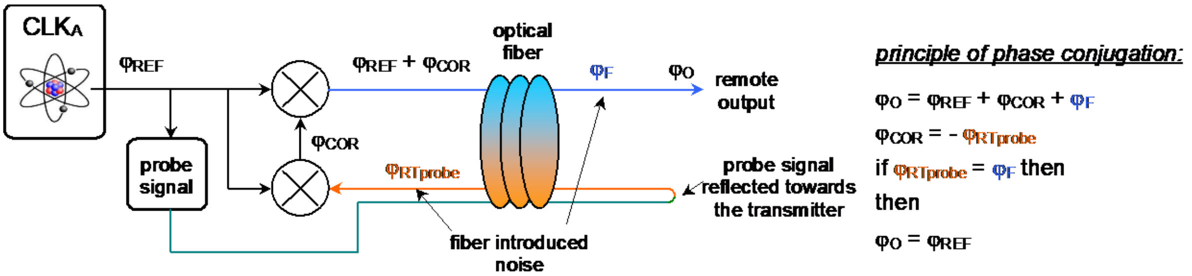


Figure 6. Passive compensation based on phase conjugation.

The phase conjugation technique is adequate for an RF frequency distribution only (i.e. no time transfer is possible), but has some advantages compared to the active compensation. This is because an actively compensated link requires exactly the same amount of phase shift to be introduced in both the forward and backward directions (see formulas in Figure 7) and thus requires either optical variable delay lines that work bi-directionally, but have a very limited range and are bulky and power-hungry, or very closely matched phase shifters or electronic delay lines. With the phase conjugation approach, the compensation is performed at one place only, so no matching is required. However, the weak point is that phase conjugation is sensitive to crosstalk and any non-linearity of the optical and electronic components, which can ruin their potential performance.

The phase conjugation technique requires a very close coupling between the phase noise affecting both probe and main signals, so in practice it requires either a dark fibre or a dark channel operated bi-directionally.

2.4.3 Two-way compensation

The scheme called *'two-way comparison'*, is in fact a replica of a satellite technique, namely the two-way satellite time and frequency transfer (TWSTFT), applied to an optical fibre. This technique is applicable only when both locations are equipped with their own clocks, possibly generating their own timescale. To determine the relation between the involved clocks it is enough to exchange their signals between two sites and measure the difference between the local and distant clock at each end, using for example time interval counters (TICs). The reciprocity of the fibre allows the subtraction of the unknown propagation delay of the fibre through a post-processing of the data collected at the ends of the link, first exchanging it between the involved locations using some other communication channel (see Figure 7 for details). This is why the two-way comparison is an off-line service, not working in real time. The institutions that are the most interested in clock comparisons are T/F laboratories providing UTC signals and research teams involved in the development of optical clocks. When used with a dark fibre or a dark channel approach operating bi-directionally, this technique can be used to assess a time difference between two distant clocks; when operated uni-directionally a two-way comparison can be used to assess the relative stability only.

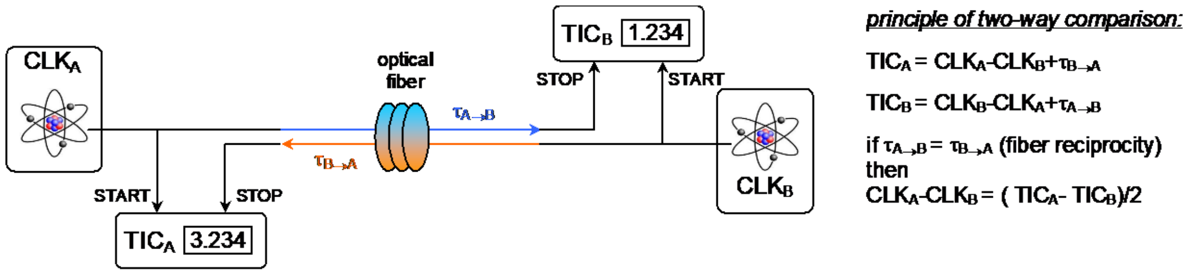


Figure 7. Clock comparison using transmission in a reciprocal fibre.

2.4.4 Protocol-based techniques

Apart from the techniques described above, which use dedicated hardware to compensate the fibre related phase noise, it is also possible to use specially designed communication protocols, operating for example over Ethernet to synchronize a number of slave clocks to a master. The advantage of using protocols is the ability to build massive multi-user dissemination systems.

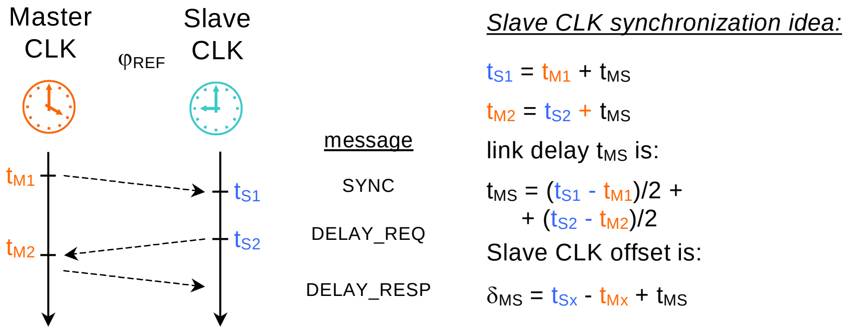


Figure 8. Network synchronization using a message exchange.

The general idea of such a system is based on two-way techniques - the exchange of messages between two involved clock domains containing information on their local timescales. As a result, the delay of the link connecting master and slave clocks (t_{MS}) can be computed at the slave or master side, as well as the slave clock offset (δ_{MS}). Using this offset the counter of the slave clock can be corrected to pace with the master. Because the philosophy of telecommunication networks is to transmit digital data in form of packets, which can be buffered inside hubs and routers (the buffering time is unpredictable and depends on actual network loading), the protocol-based techniques are dependent on a substantial support from specific hardware that has to be installed. Without such support the accuracy and stability will be severely limited. A well-known example of this principle is Network Time Protocol (NTP), which does not require any specific hardware and achieves a stability and accuracy at the microsecond level in the best possible case.

Comments:

All T/F techniques must propagate optical signals in both directions (either bi-directionally in a single fibre or uni-directionally in a pair of fibres) in order to suppress fibre-related fluctuations, i.e. phase noise or delay fluctuations distributed along the fibre. The suppression, however, is limited in both level and frequency range due to the finite propagation delay in the fibre and consequently is related to the length of the fibre. The detailed analysis is complex [7], however, making a rough estimation both bandwidth and suppression level are approximately two times higher in passive techniques (e.g. a two-way comparison or certain phase conjugators) compared to actively compensated links of the same length.

2.5 Multi-point T/F transfer and network nodes

Most of the ideas described so far, with the exception of protocol-based techniques, enable only point-to-point connections. In many situations, however, it may be necessary to supply stable T/F signals to multiple locations. Research infrastructures have developed a few designated solutions, which have been demonstrated either in a laboratory environment or in the field.

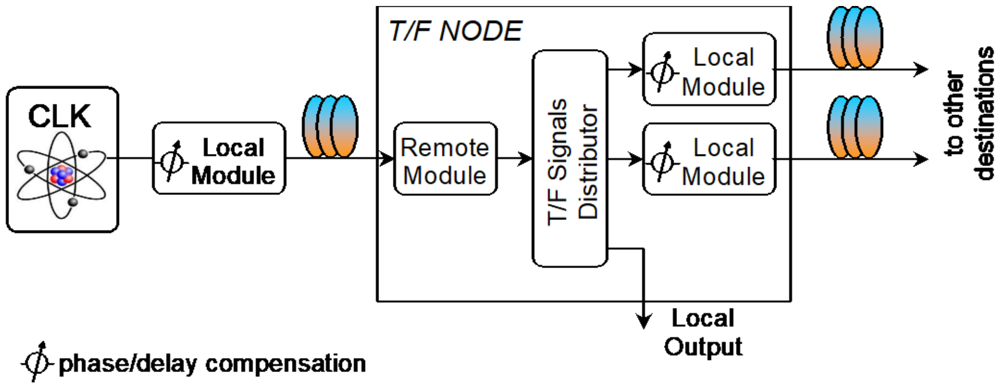


Figure 9. Multipoint dissemination of T/F signals based on a tree topology with a T/F hub.

The obvious scenario for a multipoint transfer is a multi-link structure with T/F nodes (or hubs) placed at key points of the network and serving other locations in a tree-like topology (see Figure 9). The advantage to such a solution is that it can service a large area and can easily be extended if necessary. The consecutive levels in this multipoint approach are connected in cascade. This structure is also very efficient and essential for a practical T/F dissemination, as it avoids having the reference laboratory signal propagate in as many links as there are end-users.

