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Strategy and innovation for clock services
over optical-fibre networks

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LIST OF ACRONYMS AND ABBREVIATIONS

AMP	Asynchronous Mapping Procedure
ASK	Amplitude Shift Keying
AWG	Arrayed Waveguide Grating
BER	Bit-Error-Rate
BMP	Bit-synchronous Mapping Procedure
CD	Chromatic Dispersion
CLONETS	CLOck NETwork Services: Strategy and innovation for clock services over optical-fibre networks Project
DCF	Dispersion Compensating Fibre
DCM	Dispersion Compensating Module
DP-QAM	Dual Polarization Quadrature Amplitude Modulation
DP-QPSK	Dual Polarization Quadrature Phase Shift Keying
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fibre Amplifier
FEC	Forward Error Correction
FWM	Four Wave Mixing
GMP	Generic Mapping Procedure
IEEE	Institute of Electrical and Electronics Engineers
ILA	In-Line Amplifier
IRU	Indefeasible Right of Use
ISP	Internet Service Provider
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
MZM	Mach-Zehnder Modulator
NREN	National Research and Education Network
NRZ	Non-Return-to-Zero
NTP	Network Time Protocol
ODU	Optical Data Unit
OEO	Opto-Electro-Optical
ONE	Optical Network Elements
OOK	On-Off Keying
OPU	Optical Payload Unit
OTN	Optical Transport Network
OUT	Optical Transport Unit
PMD	Polarization Mode Dispersion
PoP	Point of Presence
PSK	Phase Shift Keying
PTP	Precision Time Protocol
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
ROADM	Reconfigurable Optical Add Drop Multiplexer
SMF	Single Mode Fibre
SNR	Signal-to-Noise Ratio
SONET	Synchronous Optical NETwork
SPM	Self-Phase Modulation
T/F	Time/Frequency
WDM	Wavelength-Division Multiplexing
WP	Work Package

WR	White Rabbit
WRON	Wavelength Routed Optical Network
WSS	Wavelength Selective Switches
XPM	Cross Phase Modulation

LIST OF PROJECT PARTNER ACRONYMS

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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
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REFERENCES

[1] P. Moreira, J. Serrano, T. Wlostowski, P. Loschmidt, and G. Gaderer. ‘White Rabbit: Sub-Nanosecond Timing Distribution over Ethernet’. In *2009 International Symposium on Precision Clock Synchronization for Measurement, Control and Communication*, 1–5, 2009. https://doi.org/10.1109/ISPCS.2009.5340196.

[2] Agrawal, Govind P. *Fiber-Optic Communication Systems*. John Wiley & Sons, Inc., 2002. https://doi.org/10.1002/0471221147.ch1.

[3] W. J. Miniscalco. ‘Erbium-Doped Glasses for Fiber Amplifiers at 1500 Nm’. *Journal of Lightwave Technology* 9, no. 2 (February 1991): 234–50. https://doi.org/10.1109/50.65882.

[4] Desurvire, Emmanuel, Dominique Bayart, Bertrand Desthieux, and Sebastien Bigo. *Erbium-Doped Fiber Amplifiers : Device and System Developments*. New York, United States: John Wiley and Sons Ltd, 2002.

[5] Agrawal, G. *Nonlinear Fiber Optics*. Optics and Photonics. Elsevier Science, 2001. https://books.google.fr/books?id=wjHP0oAVcScC.

[6] Keiser, Gerd E. ‘A Review of WDM Technology and Applications’. *Optical Fiber Technology* 5, no. 1 (1 January 1999): 3–39. https://doi.org/10.1006/ofte.1998.0275.

[7] M. G. Taylor. ‘Coherent Detection Method Using DSP for Demodulation of Signal and Subsequent Equalization of Propagation Impairments’. *IEEE Photonics Technology Letters* 16, no. 2 (February 2004): 674–76. https://doi.org/10.1109/LPT.2003.823106.

[8] Ippen, E.P., and R.H. Stolen. ‘Stimulated Brillouin Scattering in Optical Fibers’. *Applied Physics Letters* 21, no. 11 (1972): 539. https://doi.org/10.1063/1.1654249.

[9] Gysel, P., and R. K. Staubli. ‘Statistical Properties of Rayleigh Backscattering in Single-Mode Fibers’. *Journal of Lightwave Technology* 8, no. 4 (April 1990): 561–67. https://doi.org/10.1109/50.50762.

[10] ‘Recommendation ITU-T G.652: Characteristics of a single-mode optical fibre and cable’, 11/2016. http://handle.itu.int/11.1002/1000/13076

[11] ITU-T Technical report ‘Optical fibres, cables and systems’, 2015. https://www.itu.int/pub/T-TUT-HOME-2015-OFCS

[12] Saleh, A. A. M., and J. M. Simmons. ‘All-Optical Networking—Evolution, Benefits, Challenges, and Future Vision’. *Proceedings of the IEEE* 100, no. 5 (May 2012): 1105–17. https://doi.org/10.1109/JPROC.2011.2182589.

[13] ‘Recommendation ITU-T G.655: Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable’. 2009.

[14] ‘Synchronization as a Service’. White Paper. NOKIA, 2016. [Online]. Available: https://onestore.nokia.com/asset/200644/Nokia_Synchronization_as_a_Service_White_Paper_EN.pdf.

[15] A. H. Gnauck, R. W. Tkach, A. R. Chraplyvy, and T. Li. ‘High-Capacity Optical Transmission Systems’. *Journal of Lightwave Technology* 26, no. 9 (May 2008): 1032–45. https://doi.org/10.1109/JLT.2008.922140.

[16] ‘The Zettabyte Era: Trends and Analysis’. White Paper. CISCO, June 2017. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.html.

[17] Savory, Seb J. ‘Digital Filters for Coherent Optical Receivers’. *Optics Express* 16, no. 2 (21 January 2008): 804–17. https://doi.org/10.1364/OE.16.000804.