Another option often discussed in the context of multipoint links is a reconfiguration of the terminals, i.e. the shift of the compensation function from the local module to the remote one (see Figure 10). This, in general, can be done for any compensation scheme (active or passive), but it usually increases the complexity of the terminals substantially, as the propagating signal must pass the fibre three times, including the compensating circuitry.

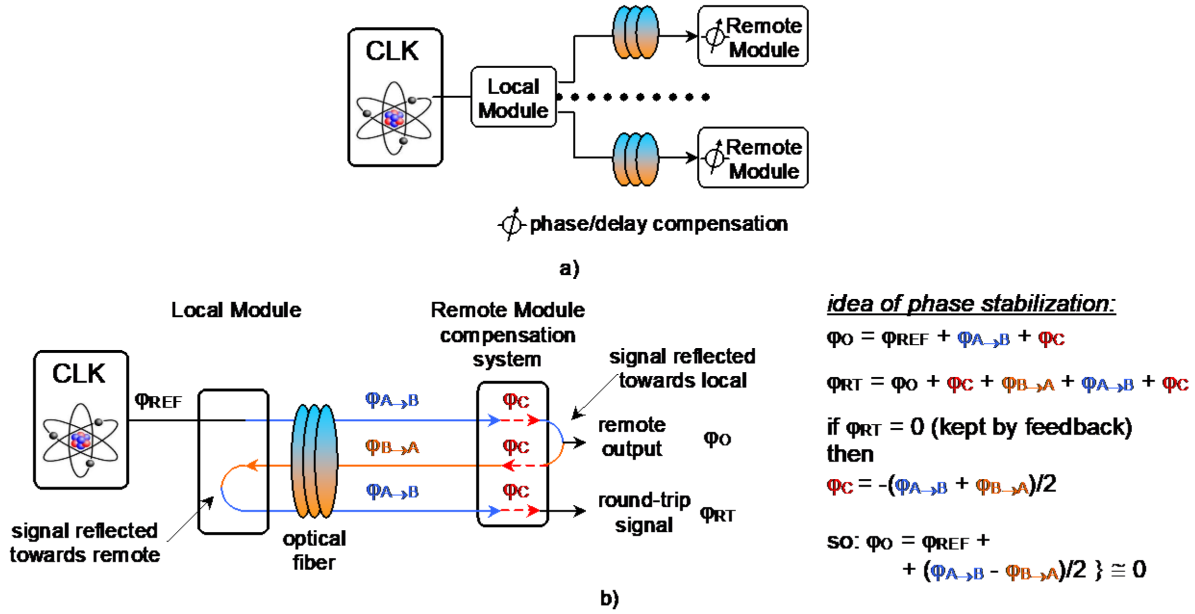


Figure 10. Multipoint dissemination of T/F signals with the phase/delay compensation functionality shifted to the remote side: the general idea (a) and the explanation of the phase stabilization in an actively compensated system (b). For simplicity, it has been assumed that the compensation received by each signal is the same (i.e. there is no mismatch).

A multipoint T/F distribution is also possible by inserting extraction (aka ‘tapping’ or ‘eavesdropping’ [8]) modules along the fibre connecting the local and remote modules (see Figure 11). This concept works because in a stabilized link the phases (as well as the delays) at the extraction point (located anywhere along the fibre) change in exactly opposite directions when observed for the forward and backward directions, respectively. Thus processing the extracted signals in such a way as to obtain the mean value of the phases (or delays) will result in stable signal at the extraction point.

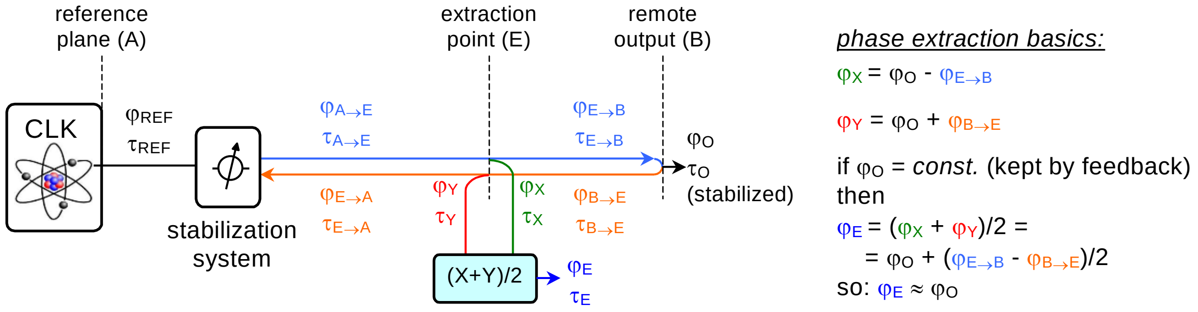


Figure 11. Illustration of an extraction of signals applied to a T/F transfer link. For simplicity, only extraction of phase-stabilized signals is shown; the idea will also work for extraction of calibrated time signals (i.e. delay stabilized).

The idea of the extraction presented in Figure 11 can be applied equally well to the extraction of an optical carrier, an RF frequency or time signal; their dissemination as a T/F service from one point to a few has been experimentally demonstrated.

Comments:

Cascaded transfer links (e.g. the multipoint dissemination scheme shown in Figure 9) offer an additional advantage due to the fact that the efficiency of the fibre-noise cancellation is inversely proportional to the fibre length (see the comment at the end of Section Terminals layer2.4). This technique is thus capable of increasing the effectiveness of the noise suppression, especially in long-haul links.

Shifting the compensation function to the remote module (see Figure 10) allows connecting multiple modules to a single local module, where the optical signal has been split into a few ports. However, the local module must ensure the reflection of the signal towards the remote module sending the signal. The wavelength of this reflected signal must be changed (by an optical frequency shifter or by using another laser) in order to avoid potential problems from Rayleigh backscattering and stray reflections from optical connectors. The simplest implementation of this concept can most likely be done in actively compensated transfer links for optical carriers and in passive conjugator systems. It could also be well suited for relatively short RF transfer links, where a change in optical frequency is not necessary.

The advantage of the extraction method (see Figure 11) is that theoretically any number of extraction points can be implemented within the limit of the optical budget. They can be added to existing links with minimal resources. Each extraction point can be a starting point of another link containing in its structure secondary extraction points, which in turn are starting points of a tree-like distribution network, and so on. There is a disadvantage, however, because in the case of a break in the main link (i.e. the link connecting the local and remote modules) the T/F signals are immediately lost at each extraction point. Thus, in comparison with separate simultaneously operating links, the reliability of this approach can be disputed, whereas the cost effectiveness is unquestionable.

2.6 Interoperability among T/F techniques

When building a larger T/F network there is, in principle, no obligation to use the same technique across the entire network. In many cases it may even be advantageous to mix available techniques to organize an efficient T/F transfer among many interested users or to introduce some level of redundancy (see ideas in Section 5). There are, however, some general and reasonable rules that should be followed. For example, the highest performance technique should always be used at the top of the network or in other words provide the backbone of the network. The output signals of this backbone then feed further links, which can rely on lower performance techniques. This scenario can be duplicated further down the network. However, in all cases the final delivered signal must match the end user needs.

Interoperability between various techniques is often either directly possible (e.g. for time signals or for RF signals), or can be implemented by adding specific equipment in the interface layer (see Figure 1). This may be e.g. a frequency synthesizer to convert one RF frequency into another, or an optical comb to convert between different optical frequencies or between optical and RF frequencies.

Various different T/F techniques have been developed to cover different requirements concerning the type of signal (optical, RF) and the necessary accuracy/stability levels (ranging from highest-level metrology to more modest industrial-oriented links). Thanks to the realizable interoperability between the techniques, efficient and hierarchical networks may relatively easily be implemented, satisfying various different T/F service needs.

2.7 Origins of fibre delay/phase fluctuations

All techniques developed and employed for the transfer of high accuracy and/or high stability T/F reference signals via optical fibre links are confronted with fibre related noise (phase/signal delay fluctuations) and need to provide means for its suppression. The purpose of this section is to briefly characterize the noise sources, in order to provide a better understanding of the current techniques developed for fibre optic T/F transfer.

The transmission of signals through any medium, including optical fibres, is to some extent susceptible to disturbances resulting from varying external conditions. In the case of fibres, the propagation delay of the signal (equivalent to an instantaneous phase or frequency change, and thus also referred to as 'Doppler noise') changes with temperature and due to mechanical stress. Similarly, the varying external conditions can influence the polarization of the light, which in turn can affect the propagation of the signal through the fibre. This phenomenon is referred to as polarization mode dispersion (PMD). This section gives a brief review of noise generating mechanisms in optical fibres, in particular in buried and aerial fibres.

Temperature affects the properties of the glass/silica constituting the optical fibre by changing its refractive index (thermo-optic coefficient) and its shape and length (thermal expansion coefficient). The thermal sensitivity of the signal delay of a single-mode fibre is around 35…40 ps/(km·°C) [9] and results mainly from the change in refractive index, as the thermal expansion coefficient is approximately 20 times lower than the thermo-optic coefficient, which for silica fibres is around 1.06×10^{-5}/°C ([10], [11]). The corresponding thermal phase sensitivity is about 8…9 ppm/°C. Due to the wavelength dependence of the refractive index, changes in temperature impact the chromatic dispersion (see below) contributing to additional phase/signal delay noise. Furthermore, temperature fluctuations lead to changes of the polarization and thus contribute to PMD (see below). Thermal effects typically become dominant after a few hours of measurement, because they are correlated with the diurnal fluctuations of the ambient air. They are large enough to make simple T/F transfer schemes, which do not implement fibre noise compensation schemes, unsuitable for the most advanced applications, in particular on larger length scales.

Buried fibre cables show a stability floor due to thermal fluctuations, measured as an Allan deviation (ADEV), for observation times longer than 1000 s. In the literature, values of around 10^{-14} - 10^{-15} at one second are quoted for underground uncompensated cables 100 km long. Using such connections one can expect delay fluctuations as high as a fraction of a nanosecond over one day and hundreds of nanoseconds seasonally.

Aerial cables are more strongly affected by temperature fluctuations due to the lack of thermal isolation guaranteed by the surrounding soil. ADEV plots therefore usually show large bumps correlated to the day-night periodicity of the ambient temperature.

Mechanical stress exerted on a fibre causes its distortion, deformation, and elongation (Hooke’s law). Besides changing the propagation delay, mechanical stress affects the polarization of the propagating light by deforming the fibre's core making it slightly elliptical. This deformation, although small, is large enough to induce a noticeable birefringence in the fibre (see the paragraph on PMD). Elongation resulting from axial tension (i.e. pulling) is of rather minor importance for underground fibre cables because of their rugged construction. The relative length changes of a bare fibre are, however, substantial, with typical values being around 1.28×10^{-3}/N [12]. This directly translates to a phase sensitivity on the order of 6 ps/(m·N) in fibre cables of lighter construction, such as patchcords and pigtails.

Other forms of mechanical stress, being importance for cabled fibres, are usually caused either by road/railway traffic for underground cables running along communication paths or by wind for aerial cables causing a swinging/quivering. Because such stress is random and distributed along the fibre its effect takes on the form of an effective phase noise. The spectrum of this noise is more or less stationary for road traffic, typically showing a peak near 20…30 Hz, which is most likely related to the mechanical properties of the soil (sometimes peaks at higher frequencies are also visible). For cables running along railway tracks and aerial cables, the noise is generally time-dependent and related directly to the railway timetable and weather conditions, respectively. Seismic waves have also been observed as sources of noise [13]. These effects account for so-called acoustic noise. It is dominant at short measurement times, but nicely averages out with time. Acoustic noise is a limiting factor for the most demanding applications, which require an ADEV below 10^{-12} at a 1 s averaging time.

A general observation is that aerial fibres display the largest phase noise, whereas the quietest, and thus the best suited for the transfer of T/F reference signals are underground cabled fibres. The farther the cabled fibres are from railway tracks or motorways, the better, whereby motorways contribute to significantly less noise compared to railways.

Polarization: as it has already been mentioned, mechanical stress affects the polarization of the light propagating along the fibre because stress introduces a deformation of fibre's core making it slightly elliptical. This deformation, although small, is large enough to induce noticeable birefringence in the fibre. In a field deployed fibre the nature of birefringence is random as it is inherited from the randomness of the vibrations responsible for it. Birefringence causes an unequal propagation speed of light polarized along some orthogonal axes that is distinguishable in each incremental length of the fibre, leading to a so-called polarization mode dispersion (PMD). PMD accumulates along the fibre, increasing with the square root of the length. The parameter commonly used in the fibre industry to describe PMD is called link design value (LDV). The problem of PMD has become crucial for multi-gigabit telecom systems, so that manufacturers of optical fibres put a lot of effort into minimizing the birefringence. As a result, fibres nowadays are characterized by relatively low LDVs, being around 0.01 ps/√km. Older fibres, however, installed in 90s of the last century display LDVs higher by up to one or two orders of magnitude making them less desirable for transferring reference signals from atomic standards. Aerial cables, especially when hooked on top of the high voltage lines, are prone to fast polarization changes during line switching, short circuit and especially lightning [14].

Chromatic dispersion: The wavelength of a semiconductor laser (used as an emitter in fibre T/F links) is dependent on temperature which, through fibre chromatic dispersion, is converted to delay fluctuations. Commercial telecom emitters (as used e.g. in small form-factor pluggable (SFP) transceivers) in the C-band have a sensitivity of about 6 pm/°C. This contributes to residual delay fluctuations of about 0.1 ps/(km·°C) (assuming a G.652 fibre) for medium to long averaging time (i.e. tens of minutes to hours), depending on the quality of the air conditioning. To suppress such effects, high-end T/F transfer systems do not use commercial SFP modules but custom-designed systems stabilized by referencing the laser to an external wavelength etalon.

Yet another contribution to phase fluctuations in optical fibres is related to the thermal dependence of the fibre chromatic dispersion. Almost all transfer systems used in practice are based on transferring two signals in opposite directions. These counter-propagating signals usually have some frequency offset between the forward and backward directions (ranging from a few MHz to 100 GHz, depending on the specific implementation); mainly to counter the problems of stray reflections, Rayleigh backscattering and other related noise. This offset converts into a phase shift, that in principle should be constant, but the thermal sensitivity of the chromatic dispersion makes it temperature (and therefore time) dependent. The thermal coefficient of chromatic dispersion fortunately is very low, on the order of $(-1.5\ldots-4.5)\times10^{-3}$ ps/(nm·km·°C) [15] or $(1.8\ldots5.4)\times10^{-8}$ ps/(MHz·km·°C), when converted to frequency units for λ=1550 nm. The resulting relative phase change scales down with a decreasing offset between the forward and backward directions. The corresponding coefficient is equal to (-0.3…-0.9) ppb/(nm·°C), so with a reasonably small offset this effect can become negligible.

In summary, phase/delay fluctuations in a fibre are caused by varying environmental conditions, such as temperature changes and mechanical stress. A large part of this fibre noise is symmetric and therefore can to a great extent be suppressed by employing fibre noise compensation schemes, which are based on counter-propagating signals, i.e. exploit the reciprocity of the fibre. For T/F transfer that require high accuracy, high stability, and/or long haul signal propagation, such schemes are of utmost importance (see Section 2.3). Noise resulting from PMD or chromatic dispersion cannot be suppressed with these schemes, as it is not symmetric. These two noise contributions, however, can be minimized by either using modern fibres, or, when no alternative is available, by a clever link design (e.g. by exploiting polarization scrambling or by small separation between laser wavelengths).

If a choice is possible or has to be made:

- buried fibre cables are less affected by environmental perturbations compared to aerial ones;
- modern fibres are less sensitive than first generation ones;
- quiet areas lying far from motorways or railways are better for T/F transfer links because they are less stressed.

For T/F transfer of the highest stability/accuracy level, the fibre noise is the dominating noise source, especially at short to medium measurement times (up to tens of minutes).

3 AMPLIFICATION/REGENERATION TECHNIQUES

Most T/F fibre optic transfer systems operate in the low-loss window of optical fibres (i.e. around 1550 nm). Nevertheless, in order to cover distances larger than 70-100 km it becomes necessary to compensate the loss in the optical fibre. A number of techniques have been developed for this purpose. When used properly they allow the spanning of distances of thousands of kilometres, making connections on a continental scale possible.

The substantial difference between optical amplification/regeneration techniques used routinely in the telecom industry and those used for fibre optic T/F transfer is due to the peculiarities of fibre optic T/F transfer, namely the requirement of a full forward - backward symmetry in order not to sacrifice the stability of delivered signals. The symmetry is required to alleviate the fibre link calibration, as otherwise the propagation delay difference between the forward and backward directions has to be taken into account for each individual amplifier.

Bi-directional optical amplifiers are not used in telecom networks because of potential problems resulting from the amplification of reflected (i.e. from connectors) or backscattered (i.e. due to Rayleigh backscattering) signals. It is thus essential to only use good-quality angled connectors (APC) and splices within a bi-directional fibre link exploiting optical bi-directional amplifiers.