[18] ‘Coherent WDM Technologies’. White Paper. INFINERA, 2016. [Online]. Available: https://www.infinera.com/wp-content/uploads/2015/07/Infinera_Coherent_Tech.pdf.

[19] ‘Exceeding 100 Gb/s in Reserqch Qnd Education Networks’. White Paper. CIENA, 2014. [Online]. Available:

http://media.ciena.com/documents/Exceeding_100_Gbs_in_Research_Networks_WP.pdf.

[20] ‘Cisco CPAK for 100-Gbps Solutions’. White Paper. CISCO, 2017. [Online]. Available: https://www.cisco.com/c/en/us/solutions/service-provider/100-gigabit-solution/white-paper-listing.html.

[21] Melle, Serge, Geoff Bennett, Chris Liou, Curtis Villamizar, and Vijay Vusirikala. ‘Alien Wavelength Transport: An Operational and Economic Analysis’. In *Optical Fiber Communication Conference and National Fiber Optic Engineers Conference*, NThF2. OSA Technical Digest (CD). Optical Society of America, 2009. https://doi.org/10.1364/NFOEC.2009.NThF2.

[22] D. Ventorini, E. Moura, L. Paraschis, O. Gerstel, M. Silva, K. Wollenweber, A. J. Silverio, P. P. H. Junior, and L. A. C. H. Silva. ‘Demonstration and Evaluation of IP-over-DWDM Networking as “Alien-Wavelength” over Existing Carrier DWDM Infrastructure’. In *OFC/NFOEC 2008 - 2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference*, 1–6, 2008. https://doi.org/10.1109/OFC.2008.4528272.

[23] ‘Recommendation ITU-T G.709: Interfaces for the optical transport network’. 2016.

[24] ‘Recommendation ITU-T G.872: Architecture of optical transport networks’. 2017.

[25] ‘Recommendation ITU-T G.8251: The control of jitter and wander within the optical transport network (OTN)’. 2010.

[26] ‘Recommendation ITU-T G.8262: Timing characteristics of a synchronous Ethernet equipment slave clock’. 2010.

EXECUTIVE SUMMARY

This deliverable, D1.2 “Current and Emerging Commercial Optical Transport Standards”, is part of Task 1.2 of Work Package 1 of the CLONETS project. The deliverable provides an overview of the current network status of National Research and Education Network (NREN) facilities, which was obtained through a survey of NRENs, and reviews the current and emerging fibre communication technologies deployed by NRENs. The deliverable focuses on the NRENs’ capacity for integrating a Time and/or Frequency (T/F) transfer service and the deployed fibre-optic networking techniques’ compatibility with T/F transfer techniques. The aim of the deliverable is to enable scientists to gauge the implications the integration of newly developed T/F technologies would have for an NREN.

As said, this deliverable presents the results of a survey of NRENs on their fibre network infrastructure, to which 16 NRENs replied. The review focuses on the capacity for integrating a T/F transfer service into an NREN network and on the compatibility of current and emerging fibre-optic networking techniques with T/F transfer techniques.

The optical fibres of the NRENs’ networks are either leased from suppliers or are owned, whereby the (co-)ownership is generally established through an Indefeasible Right of Use (IRU) contract. On average the fibre contracts are renewed every 11 years and the equipment manufacturer contracts every 3.5 years. These timescales dictate the evolution of the fibre networks and need to be considered when designing an integrated T/F transfer service. As NRENs operate on a national scale, their networks span thousands of kilometres. A T/F transfer service wanting to exploit these expansive networks and their connectivity is required to be compatible with long-haul fibre links and the optical transport techniques they employ.

Thirteen of the surveyed NRENs replied that they deploy Wavelength-Division Multiplexing (WDM) technology in their network, of which ten of these NRENs are currently exploiting less than a fourth of their available optical channels. However, the NRENs generally envision to use a larger percentage of their optical channels in the future. T/F transfers could potentially be implemented as an Alien lambda[1] occupying an optical channel in an NREN DWDM network, especially since fifteen of the NRENs replied that they would be willing to adopt such an approach in their network. However, most NRENs (12 replies) are uni-directional by design. They therefore do not support a bi-directional propagation of the signals, a feature the highest performance T/F transfers rely on for noise cancelling and calibration purposes. Consequently, an implementation of such a bi-directional service requires the modification of existing WDM transport links or the establishment of a new link to allow for bi-directional transmission. With regard to installing T/F related equipment in the network, all NRENs answered that they could provide access for installation. Overall, there appears to be a willingness from NRENs to accommodate high performance T/F transfers in their networks.

Since the optical transport techniques employed vary from NREN to NREN, there will be different ramifications for the implementation of a T/F transfer service depending on the specific network. Differences between optical fibre links include amongst others: the physical properties of the optical fibre, modulation techniques, amplification techniques, chromatic dispersion (CD) and polarization mode dispersion (PMD) compensation techniques. As telecommunication networks try to meet the incessant demand for higher data rates, new optical transport techniques are being developed and employed. Among these trends are optical amplifiers, coherent detection, advanced modulation formats, new DWDM techniques (e.g. Superchannel and Flex grid) and Digital Signal Processing (DSP) techniques. In the survey, developing coherent systems, 400 G service (Superchannel) and Flexgrid appear as top

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[1] An Alien Lambda is, in the context, defined as a photonic Dense Wavelength-Division Multiplexing (DWDM) signal carrying user data that is transported transparently without Opto-Electro-Optical (OEO) conversion through the DWDM network (networks) running the equipment of a different make than the signal ingress/egress end-points.

priorities in the next development phase of NRENs. Overall, there is a move away from opto-electro-optical (OEO) conversion in optical fibre links and towards coherent optical transport networks.

While some of the developments are conducive to the implementation of T/F transfer techniques, others might make the implementation of a T/F transfer less evident. Any viable integration of a T/F transfer into a network requires an awareness of the optical transport techniques employed to ensure their compatibility. Generally, the implementation of T/F transfer methods is feasible.

1 INTRODUCTION

In their role, as specialized Internet Service Providers (ISPs) to research and educational communities, National Research and Education Networks (NRENs) have not only traditionally been early adopters of new technologies, but continue to provide a platform for innovation and the establishment of new services. With the development of new technologies, optical fibres have become a convenient, reliable, high-performing and viable medium for the dissemination of time and/or frequency (T/F) reference signals. The integration of a T/F distribution service into the fibre optic network of the NRENs would therefore pave the way for a new high-performance T/F transfer service. The European Clock Network Services project CLONETS is working towards this vision of a fibre-optic based time and frequency distribution service. The aim is the creation of a sustainable, pan-European network providing high-performance "clock" services to European research infrastructures and support to a multitude of lower performance T/F services. For the implementation of T/F services in NRENs, it is important to understand the general infrastructure of the NRENs, the fibre-optic networking technologies employed by them and their capacity to integrate T/F transfer techniques. Chapter 2 presents an overview of the current NREN fibre infrastructure and technology. Chapter 3 gives a more detailed description of transport link construction and the equipment used, including the various transmission impairments which are commonly met and the methods for dealing with them. Finally chapter 4 presents the currently emerging network technologies and their implications for T/F transfer links, followed by the conclusion.

2 NREN FIBRE NETWORK INFRASTRUCTURE

In this section, we will describe a standard European NREN structure and the T/F transfer techniques employed in their networks, including a brief overview of the ownership and contractual status of the networks. This information was obtained in a survey conducted by RENATER in the summer of 2017.

2.1 General information about European NRENs

Under current contracts, most NREN networks renew the fibre and equipment manufacturer contracts on a basis of an average of every 11 years and 3.5 years, respectively. Four facilities "own" the majority (≥70%) of their fibre, whilst twelve facilities rent the majority (≥70%) of their fibre from suppliers. We should be careful when using the verb "to own". The Indefeasible Right of Use (IRU) contract is strongly associated with telecommunication networks as fibre cable owners do not normally sell their fibres but offer IRUs. An IRU is a permanent contractual agreement implying rights and obligations of co-ownership during the contract. Some NRENs "own" their fibres but the fibre path may change through time. This, however, means that a change of fibre and communication components is unlikely to occur in a short term. Any feasible T/F transfer design should take the current NREN optical communications systems into account.

Table 1 gives an indication of the network scales. Most of the networks operate to cover a total length of more than 1000 km. It points out that a successful T/F transfer should be compatible with long-haul optical fibre systems.

Length (km)	Number of facilities
0 – 1000	1
1000 – 5000	6
5000 – 10000	4
10000 – 15000	5

Table 1. NREN facility fibre length category.

With regards to the installation of T/F related equipment in the network, the NREN facilities were asked whether they had any free access to implementing such equipment. All facilities state that access for installation is possible, however, two facilities express that the access is restricted, subject to prior agreement. Implementation of T/F techniques on NRENs requires these arrangements to be taken into account in advance.

2.2 Overview of the optical spectrum and the WDM technology deployed in the networks

Ten facilities are currently using 25% or less of their optical channels, as displayed by the blue bars in Figure 1. Overall, the facilities expect to utilise a larger percentage of the channels in the future, as indicated by the orange bars. State of the art T/F transfers require either dark fibres or dark channels. Figure 1 shows that obtaining the provision of optical channels for the deployment of T/F transfer services is an important next strategic step.

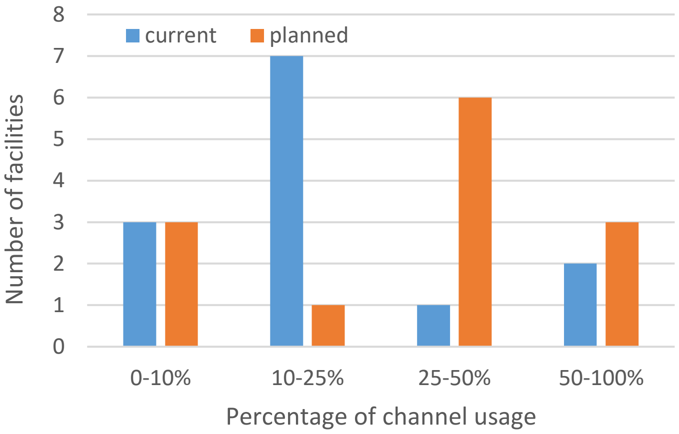

Figure 1. Optical channel usage in surveyed NRENs.

Currently, ten NRENs are sharing their optical spectrum with other entities. In particular, the Alien Lambda approach was considered. In this document, we define an Alien Lambda as a photonic Dense Wavelength-Division Multiplexing (DWDM) signal carrying user data that is transported transparently without Opto-Electro-Optical (OEO) conversion through the DWDM network (networks) running the equipment of a different make than the signal ingress/egress end-points. Fifteen groups out of the sixteen are willing to adopt this approach (one response is missing). Caution is raised on how to mitigate losses induced by additional Alien Lambda equipment.

Twelve facilities state that their networks are set up for mono-directional transmission (as expected of long haul telecommunication networks), that is, the fibre links only support the transmission of light in one direction through the fibre with the transmission in the reverse direction being blocked. Only one facility adapts a hybrid method to enable bi-directional transmission. The conversion from a status quo mono-directional transmission setup to a bi-directional one might not be straightforward.