3.1 Bi-directional erbium-doped fibre amplifier (EDFA)

Erbium doped fibre is an amplification medium well-suited to provide an optical gain in the wavelength range from about 1530 nm to 1560 nm. EDFAs operating at longer wavelengths in the so-called L-band are also available. Er-doped fibre is inherently bi-directional because the stimulated emission, i.e. the physical gain mechanism in EDFAs, is direction-independent providing nearly the same gain for both the forward and backward signals. It is important to note that the Er emission is certainly not flat (e.g. at the edges of the EDFA pass-band or near the wavelength of 1540 nm), and thus gains for the forward and backwards signal can differ here.

The general structure of bi-directional Er-doped fibre amplifiers (aka ‘bi-EDFA’ or single path bi-directional amplifier - ‘SPBA’) differs from that of standard telecom EDFAs only in the omission of optical isolators (see Figure 12). Using EDFAs in a bi-directional fashion is challenging, as a careful link design is necessary. Their gains have to be judiciously chosen in order to minimize the propagation of unwanted signals (like e.g. Rayleigh backscattering) and to not cause optical instabilities or potentially even trigger oscillations. The gain adjustment is done either by running a simulation model of the entire fibre link or by a cumbersome trial-and-error approach in real operating conditions. Additionally, the effective fibre length is extended when the fibre loss is compensated, which substantially lowers the threshold for nonlinear effects, especially for Brillouin scattering. In practice the gains of such amplifiers have to be limited to 20…22 dB, which generally limits the distance between two amplifiers to under 70-100 km. For fibre links with a relatively large wavelength offset between the forward and backward directions, so-called wavelength-selective isolators (WSI) can be implemented to block the path of the backscattered and/or reflected signals. This approach cannot, however, be used in optical carrier transfer links, where the frequency separation between the two propagation directions is on the order of 10s of MHz.

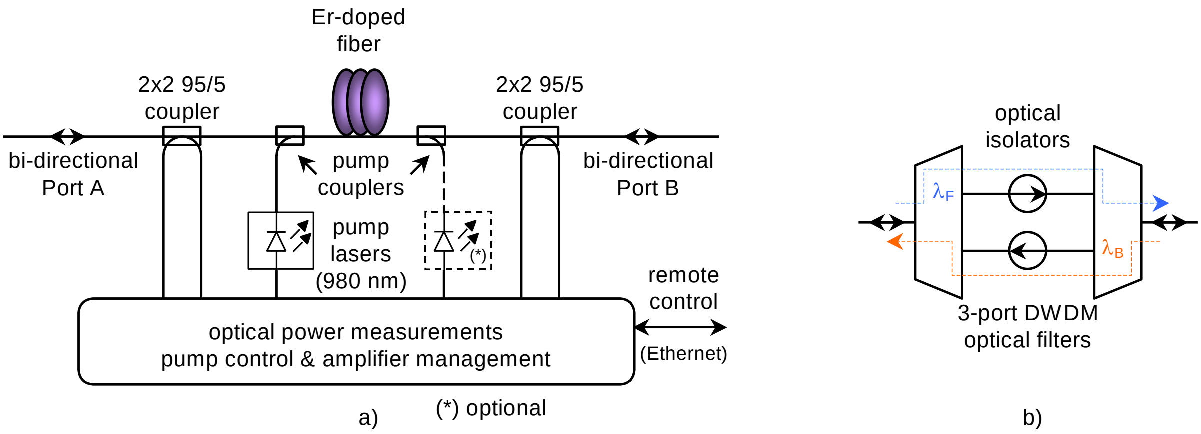


Figure 12. General structure of a bi-directional EDFA (a) and a WSI (b).

The big advantage of bi-directional EDFAs is that these are lumped devices, not requiring an injection of any additional high-power signals into the fibre network. Network operators generally prohibit the transmission of signals with power levels greater than 0 dBm, if no special safety precautions are taken. The EDFA technology (although uni-directional) is well known to optical network operators and therefore their implementation in the network infrastructure might more readily be approved.

Bi-directional EDFAs can be used in fibre links transferring T/F signals.

3.2 Bi-directional Raman and Brillouin amplifiers

Raman and Brillouin amplifiers belong to the class of distributed devices, which employ a standard transmission fibre as a gain medium. The physics behind the gain generation differs substantially from the stimulated emission exploited in Er-doped amplifiers. It relies on a nonlinear process; the inelastic scattering of photons on nearest-neighbour pairs in the fibre crystalline lattice or on phonons, vibrational quanta in the lattice. From the technical point of view, both types of amplifiers (Raman and Brillouin) are a combination of pump lasers and associated couplers, which inject the pump power into the transmission fibre. The big advantage of this technology is that the fibre, which under the no-pumping-condition causes a signal loss, provides gain instead. Thanks to such non-linear amplifiers large spans are possible, extending up to 200 km.

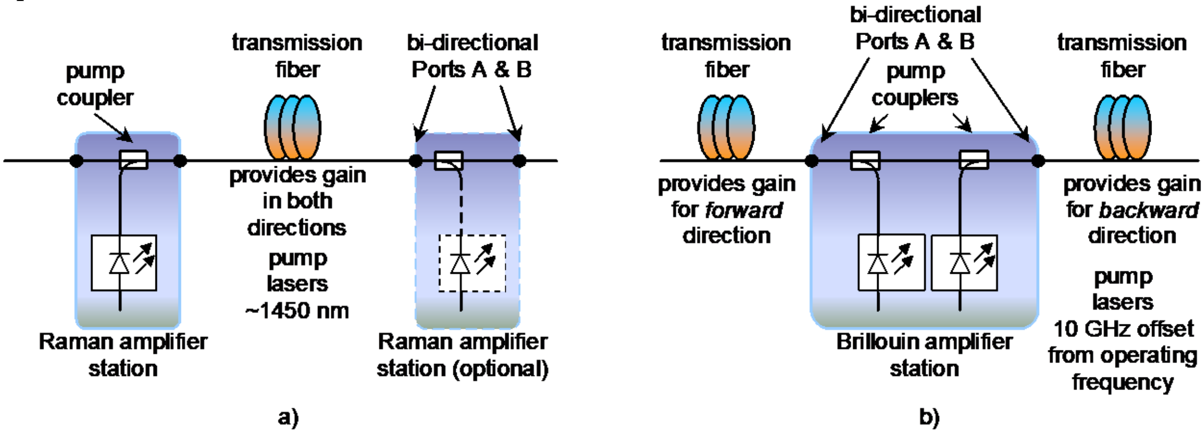


Figure 13. General structure of a bi-directional Raman (a) and a Brillouin (b) amplifying station.

Raman amplifiers

Raman amplification (see Figure 13a) is a bi-directional process, which can reach gains of up to 10 dB at the cost of very high pump power, on the order of hundreds of mW. The bandwidth is relatively broad, around 15-20 nm (although it is not as flat as in the case of EDFAs), so no special control of the pump wavelength is required. The fibre can be pumped from either a single side or both sides, depending on the required gain. It is important to note that the effective length of the amplification is inversely proportional to the fibre attenuation coefficient. Typical values of 0.2 dB/km@1550 nm correspond to ~20 km. The Raman gain coefficient is dependent on the fibre type and is unfortunately a few times lower for standard G.652 fibres compared to e.g. G.655 or dispersion compensating fibres. For a successful Raman amplifier operation it is also essential to de-polarize the pump laser, as the gain is polarization dependent, and to minimize any optical losses along this effective length as otherwise the gain is substantially reduced.

Raman amplifiers can be used in fibre links transferring T/F signals.

Brillouin amplifiers

The Brillouin amplifier (Figure 13b) is from a technical point of view quite similar to the Raman amplifier, but the physics generating the gain is slightly different, such that a gain is only obtained in the direction opposite to the pump propagation. It is thus interesting to note that although the optical signals inside a Brillouin amplifier propagate bi-directionally, only one direction is amplified.

To implement a fully bi-directional Brillouin amplifier two independent fibre spans must be pumped, providing an independent and possibly unequal gain in each direction (contrary to EDFAs and Raman amplifiers, for which the gain is practically direction-independent). The gain profile of a Brillouin amplifier is narrow, only about 10 MHz wide, and is offset by about 10…11 GHz from pump frequency, whereby the actual value depends on the particular fibre. This requires a control of the pump frequency at the level of a few MHz. Due to an inherently narrow bandwidth, the application of Brillouin amplifiers is practically limited to optical carrier transfer links only. The available gain is quite large, on the order of 30…60 dB, with modest pumping power requirements, usually below 20 mW.

Brillouin amplifiers can only be used in fibre links transferring optical frequency.