Eleven facilities have set up conventional T/F transfers over the network, including one case of IEEE 1588 Synchronous Ethernet, eleven cases of Network Time Protocol (NTP), one case of Precision Time Protocol (PTP) and one case of frequency transfer. One facility implemented the more modern White Rabbit protocol (WR) [1]. This illustrates the potential to upgrade to more accurate T/F transfer standards. More details on the technical aspects of the NREN settings are discussed in the following section with a brief introduction to long-haul optical fibre communication techniques.

3 A BRIEF SUMMARY OF OPTICAL TRANSPORT SYSTEMS AND THEIR NREN EMPLOYMENT

3.1 Long-haul optical transport links

Figure 2 shows a block diagram of the three main elements of a simplified optical transport system. Electrical signals are first converted to optical signals by an optical transmitter and then fed into the communication medium, optical fibre. An optical receiver at the other end of the optical fibre detects the optical signal and produces electrical data. Optical amplifiers and dispersion compensation modules are often added to mitigate fibre impairments [2]. In this section, key elements of the NREN optical communication systems are introduced in turn, showing the background for employing optical T/F transfer methods.

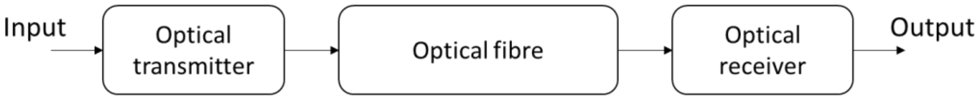

Figure 2. Block diagram of an optical transport system.

3.1.1 Optical transmitter

The function of an optical transmitter is to process and convert incoming electrical data signals into an optical form before feeding it into optical fibre. A basic optical transmitter consists of an optical source and a modulator. Bit-Error-Rate (BER), is the main indicator to evaluate the quality of a telecommunication link. It measures the number of received bits of a data stream over a communication medium that have been altered due to noise, interference, distortion or bit synchronization errors. A high Signal-to-Noise Ratio (SNR) and a narrow linewidth of the optical source are highly desirable to obtain the lowest BER.

The carrier signal is modulated with an input signal for the purpose of conveying information. Different types of modulation techniques are implemented to increase the bit rate. The bit rate can be increased through a faster modulation (number of symbols per second or baud rate) and/or a larger number of bits per symbol (higher constellation).

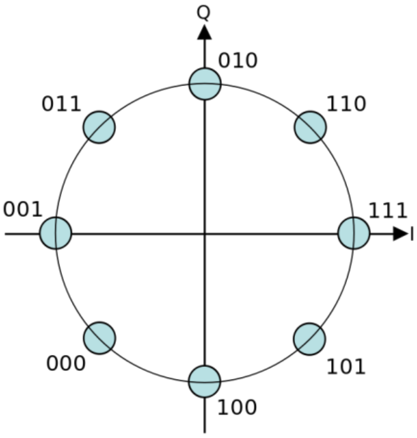

Figure 3. A constellation diagram for Gray encoded 8-PSK.

A variety of modulation techniques are employed in the surveyed networks, including eight cases of Amplitude Shift Keying (ASK), two cases of Phase Shift Keying (PSK) and more sophisticated modulation techniques, such as four cases of Quadrature Amplitude Modulation (QAM), four cases of Quadrature PSK (QPSK), twelve cases of Dual Polarization QPSK (DP-QPSK) and one case of Dual Polarization QAM (DP-QAM). Understandably, optical systems tend to adopt more advanced modulation formats to cater to the increasing data rate demand. The modulation formats do not have a direct impact on other channels as long as the overall optical power is kept low. Adding a new modulation format at the emission side requires the use of a new receiver able to detect the new format. The T/F services will have to comply with the modulation format acceptable at the receiver end, if they use that equipment instead of separate, T/F-compatible equipment..

3.1.2 Optical fibre

Optical fibre is a non-perfect transmission path causing impairments to optical signals. This section reviews the transmission impairments and the conventional techniques employed to overcome them. We will consider Single-Mode Fibres (SMFs), which are employed by NRENs to support metro-scale and long-haul transmission. Optical fibres, composed of silica, allow for minimal losses at 1.55 µm and thus the C-band (1.53-1.565 µm) ([3], [4]) is preferred for long range transmissions. For this reason, semiconductor laser optical sources operating at single narrow-line wavelengths near 1.5 µm are widely employed for long-haul communications. In this section, the fibre properties are explained with a brief introduction to optical components used for fibre impairment mitigation.

Losses

Optical signal power in a silica fibre decreases exponentially with fibre length. The loss, i.e. the exponential decay rate, is described in units of dB/km. In the short wavelength range, losses are dominated by Rayleigh scattering, whereas in the long wavelength range, losses are mainly due to infrared absorption by the medium. In silica fibres minimum losses occur at 1550 nm.

Erbium-Doped Fibre Amplifiers (EDFAs) are the most commonly used equipment to compensate the loss thanks to their excellent performance at 1.55 µm. Further to their operating wavelength range advantage, EDFAs can amplify optical signals with a relatively flat gain, a high pump power utilization (>50%) and a low noise figure. EDFAs have been a key technique driving the development of DWDM networks [4].

Chromatic Dispersion (CD)

Due to the wavelength-dependent refractive index of optical fibres, wavelengths propagate at different speeds in the fibre, resulting in a spreading of the optical pulse in time. This phenomenon is referred to as Chromatic Dispersion (CD). CD for a standard SMF is 17 ps/nm/km at 1.55 µm. CD is a key limiting factor for high-speed optical communication systems. Typically, for example, upgrading a 1.55 µm Non-Return-to-Zero (NRZ) system from 1 Gbps to 10 Gbps, causes the achievable reach to drop by two orders of magnitude, i.e. from 1836 km to 18 km, and upgrading to 40 Gbps causes the range to further drop, i.e. approximately to 1.14 km. Any successful T/F transfer method must account for the impact of CD [5]. Dispersion Compensating Fibre (DCF) with a large negative dispersion (-170 ps/nm/km) has been developed to compensate for the CD in the optical fibre [6].

Polarisation Mode Dispersion (PMD)

Two orthogonal polarisation modes in a fibre travel at different speeds due to small variations of the fibre geometry; the resulting interference between the two polarisation modes and the consequent optical pulse broadening, is referred to as Polarisation Mode Dispersion (PMD). The PMD induced time delay is proportional to the square root of the distance with a coefficient expressed units of $\mathrm{ps}/\sqrt{\mathrm{km}}$ with typical values ranging from 0.1 to 1 $\mathrm{ps}/\sqrt{\mathrm{km}}$. For a typical link transmission distance no longer than 100 km, the impact of PMD scaling with the square root of the fibre length is relatively small as compared to that of CD. Coherent systems detect the linear transmission impairments of CD and PMD at the receiver and apply Digital Signal Processing (DSP) to equalise and remove these signal impairments [7].

Non-linear impairments

Apart from linear impairments (CD and PMD), which are not proportional to the optical intensity, nonlinear impairments of optical fibre produce a signal distortion that increases dramatically with optical intensity. The Kerr effect, one of the major nonlinear impairments, is the variation of the refractive index of the transmission media with the instantaneous optical intensity, giving rise to the phenomena of Self-Phase Modulation (SPM), Cross Phase

Modulation (XPM) and Four Wave Mixing (FWM) [5]. Another fibre nonlinear impairment arises from interactions between the optical field and the medium through molecular vibrations, as in Brillouin scattering [8] and Raman scattering [9].

3.1.3 Receiver

The function of an optical receiver, or a photodetector, at the end of the optical fibre is to convert optical signals into electrical signals. The requirements for photodetectors are high sensitivity, fast response, low noise, and high reliability.

3.2 Wavelength-division multiplexing and wavelength-routed networks

Wavelength-Division Multiplexing (WDM) is essentially frequency-division multiplexing at optical carrier frequencies. Optical carriers generated by narrow linewidth semiconductor lasers are multiplexed at the transmitter end before being fed into the optical fibre using passive filters or Reconfigurable Optical Add-Drop Multiplexers (ROADMs), for example. The optical carriers are positioned at a frequency spacing of, e.g. 100 GHz or equivalently 0.8 nm for dense WDM (DWDM). At the receiver, the carriers are separated using wavelength filtering techniques. Wavelength multiplexing and de-multiplexing can be, for example, achieved with Arrayed Waveguide Gratings (AWGs). AWGs operate with a low insertion loss and high suppression of adjacent channels. Figure 4 shows a schematic of a WDM system. On the left, an optical transmitter emits an optical carrier at a certain wavelength as marked with a specific colour. The carrier is then multiplexed with other carriers via the wavelength multiplexer before being sent into fibre. The de-multiplexing reverses the process as the aggregated carriers are separated into different ports and sent to a receiver.

A key feature of DWDM based on ITU-T Recommendation G.692, is that discrete wavelengths form an orthogonal set of carriers with a spacing of 50 GHz or 100 GHz (0.8 nm). European NRENs use both spacings. The channels can be transmitted, routed and switched without interfering with one another, provided the overall optical power is kept sufficiently low to avoid nonlinear effects. WDM compliant with the ITU standard is based on a specific channel frequency spacing ([10], [11]). The ITU-T Recommendation G.692, one of the most widely applied standards, utilises a grid of frequencies referenced to 193.100 THz (or 1552.524 nm in equivalent) with a spacing of 100 GHz (0.8 nm) for the carrier selection.

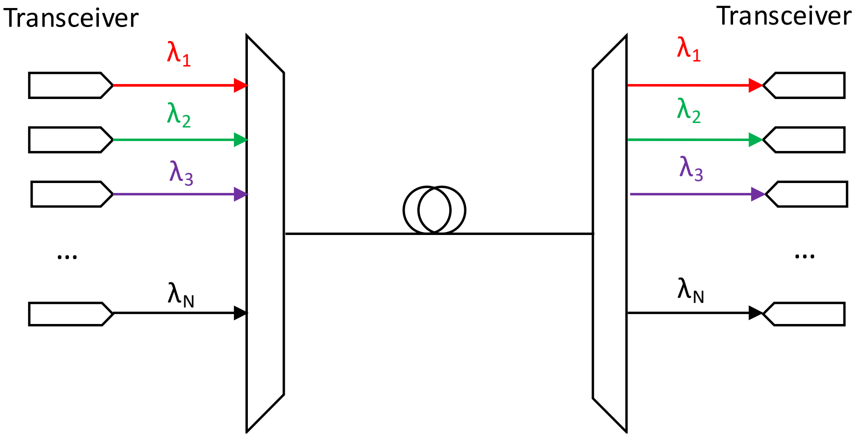

Figure 4. A WDM transport system.

Wavelength Routed Optical Networks (WRONs) comprise optical transmitters, receivers and ROADM, interconnected by optical fibres [12]. A ROADM has the ability to add, block, pass or redirect light beams of various wavelength from a WDM. This is achieved through the use of two major technologies: Wavelength Selective Switches (WSS) and Planar light wave circuit. WSSs can route individual wavelengths from the input port to the output port. A ROADM operates to drop an optical carrier to a receiver, or conversely, add one from a transmitter to the output port. Optical amplifiers are placed at intermediate points to compensate the losses of WSSs. It should be pointed out that ROADMs are only deployed at a Point of Presence (PoP) where traffic is generated, routed or extracted. ROADMs or even filters are not normally found in the In-Line Amplifier (ILA) node, which boosts the signal power mono-directionally between two PoPs. A typical NREN topology is described in the next section.

3.3 NREN implementation

Fibres compliant with ITU-T G.652D and G.655 are commercially available and employed by NRENs. G.652D is the most popular option used by 12 out of 14 facilities at a percentage of more than 50%. G.655, on the other hand, offering better performance at a cost, is used by 9 facilities at a percentage of 20%. The fibre characteristics are shown in Table 2.