Comments:

Both Raman and Brillouin amplifiers require injecting high optical powers into the network. Such amplifiers are safe to use only in the dark fibre scenario, otherwise there is a risk for interfering with live telecom traffic. Raman amplifiers are occasionally used in telecom networks as low-noise pre-amplifiers, which are pumped counter-directionally, i.e. the pump wavelength propagates in the direction opposite to the telecom signals. When the telecom network employs such Raman amplifiers, the T/F service using a dark channel approach (the telecom equipment is bypassed - see Section 2.3.2) benefits from the Raman gain. However, this situation requires a careful control of power injected into the common fibre (i.e. shared with the telecom data traffic) because the T/F signal may be boosted to a high power level, which can trigger a non-linear interaction between the T/F signal and the telecom data inside the fibre. Whenever Raman and Brillouin amplifiers are employed and T/F and data traffic signals coexist in the same fibre, a careful analysis is required.

3.3 Repeater laser stations

A repeater laser station (RLS, see Figure 14) is a solution that can be applied to optical carrier transfer systems and is especially effective when the optical line presents elevated losses. This technique relies on an optical phase locked loop (OPLL) to phase lock the frequency of a low noise laser (e.g. a fibre laser) in the RLS to the light received from the previous segment of the link.

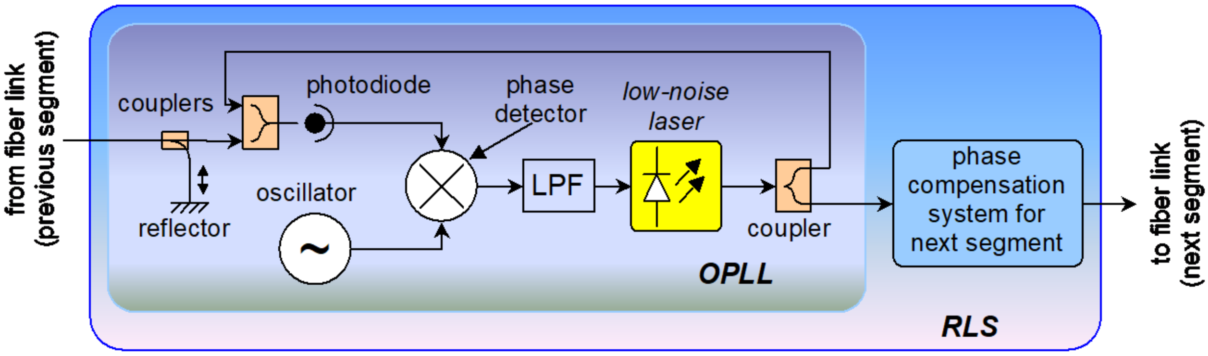


Figure 14. Simplified block diagram of an RLS.

The RLS plays the role of an intermediate node in a cascaded link scenario and, by dividing the total length of the fibre into shorter segments, it can be more efficient in reducing the fibre noise (see the comments at the end of Section 2.5). The RLS scheme can be extended to provide at least 4 or 5 outputs, which simultaneously feed additional compensated links [16].

The input optical power necessary to drive the RLS is about -60 dBm. It is reasonable to only consider using RLS on links which are based either on a dark fibre or a dark channel, as otherwise the potential of this complex technique will be lost by the fibre asymmetry.

Repeater laser stations can only be used in fibre links transferring optical frequency.

3.4 Injection locking

Injection locking is a technique in which the laser of an intermediate station is seeded by the light from the previous segment of the link. The optical power necessary to seed the laser is quite low (below about -40 dBm) so that this technique is well suited for the regeneration of optical signals in fibre links with long fibre spans. The bandwidth of the seeded laser is also quite low (tens to hundreds of kHz), so that injection locking is only applicable to optical carrier frequency transfer links, similar to the above described RLSs. Parasitic reflexions from the fibre network can perturb the injection lock, and without proper mitigation can be a limitation of this technique.

Injection locking can only be used in fibre links transferring optical frequency.

3.5 Semiconductor amplifiers

Semiconductor optical amplifiers (SOA) employ a technology similar to that of semiconductor lasers, however, lack the optical resonator in the structure. The gain spectrum of such amplifiers covers a relatively broad wavelength range that, depending on the semiconductor material used, can potentially cover the entire spectrum used in fibre optic communications. The achievable gain is about 15…20 dB and most of the SOA structures can operate bi-directionally. However, the noise performance of SOAs is modest, worse than that of the fibre amplifiers described above. They can also be a source of nonlinearities due to the short lifetime of carriers inside semiconductor. Such amplifiers can, on occasion, be used, when a moderate T/F transfer is the goal.

Semiconductor amplifiers can be used in links transferring any T/F signals.

4 IMPLEMENTATIONS OF FIBRE T/F TRANSFER TECHNIQUES

The purpose of this section is to give a review of the practical implementations of various transfer techniques that have been developed either by research infrastructures or academic/scientific labs.

4.1 Frequency transfer

Fibre optic frequency transfer can be realized by sending either an ultra-stable un-modulated optical carrier or an optical carrier modulated by an RF signal. Various techniques can be applied to obtain this. Some of them have reached a technology readiness level adequate enough to be considered as useful for industrial/telecom applications.

4.1.1 Optical carrier transfer

Optical carrier transfer is a high-end technology, interesting mostly for science and metrology, but also of potential interest to innovative industry or spectroscopy laboratories. This technology allows for the creation of an international network of optical clocks and could form the basis for an extended network providing a highest-level reference for time and frequency metrology applications. For this purpose two techniques have been extensively investigated: a stabilized transfer (see Section 2.4.1) and a two-way comparison (see Section 2.4.3).

Stabilized transfer

The stabilized transfer of an ultra-stable optical carrier is based on the general idea presented in Section 2.4.1, where a Michelson interferometer with two arms of unequal length is used to sense the phase fluctuations of the optical signal. The correction is usually applied at the local terminal by controlling an acousto-optical frequency shifter (often also called an acousto-optical modulator - AOM).

The uncertainty introduced on the optical carrier by this transfer technique is below 10^{-19} after 10^4 s of integration time, implemented on a single bi-directional fibre over a thousand kilometres long ([7], [17]-[19]).

For fibre spans longer than about 100 km the optical losses need to be compensated for. This is done by introducing intermediate bi-directional amplifiers and/or regeneration stages ([18], [20], [21]). For this purpose, specific apparatus have been developed, which are compact, can be rack-mounted and can be remotely controlled in order to avoid frequent maintenance in intermediate, and usually unmanned, shelters. Depending on the terminal layer, the lock-systems of the optical carrier are not yet all fully maintenance-free, thus human intervention may still be necessary in the laboratories located at the ends of the link.

Stabilized optical carrier transfer mainly finds its application in metrological comparisons of optical clocks, high precision spectroscopy and VLBI for geodesy and radio astronomy applications. The same technique has also been implemented using two parallel uni-directional fibres, avoiding the installation of dedicated amplifiers. With this configuration the residual fibre noise is at the level of 10^{-16} after 10^4 s of integration time [22], which is suitable for industrial purposes. Within the OFTEN project, a study and experiments with the stabilized transfer of an optical carrier using the DWDM channel approach (see Section 2.3.2) are being performed.

Two-way comparison

A two-way comparison is based on the principle presented in Section 2.4.3. Two ultra-stable optical carriers with approximately the same wavelength are injected into opposite ends of the fibre link. Post-processing the frequency data acquired at the two ends of the fibre rejects the noise contribution of the fibre link. This technique has uniquely been employed for metrological comparisons of optical clocks. It has been demonstrated to introduce an uncertainty to the optical carrier below 10^{-20} after 10^4 s of integration time ([23], [24]), if a single bi-directional fibre is used. When implemented with a pair of uni-directional fibres the uncertainty increases to 10^{-17} at 10^4 s of observation time [24].

Similar considerations on the amplification/regeneration and the automatization made regarding the stabilized optical carrier transfer technique also apply to long-haul two-way links.

4.1.2 RF frequency transfer

The dissemination of an RF signal is typically performed through an amplitude modulation (using either sinusoidal or square waveforms) of the optical carrier with a referenced RF or microwave signal. At the remote end the RF modulation is detected with a fast photodiode.

There are many applications for RF frequency transfer, as the transferred signal exists in the electrical domain and therefore can conveniently be accessed by a user. Potential applications can be found in e.g. the field of telecommunications, navigation, defence, geodesy, finance, as well as in scientific disciplines such as radio astronomy, spectrometry and fundamental physics.

Stabilized transfer with optical compensation

An RF transfer with optical compensation is based on the general idea presented in Section 2.4.1, where the correction is applied through a variable optical delay. This can be a mechanically regulated delay line (regulation range below a nanosecond, with a response time on the order of seconds), a spool of fibre that undergoes controlled temperature variations (regulation range around tens of nanoseconds, with a very slow response time on the order of minutes/hours) or a piece of fibre wound on a piezoelectric stretcher (regulation range of only a few hundreds of picoseconds, but with a fast response time below a millisecond). These systems are able to stabilize the propagation delay, but are usually only used for phase stabilization.