Using coherent technology, meaning having DSP to counterbalance CD as well as the PMD, gives NRENs the opportunity to use G.652 fibres without degrading the performance of the link. In order to analyse the received signals, the operation of DSP modules requires a minimum level of CD and PMD. This explains why some NRENs are deliberately adding some CD via Dispersion Compensation Modules (DCMs) at the extremity of G.655 links.

G.652D compliant				G.655 compliant			
λ [nm]	Attenuation coefficient [dB/km]	CD coefficient [ps/(nm·km)]	PMD coefficient [ps /√km]	λ [nm]	Attenuation coefficient [dB/km]	CD coefficient [ps/(nm·km)]	PMD coefficient [ps /√km]
1310	0.40		0.20	1310			
1550	0.30	13.3 ≤ CD CD ≤ 18.6	0.20	1550	0.35	≤ 2.80	0.20
1625	0.40	17.2 ≤ CD CD ≤ 23.7	0.20	1625	0.4	≤ 11.26	0.20

Table 2. ITU-T fibre characteristics recommendations ([13], [14]).

A schematic of a typical telecom link in an European NREN is given in Figure 5. The average link loss between two ILAs is 17.9 dB, equivalent to 89.5 km assuming a 0.20 dB/km loss per unit length. The maximum link loss ranges from 20 to 53 dB. The average link loss between two PoP is 44 dB, equivalent to 220 km. This implies that there are, on average, two ILAs between two PoPs. The implications of using these long uncompensated links for an implementation of a T/F transfer should be carefully taken into consideration. The surveyed chromatic dispersion falls in the range from 4 to 22 ps/(nm·km), in line with the value of G.652 compliant fibre [10]. To compensate the CD over the network, ten facilities use DCMs among which four employ fibre Bragg gratings complementarily and five employ transceiver DSP modules. Four NRENs use DSP alone. T/F transfer methods using a DSP compensated link should take into account that the link itself is not CD-compensated.

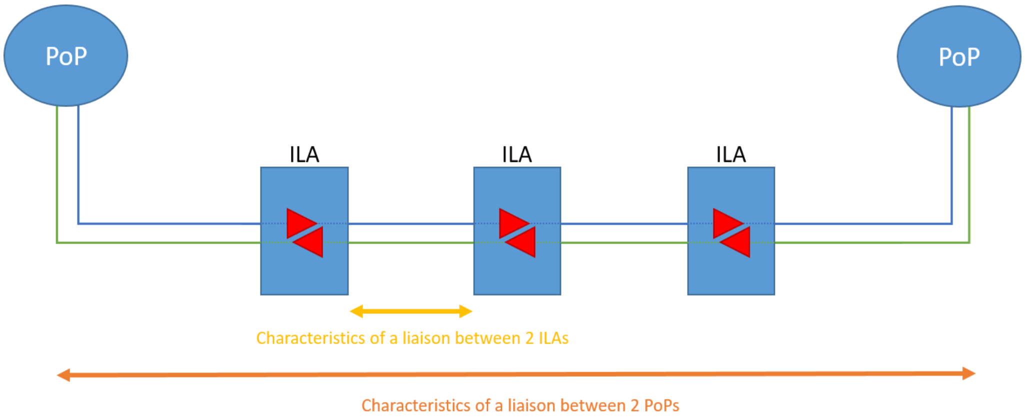

Figure 5. A typical telecom link in a European NREN.

Currently, packet-based techniques, e.g. IEEE 1588v2 or Precision Time Protocol (PTP) are used to provide T/F transfers [14]. The principle of PTP is based on the exchange of a time stamped packet between a master clock and a slave clock, assuming a symmetrical delay between the two clocks. However, the mono-directional transmission allows asymmetry in transmission. For example, a fixed asymmetry introduced by a fibre path length difference gives a 2.5 ns/m synchronisation error. Even larger time errors are introduced by packet processing and switching components in flexible WRONs. Optical Timing Channels (OTCs), considered by several NREN facilities, could transmit PTP packets in a dedicated channel bypassing optical network units that introduce unbalanced time delays.

4 EMERGING OPTICAL TRANSPORT TECHNIQUES

4.1 Towards coherent optical transport networks

With the invention of new WDM technologies and with the aid of chromatic dispersion compensating fibre, the capacity of fibre has moved from 2.5 Gbps to 10 Gbps per wavelength [15]. 10 Gbps per wavelength is achieved by intensity modulation or On-Off Keying (OOK) with direct detection. This scheme, however, cannot meet the growing demand for data rates, increasing by 40% per year [16], due to its low spectral efficiency and susceptibility to fibre impairments such as CD and PMD. High-order modulation formats and powerful coherent detection with digital signal processing have been developed to deliver data rates beyond 10 Gbps per wavelength covering the same optical reach [17].

Modulation format	Bits/symbol
BPSK	1
QPSK	2
8QAM	3
16QAM	4

Table 3. Modulation formats.

High-order modulation formats, as shown in Table 3, are achieved by encoding with a nested Mach-Zehnder Modulator (MZM). It is possible to increase the number of bits per symbol without necessarily increasing the sensitivity to fibre impairments. Furthermore, two carriers with orthogonal polarisations can be generated at the transmitter. The advantage of the polarisation modulation is to lower the processing speed requirements on the opto-electronics. At the receiver, the optical signal is first split into two orthogonal polarisations. The resultant signals are optically mixed with a local oscillator, allowing the phase components of the signal to be extracted. The optical signals are detected and converted into the electrical domain by two pairs of balanced photodetectors. DSP is employed to compensate CD and PMD and to recover the carrier frequency. Coherent optical transport systems transmitting a data rate of more than 100 Gpbs per wavelength with an optical reach of 9,000 km have been demonstrated ([18], [19], [20]).

Spectral efficiency, calculated as the number of bits transmitted per Hz of optical frequency, is a measure of the optical transport efficiency. For example, the spectral efficiency of 10 Gbps per wavelength is only 0.2 bit/Hz for a 50 GHz ITU grid, while 100 Gbps per wavelength provides a ten times improvement in spectral efficiency at 2 bits/Hz. The more bits transmitted per channel, the greater is the improvement in spectral efficiency and the increase in overall network capacity and the lower is the cost per bit of the optical transport. The downside of an advanced modulation format is its need for a higher signal-to-noise ratio, which limits the transmission distance. Coherent detection with signal processing aims to mitigate these effects and to enhance the transmission distance.

Research has been exploring the option of allocating spectrum to improve the spectral efficiency. One enabling technique is to utilise flexible WSS at a frequency spacing of 12.5 GHz (Flexgrid). The new standard will support a mixture of channel sizes with steps of 12.5 GHz, to accommodate existing services, such as 100 GHz, future 400 GHz and 1 THz optical rates (ITU G694.1).

In the survey, developing coherent systems, 400 G service (Superchannel) and Flexgrid appear as top priorities in the next development phase of the NRENs. T/F transfer methods being developed need to take into account compatibility with the NRENs' development.

4.2 Alien Lambda

The schematic shown in Figure 4 for a WDM system is a simplified view of the real implementation. In reality, the WDM system terminates at the transceivers and the optical signal is converted to an electronic signal and then back to an optical signal before being carried by low-cost short-reach non-WDM optics to clients, i.e. the signal undergoes an OEO conversion [21]. The non-WDM optics are marked as grey in Figure 6. The reason why the transponders are separated from the client non-WDM optics is because they are engineered to provide a reliable long-haul transmission with optimisation, control and management of the WDM signals.

The industry has explored the possibility of all photonic network concepts and looked into options to remove the existing OEO conversion, although options allocating lambdas to every client are limited. The concept of an alien lambda has been introduced as an attempt to remove additional OEO conversions because some specific client signals, such as metrological signals, may lose their characteristics, e.g. spectral purity [22]. This is obtained by relocating the WDM transponders to the client's systems, as illustrated in Figure 6. An alien lambda which has a different optical wavelength from the WDM can be set up to bypass the vendor's transponders. The utilisation of the optical channels needs to be carefully planned and the correct amount of optical power needs to be injected.

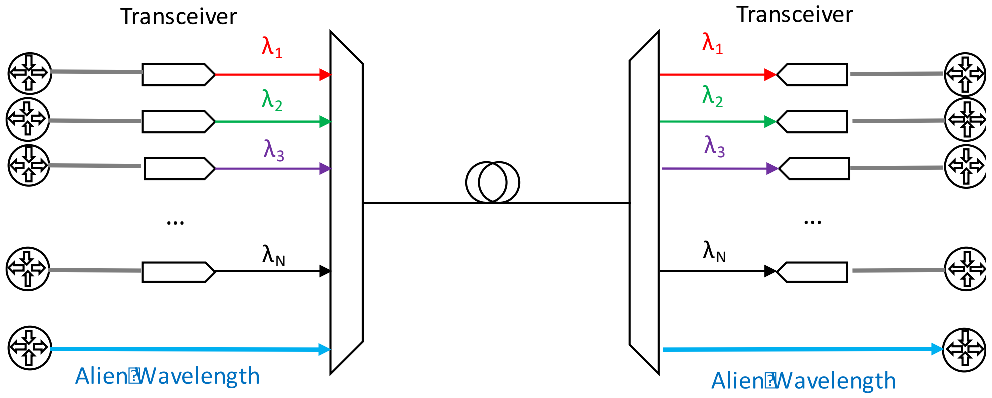

Figure 6. A WDM transport system adapting an Alien Lambda channel.

In 2009, SURFnet and NORDUnet established a 40 Gbps link between Amsterdam and Copenhagen with an adjacent concurrent 10 Gpbs channel. The industry has taken initiatives in bringing forth alien lambda, for example, ADVA, Cisco and Packetlight. There is a debate on whether the alien lambda system has operational reliability and economic benefits [21]. Despite the doubt on whether the alien lambda will take over conventional WDM systems, the transmission of an alien channel has been demonstrated. It seems that T/F signals can be inserted into existing WDM systems as an alien channel. It should be noted that extra steps need to be taken to adopt a bi-directional transmission in current WDM transport links (Section 3.1) and that the CD compensated by the coherent detectors needs to be taken into account.

4.3 Optical Transport Network (OTN)

OTNs as defined in ITU-T G.709 [23] and in ITU-T G.872 [24] are a set of Optical Network Elements (ONEs), e.g. optical amplifiers, switches, multiplexers, etc. connected by optical fibre links, which can have the functionality to transport, multiplex, switch, manage, supervise the optical channels carrying client signals. There exist two classes of Optical Transport Units (OTUs): the OTUk and the OTUCn. We will briefly describe the differences between the two and focus on OTUk, which is more commonly used. An OTUk signal consists of a 4080 column by 4 row frame, including 256 columns allocated to contain Forward Error Correction (FEC), and is operated at various bit rates represented by the value of k. The OTUCn does not include an FEC area and is operated at n-times the basic rate represented by OTUC. The OTUk contains an Optical Data Unit (ODUk) and the ODUk contains an Optical Payload Unit (OPUk). The OTUk and its ODUk perform digital section and have path layer roles.

OTN aims to combine the benefits of the SONET/SDH technology with the bandwidth expandability of DWDM. OTN specifies a digital wrapper, which is a method for encapsulating an existing frame of client data, which is designated as payload, regardless of the native protocol, i.e. OTN offers protocol transparency. This process is called mapping. Client signals are mapped into an Optical Payload Unit (OPU), then into an Optical Data Unit (ODU) and finally into an OTU, each level of mapping aggregating lower layers and adding specific information. A key element of a digital wrapper is a Reed-Solomon FEC mechanism that improves the error performance on noisy links.