The frequency instability (measured as a ADEV) introduced by this technique on an urban 86 km long loop operated bi-directionally has been demonstrated to be below 10^{-18} for a one-day integration time [25]. The transmitted frequencies are up to 10 GHz, which makes this technique suitable for the dissemination of the Cs primary standard and for experiments with particle accelerators.

Due to the mechanical components and the spools of fibre used in this approach, the resulting systems are large and power hungry. The transmission range is limited by the available long-term regulation range. Assuming that the spooled fibre is 20 km long and its temperature can be varied by 40°C one can obtain a regulation range of approximately 30 ns, which is certainly not enough for links longer than 50…100 km. The ultimate limitation of the compensator itself is thus reached and cannot be easily overcome in the future.

A different concept of an optically compensated RF transfer link has been developed at the University of Western Australia [26], where two CW carriers are transmitted whose beat frequency at the receiver end is stabilized by acting on one of the CW carriers with a frequency shifter at the transmitter end. The technique is in principle a modification of the active compensation technique (see Section 2.4.1), where the error signal is constructed from the two optically detected round-trip beat notes.

Stabilized transfer with electronic delays

In this approach, based on the general idea presented in Section 2.4.1, the compensation is moved from the optical to the electrical domain. This results in a compact system that is able to stabilize the propagation delay of the link, and thus is suitable not only for frequency transfer, but also for time transfer. A version of this system also incorporating time transfer is commercially available under the name ELSTAB (see Section 4.2.2).

At the short term this technology is currently limited by the electronics (mostly by the white phase noise of the delay lines), resulting in an ADEV of 10^{-13} at 1 s of interrogation time, which decreases with a slope inversely proportional to the averaging time (τ^{-1}), reaching 10^{-17} for 10^5 s of integration time. The long-haul implementation of this technique on a 615 km long fibre link operated bi-directionally, with bi-directional amplifiers (see Section 3.1) installed in intermediate shelters to compensate for power losses confirms these numbers [27]. The delivered RF signals are at 10 MHz and 100 MHz and can easily be changed to any value within this range.

The system has also been evaluated in an optical DWDM network using the DWDM channel approach for lengths of up to 3000 km [28]. The obtained results depend on the actual distance but even at 3000 km the residual link instability (due to the asymmetry in DWDM telecom networks) is substantially lower than commercial Cs clock instability (ADEV below $2\ldots3\cdot10^{-15}$ at 10^5 s).

The infrastructure allows a multipoint distribution [29] and is an unmanned, continuously operating system. However, there still is room for substantial improvements concerning both the short- and the long-term stability.

Stabilized transfer with phase conjugators

Many techniques based on the general idea presented in Section 2.4.2, have been developed using either three or two lasers ([30]-[36]). Phase conjugation seems to have a good potential for building dissemination links with very good parameters, although it requires a careful design because of potentially very harmful effects resulting from circuit non-linearities.

The technique has been demonstrated on a 150 km bi-directional link distributing an RF signal at 80 MHz without amplification and reaching the 10^{-17} level in 10^4 s ([30], [31]). This particular implementation requires two ITU channels in the same fibre, since the two lasers need to operate at different wavelengths.

Phase conjugation can be effectively achieved using an active feedback rather than just passive mixing ([32], [35], [36]). The technique has been demonstrated to achieve an instability (ADEV) of $5\cdot10^{-19}$ at 10^5 s [36] across 40 km of urban fibre network.

4.2 Time transfer, RF frequency + time transfer

In order to transfer time, it is necessary to send markers that are referenced to the realization of UTC to the remote end of the fibre. As it has already been mentioned in Section 2, for this it is necessary to not only to assure the stability, but also to determine the delay between UTC and the transferred markers. There are generally three approaches: the first is based on a two-way comparison (see Section 2.4.3), the second uses an active stabilization of the link delay (see Section 2.4.1) and the last one is based on protocol techniques (see Section 2.4.4).

4.2.1 Two-Way Optical Time Transfer (TWOTT)

An economical solution for a time transfer with a picosecond stability is the Two-Way Optical Time Transfer (TWOTT) system, which implements standard SFP optical transceivers to transfer the timing information between two or more terminals over several hundreds of kilometres. This technique has been used in the Czech Republic between IPE and BEV, using uni-directional DWDM channels over 550 km each way, with the lowest TDEV noise being 30 ps for a 20 s averaging interval [37]. The use of a bi-directional dark channel improves the TDEV noise by about one order of magnitude, e.g. to 2.2 ps for a 512 s averaging interval over a distance of 180 km [38]. This represents a very economical solution suitable for both DWDM channels over telecom systems and dedicated dark channels. The latter can be easily combined with a stabilized optical carrier frequency transfer, e.g. [39]. In Germany, a TDEV performance better than 60 fs for averaging intervals from 100 s to 10000 s has been achieved using single mode SFPs at 1550nm [39]. This is an economical solution for short range time transfer over a few kilometres.

4.2.2 Electronically stabilized (ELSTAB) fibre-optic T/F distribution

The pioneering ELSTAB dedicated hardware system has been developed at AGH University in Poland. It’s a fibre optic system comprising of an active stabilization of the propagation delay, bi-directional fibre optic amplifiers and a procedure enabling the calibration of a two-way time transfer. Lab demonstrations over 480 km have shown a time deviation below one picosecond [40]. A stabilized propagation of the time signal in the link is realized by marking the occurrence of the 1 PPS time signal through the introduction of a specific phase modulation on a 10/100 MHz square-wave signal. At the far-end transceiver, a de-embedder is used to extract the 1 PPS pulses.

ELSTAB has been operational on a 421.4 km long fibre link between GUM in Warsaw and AOS in Borowiec since 2012, comparing the UTC(PL) and UTC(AOS) atomic timescales with a total uncertainty of 150 ps. This link has been used to test the BIPM calibration technique called METODE (MEasurement of TOtal DElay) and the results show discrepancy of 0.7 ns, which itself is lower than METODE uncertainty, estimated to be 0.8 ns [41]. Within the Optimeproject [42] ELSTAB has been used to create a network connecting a few partners in Poland. This technique is also operational in Germany over a 446 km telecom fibre link, used to provide UTC(PTB) from Braunschweig to a synchronization test centre of the Deutsche Telekom in Bremen with stability below 10 ps [43].

4.2.3 Two-way optical time and frequency transfer over a stable optical carrier

There is another technique, which employs a Two-way time transfer on the same fibre, using bi-directional propagation; it employs SATRE (Satellite time and ranging equipment) typically used by National Measurement Institutes for TWSTFT, which is supplied by TimeTech GmbH [44]. This technique has been implemented using the dark channel approach. It can also be combined with ultra-stable frequency transfer, thus providing both a frequency reference and a precise and accurate time reference. The optical phase is used to carry both the frequency information and the timestamps by modulating a very narrow optical carrier at 1.55 µm with spread spectrum signals using the SATRE two-way satellite time transfer modems. This system has achieved an absolute time accuracy of 250 ps and a long-term timing stability of 20 ps at LPL in France over 540 km [45] and thus outperforms the conventional GNSS time transfer methods.

The uncertainty of this time transfer method has also been carefully evaluated at PTB where an accuracy budget of 74 ps has been achieved. The time transfer was demonstrated over a 73 km link using a dark fibre approach exhibiting an agreement with GPS at the level of 0.7 ns [46].

4.2.4 PTP and White Rabbit

The idea presented in Section 2.4.4 is exploited in a network protocol called Precision Time Protocol (PTP, aka IEEE1588 [47]), whose purpose is to provide a networked, packet-based time synchronization between different nodes. PTP is capable of synchronizing remote clocks at the microsecond level over long distances. This requires establishing a Master/Slave scheme and properly measuring the time skew generated by the clock offsets and the network delays. The latter is evaluated through the exchange of precise timestamps in a given network segment.

PTP limitations are mostly due to free-running clocks operating at the remote sites and at each intermediate node (in practice there may be many slave clocks that synchronize to the master clock using the above described idea), the asymmetry between the forward and backward delays (in Figure 8 a full symmetry is assumed, however in practice such systems operate uni-directionally) and the relatively low frequency of exchanging synchronization messages.

PTP, running over the Ethernet network, is of interest in situations for which regular high-speed telecom data transmission is required along with time synchronization, especially if this includes multiple locations within a limited area (e.g. campus, laboratory etc.). It should be noted, however, that a successful operation of PTP requires designated switches with PTP support (i.e. which apply special treatment to PTP messages) to be installed throughout the network.

PTPv2 consists of an industrial evolution of PTP, which provides a significant improvement in the accuracy of the time synchronization. Since PTPv2 is packet-based, its operation can be affected by data traffic. Additionally, the synchronization level is limited for applications requiring a time precision better than one nanosecond.

A step in the direction of higher precision is made by White Rabbit PTP (WR-PTP). WR-PTP is the result of a multi-collaborative WR project [48] lead by CERN involving industrial partners, academic partners and research laboratories. WR-PTP can be regarded as an implementation of PTP over Gigabit Ethernet (GbE) through an optical fibre network. Its original goal was to ensure a synchronization of more than 1000 of users located within an approximately 5 km radius with a sub-ns accuracy and to simultaneously handle a deterministic and reliable data delivery over the Ethernet.

To achieve these goals, WR-PTP relies on the synchronism between all routers in a network, which has been developed for synchronous digital hierarchy (SDH) optical networks, and consecutively has been adopted in Synchronous Ethernet (SyncE). To improve the resolution of the link delay measurement, a precise hardware phase detector is employed in order to accurately measure the phase difference between the frequency signals sent down the fibre from the Master and looped back by the Slave. WR usually operates bi-directionally with a large wavelength difference between the forward/backward directions (1310/1490 nm). This introduces a substantial asymmetry in the propagation delay that affects the link delay assessment. The delay is estimated assuming a known fibre dispersion and fibre length. Similarly as for PTP, all switches in a WR-PTP network must support the specific requirements of the WR protocol and include necessary hardware modifications when combined with standard GbE equipment.

The limitations of WR-PTP result mainly from the practise of using standard telecom modules (such as, e.g. SFP optical transceivers that have a moderate wavelength stability and accuracy). Using a 1310/1490 nm wavelength pair implies a huge backward/forward wavelength separation, which makes the prediction of the exact delay asymmetry difficult. The low rate of synchronization corrections (WR-PTP messages are designed to coexist with normal data traffic and do not add a lot of overhead) induce some limitations, related to the stability of the local oscillator.

White Rabbit was originally intended for the synchronization of equipment within a range of 10 km. However, the original firmware has been modified to allow for longer round trip time measurements extending the synchronization range to up to 1000 km. White Rabbit has been implemented over long distances using existing communication fibre networks, such as a 950 km White Rabbit link using a uni-directional fibre pair between Espoo and Kajaani, Finland [49]. Standard DWDM SFPs in the C-band range can be used for this method.

The time transfer on this link was compared (after an initial calibration) against a clock comparison by GPS precise point positioning (PPP). The agreement between the two methods remained within ±2 ns over a three month measurement period. Another White Rabbit implementation has been realized in the Netherlands between Delft and Amsterdam, by cascading two links of 137 km each [49]. In this case, the WR links were realized using a bi-directional approach, requiring dual wavelength DWDM SFPs and a dedicated amplifier design, creating a bi-directional path for the wavelengths outside the usual C- and L-wavelength bands. The measured time offset between the starting and end points of the link was within 5 ns with an uncertainty of 8 ns, mainly due to the estimated delay asymmetry caused by chromatic dispersion.

WR-PTP also provides frequency transfer and has demonstrated frequency stability of the order of 10-15 @ 1 day for distances up to 500 km [49][58].

White Rabbit is certainly the best-known high-performance solution for T/F dissemination over a limited area supplying many users, such as large research infrastructures, scientific laboratories, university campuses, etc. Dedicated modules are currently available as commercial products from a few companies in Europe. It is also possible to manufacture everything from scratch because all the necessary software and hardware projects can be downloaded free of charge from a dedicated server due to open software/hardware philosophy of WR.

4.2.5 Frequency Comb

A precise time synchronization, as well as a frequency transfer, can be obtained by using a frequency comb with a digital feed forward. A 120 km DWDM telecommunications fibre link in Long-Bridge, China, has measured a time synchronization instability of sub-40 ps [50]. A dense wavelength division multiplexing (DWDM) approach was used in a bi-directional transferring system, in which the forward and backward signals run in six wavelength channels determined by the DWDM ITU-grid (channel #33 and #34 are used to transfer frequency, #30 and #31 for time synchronization, #36 and #37 for data communication respectively) without interfering with each other. The phase noise is digitally corrected at the remote end.

4.3 Optical carrier + RF frequency + time transfer

A few different techniques, which allow a joint transmission of reference signals in both the optical and the electrical domain, have been proposed. All of them are capable of transferring an optical frequency. These techniques are often still in the initial phases of their development or have been demonstrated in a proof of concept experiment. Nonetheless, they have the potential to push forward the limits of fibre optic T/F transfer. These methods are presented in this section.

A technique that has the potential to combine all three categories of T/F transfer – optical frequency, RF frequency and time – is the transmission of an optical frequency comb over a group-delay stabilized fibre link. This technique has been pioneered at NPL ([51], [52]) and is based on an active compensation using group-delay actuators (fibre stretchers and temperature-controlled spools). The error signal is derived from the round-trip phase of multiple optical carriers contained within the comb, which as a result are all stabilised simultaneously. A microwave transfer is possible by detecting the repetition rate of the transmitted comb, while the time transfer is realised by marking out, with an increased amplitude, a single optical pulse determined by the 1 PPS signal. A time transfer accuracy of around 100 ps has been achieved on a 159 km installed fibre network, using a single ITU 100 GHz channel [52], while fractional frequency stabilities of 2×10^{-18} (optical) and 4×10^{-17} (8 GHz) for timescales of a few thousand seconds have also been demonstrated [51], albeit only over a few km of fibre.

The other approach used to transfer the time marks was to chirp the optical carrier in the standard setup (i.e. using a fibre Michelson interferometer). The idea is based on the assumption that in a phase-stabilized link the instantaneous value of the frequency (optical) is the same at both the local and the remote end, thus the measurement of the remote frequency should allow the detection of the time tags marked by a linear chirp of the input light. In the proof of principle experiment described in [53], the transfer of time information and simultaneously of optical frequencies at both ends of the link were investigated without an actual extraction of the optical carrier at the remote end and a check of the impact of chirping on this extraction. In a 149 km long link, the instability of the time transfer (in form of 1000 pulses per second) is on the order of 2 ns for an averaging time of 1 s (expressed as a time deviation - TDEV), with a flicker noise floor around 200 ps.

Yet another idea, that has been recently evaluated [54], is based on imposing the time and frequency information on the ultra-stable optical carrier through an intensity modulation with the extinction ratio limited to approximately 3 dB. The system has been tested in a proof-of-concept experiment based on a standard Michelson interferometer used in optical carrier transfer experiments and supplemented with ELSTAB local and remote modules responsible for the RF and the time transfer. At the remote end, a clean-up laser was implemented to remove the amplitude modulation from the optical carrier. The parameters obtained on a 60 km long urban fibre were: $5{\cdot}10^{-20}$ (modified ADEV - MADEV) at 10^4 s for the optical carrier, below 10^{-17} at one day for the 10 MHz signal, below $2{\cdot}10^{-13}$ (TDEV) for averaging times $10^2 \ldots 10^4$ and below 1 ps for times up to 10^5 for the 1 PPS.

4.4 Other techniques

The implementations discussed above in this Section present the mainstream T/F transfer techniques. There are also other techniques which are occasionally implemented, but offer either a much lower performance (e.g. one-way uncompensated links, one-way two-colour links) or no longer can be implemented due to a change of the telecom infrastructure needed to support them (e.g. transfer based on processing SDH frames, transfer using a so-called passive listening in SDH STM-64 networks). These are just listed here to complete the picture, but will not be discussed further. Details of these techniques can be found in the literature, e.g. ([55]-[57]).

5 T/F TRANSFER – A GLOBAL VISION

In this Section, we sketch how a global network for T/F transfer might look like. The foundations of future networks have already been implemented to some extent thanks to a number of research projects, active on both European and national levels (NEAT-FT, OFTEN, OPTIME, LIFT, REFIMEVE, White Rabbit, DEMETRA). These includes fibre transfer links that connect metrological and research laboratories, involved either in the development of optical atomic clocks, in the development of international atomic time scale, or in both of these areas. At present, the network serves only scientific users. In order to make T/F signals available to other potential users in the future, the core of this existing network will need to become more interlinked with an increased reliability. Additionally, it will be essential to have the required technology ready for extending this network to reach end users. These users may have various requirements concerning not only the type of the signal (optical carrier, RF frequency, time) and its stability and accuracy parameters, but also may differ in the available infrastructure (at the optical communication layer – dark fibre, dark channel, DWDM channel), reliability (e.g. backup requirements) level or time duration of accessing the signals (continuous or on-demand service).