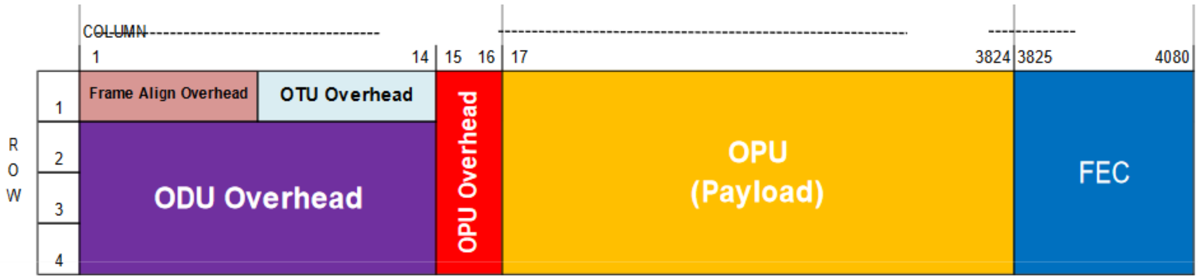

Figure 7. OTU(k = 1, 2, 3, 4) frame structure: 4 rows of 4080 columns, each cell containing a byte.

OTU	ODU	Common name	OTU nominal bit rate	ODU nominal bit rate	ODU bit rate tolerance
	0	1.25G	NA	1.244 Gbps	±20 ppm
1	1	2.5G	2.666 Gbps	2.488 Gbps	±20 ppm
2	2	10G	10.709 Gbps	9.953 Gbps	±20 ppm
3	3	40G	43.018 Gbps	39.813 Gbps	±20 ppm
4	4	100G	111.809 Gbps	104.794 Gbps	±20 ppm

Table 4. Some characteristics of existing OTU containers.

The OTN is not required to transport synchronization since there is no requirement for the different optical channels to be synchronous. However, it is required to limit jitter and wander accumulation [25]. Therefore, if the client service (for example, SDH, SONET, Synchronous Ethernet) requests a synchronous transmission, the OTN can support it by implementing a timing "transparent" service mapping, such as BMP, AMP or GMP:

- Bit-synchronous Mapping Procedure (BMP) is the simplest mapping mechanism. It involves no rate adaptation and can be used if the server rate is explicitly derived from the client rate.
- Asynchronous Mapping Procedure (AMP) is a mechanism that maps a client into a server when the two rates are asynchronous or independent. In these scenarios, both the client and server have equivalent nominal bit rates but each has some tolerance. As a result, it is possible for the client rate to be higher than the server or the server rate to be higher

than the client at any given instance. To accommodate this, AMP has both negative and positive justification capabilities. It maps a ±20 ppm client into a ±20 ppm server.

- Generic Mapping Procedure (GMP) is the most advance mapping technique. It is based on a delta-sigma modulator-based approach, with an equal distribution of stuff and data in the transport container and an asynchronous mapping into the ODU payload. It manages an adaptation mechanism to accommodate both the rate differences and wider client bit rate tolerances of up to ±100 ppm.

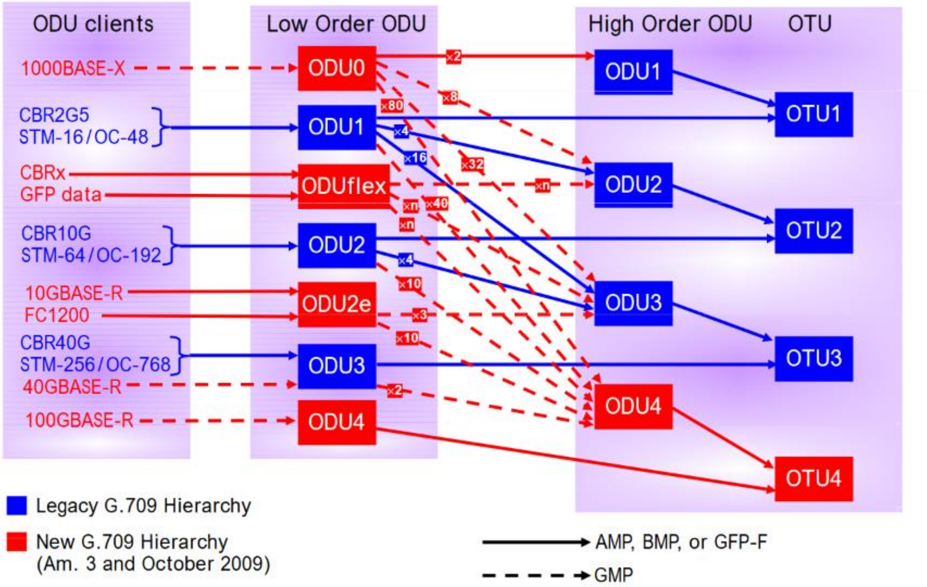

Figure 8. Mappings of the supports for the transport of synchronisation.

Some more advanced architectures are currently under study. The ITU-T G.8262 [26] recommendation outlines, for example, the minimum requirements for timing devices used in synchronizing network equipment that supports Synchronous Ethernet. This type of architecture would support a clock distribution based on network-synchronous line-code methods.

5 CONCLUSION

In this review, the conventional and emerging optical transport techniques are discussed, highlighting the areas related to a potential T/F employment. The current network status of NREN facilities are presented. It is feasible to implement T/F transfer methods in NRENs. However, it should be noted that with the exception of the dark channel or dark fibre approaches, T/F transfer methods need to cope with mono-directional links when utilising WDM systems that include optical amplification, and with chromatic dispersion when optical dispersion compensation is not provided.