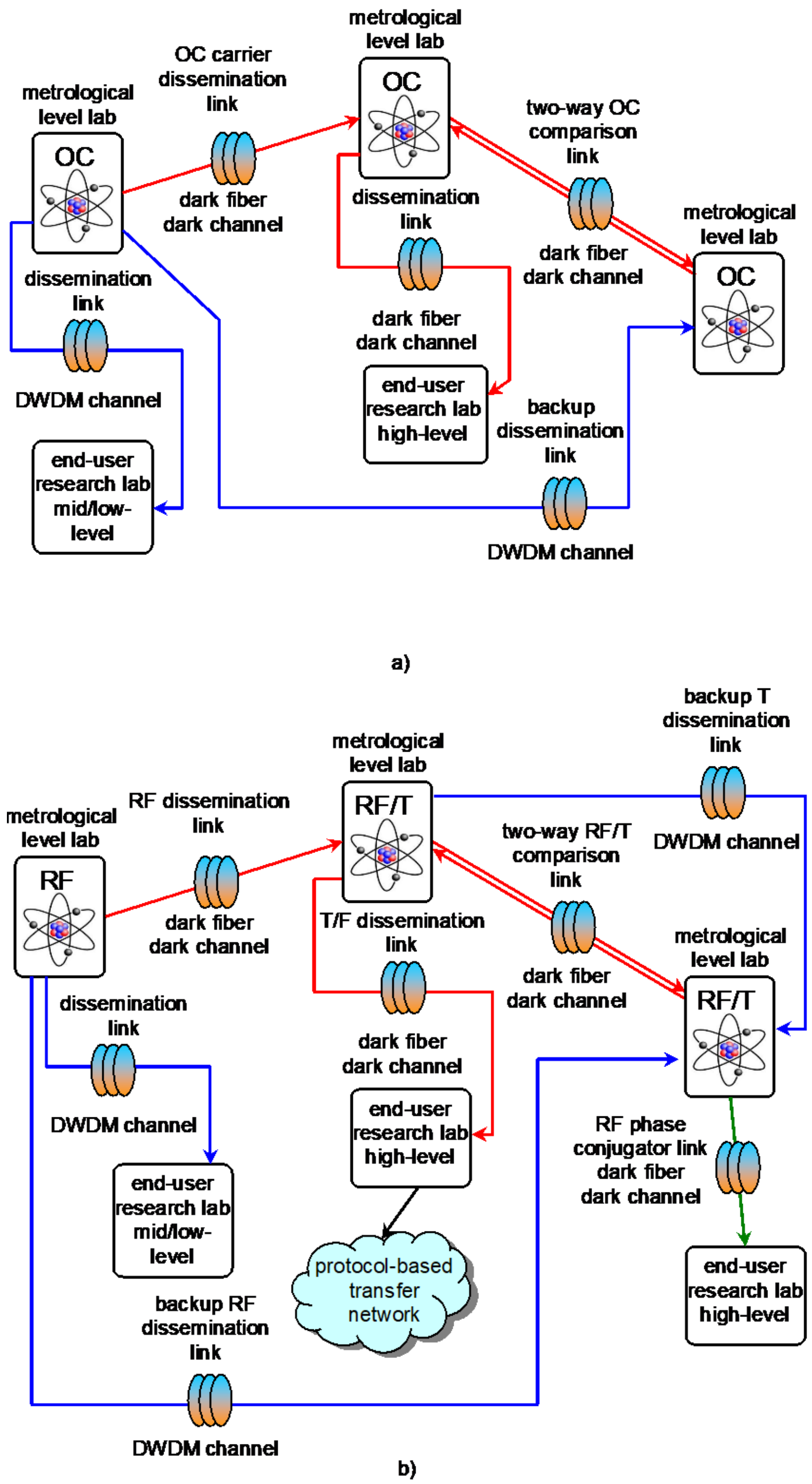


Figure 15. Example networks for T/F transfer: (a) optical carrier and (b) RF/time transfer.

As shown in Sections 2 and 3 of this document, there currently is a wide spectrum of techniques, developed by various different research infrastructures and university laboratories, available. The progress in this field continues as the transfer of T/F over an optical fibre is still an active area of research. Nevertheless, these existing techniques may potentially fulfil many (if not all) requirements necessary for building a global, pan-European network, connecting high-end metrological laboratories with end users with various different demands. A general view of such a network is presented for an optical carrier transfer in Figure 15a and for an RF and time transfer in Figure 15b.

The presented idea assumes that a number of high-level, metrological laboratories forming the core of the network are connected either by disseminating stabilized links or by two-way comparison links. These links should be able to ensure the highest stability and accuracy for T/F transfer as required by these metrological applications. The links should use either dark fibre or dark channel approach, depending on local conditions and availability.

To increase the reliability of the network, backup connections (i.e. redundant, duplicate connections) should also be created in case of a main link failure. These links may offer a lower performance, but should simultaneously be more widely available and possibly less expensive. This gap could potentially be filled by DWDM links, which have the additional advantages of being flexible (i.e. may be created on demand) and of having the telecom network operator take on the burden of their reliability.

A variety of tools and techniques are already available for connecting users to such a potential T/F fibre network with further techniques being developed. The technique or the combination of techniques employed will most likely depend on the demands and requirements of the specific user or users. The users could be connected to the network using the same technologies that connect top-level laboratories, i.e. the actively- or passively- stabilized links using a dark fibre/channel approach, when the quality requirements are high or DWDM links (or even maybe un-stabilized one-way links) when the stability/accuracy requirements are lower. For serving a larger number of users in close proximity (a few kilometres) of each other, protocol-based techniques (such as White Rabbit) are a very good option.

6 CONCLUSION

A substantial number of fibre T/F techniques have been developed. Some of them have been tested in the laboratory only, whereas others have also been tested in the field. Thanks to the activity of several European institutes, prototype fibre links allowing the comparison of state-of-the-art optical clocks and caesium fountains are being operated. Such links are at the heart of modern metrology and must be converted into permanent links to guarantee further progress and allow the exploitation of the developed infrastructure. Several technologies, such as WR-PTP, ELSTAB, repeater laser station, have led to the development of prototype systems, whose performance has been evaluated and who are now offered as commercial products, while bi-directional amplifiers are proposed by several manufacturers in Europe.

The various techniques mentioned in this document have been collected in Table 2. The purpose is to give an overview only, as it is not possible to include all information in such a short description. The information on the distance and the performance is based on the data available from the literature. In some practical implementations achieved metrics might be better, it was however decided to use experimentally proved values in this text. This information is given in a very simplified form, showing rather an order of magnitude instead of exact values. This also applies to the technology readiness level (TRL, [59]), in particular as there often are multiple laboratories each having developed their own variation of a particular technique. Furthermore, it is important to keep in mind that research continues to be done; new concepts are being tested and performances are being pushed to their limits. More information can be found in relevant literature that is listed in the references.

fibre noise suppression scheme	communication link type	demonstrated distance	demonstrated performance (ADEV, TDEV, uncertainty)	relevant reference	TRL [59]
CW optical carrier					
active cancellation	bi-directional dark fibre and channel	> 1000 km	10^{-15} @ 1s; 10^{-20} @ 1d	[16]-[22]	8
two-way comparison	bi-directional dark fibre and channel	50…100 km	10^{-17} @ 1s; 10^{-21} @ 1d	[23], [24]	5
Optical frequency comb					
active cancellation	bi-directional dark fibre and channel	50…150 km	TDEV 500 fs @ 1s	[50], [51], [52]	4-5
RF/MW carrier					
active cancellation with optical delays	bi-directional dark fibre	< 100 km	10^{-14} @ 1s; 10^{-18} @ 1d	[25]	4
active cancellation with electronic delays (ELSTAB)	bi-directional dark fibre	> 600 km	10^{-13} @ 1s; 10^{-17} @ 1d	[27], [29], [40]	8
	uni-directional DWDM channel	up to 3000 km	10^{-15} @ 1d for old DWDM 10^{-16} @ 1d for coherent DWDM	[28]	8
White Rabbit PTP	uni-directional DWDM channel	100…1000 km	10^{-15} @ 1d	[49], [58]	8-9
phase conjugation	bi-directional dark fibre	100…150 km	10^{-18}…10^{-19} @ 1d	[30]-[36]	5-6
Time					
two-way comparison	bi-directional dark fibre or channel	~ 600 km	TDEV ~ 2 ps	[38], [39], [45], [46]	5-6
	uni-directional DWDM channel	~ 500 km	TDEV ~ 30 ps calibration through GPS	[37]	6
optical frequency comb	bi-directional dark fibre	> 100 km	calibration uncertainty < 40 ps	[52]	4-5
active cancellation with electronic delays (ELSTAB)	bi-directional dark fibre	> 600 km	TDEV < 1 ps calibration uncertainty < 40 ps	[27], [29], [40]	8
protocol-based (White Rabbit PTP)	uni-directional DWDM channel	> 1000 km	verified with GPS disagreement within ±2 ns	[49]	8-9
	bi-directional dark fibre	40…80 km	calibration uncertainty < 10 ns	[48]	8-9

Table 2. Examples of developed fibre T/F transfer techniques and their general characteristics.