Fostering the Innovation Potential of Research Infrastructures

INFRAINNOV-2-2016: Support to Technological Infrastructures

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

Grant Agreement Number: 731107

Deliverable D1.3

Best Practice Guide “Alien Wavelength Services”
Final

Version: 1.0
Lead author(s): Vladimir Smotlacha, CESNET
Date: 28/06/2018

This project receives funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 731107

DOCUMENT INFORMATION

Project and Deliverable Information

Project Acronym:	CLONETS
Project Ref. №:	731107
Project Title:	CLONETS – CLOck NETwork Services: Strategy and innovation for clock services over optical-fibre networks
Project Web Site:	http://www.clonets.eu
Deliverable ID:	D1.3
Deliverable Nature:	Report
Dissemination Level*:	PU
Contractual Date of Delivery:	30/09/2017
Actual Date of Delivery:	28/06/2018
EC Project Officer:	Patricia Postigo-McLaughlin

* The dissemination level is indicated as follows: **PU** – Public, **CO** – Confidential (only for members of the consortium, including the Commission Services), **CL** – Classified (referred to in Commission Decision 2991/844/EC).

Document Control

Document	Title:	Best Practice Guide “Alien Wavelength Services”
	ID:	D1.3
	Version:	1.0
	Status:	Final
	Available at:	http://www.clonets.eu
	File(s):	CLONETS_Deliverable_D1.3_V1.0.pdf
Authorship	Lead author(s):	Vladimir Smotlacha, CESNET
	Contributors:	Anne Amy-Klein, UP13 Eva Bookjans, OBSPARIS Emilie Camisard, RENATER Jochen Kronjäger, NPL Pawel Nogas, PIKTIME Paul-Eric Pottie, OBSPARIS Nicolas Quintin, RENATER Jan Radil, CESNET Łukasz Śliwczyński, AGH Philip Tuckey, OBSPARIS Robert Urbaniak, PIKTIME Radek Velc, CESNET Josef Vojtech, CESNET Aleksander Weinert, PSNC
	Reviewed by:	Eva Bookjans, OBSPARIS Ondřej Číp, UPT AV CR (ISI)
	Approved by:	Philip Tuckey, OBSPARIS

Document Change History

Version	**Date**	**Status**	**Comments**
1.0	28/06/2018	First published version	

Document citation record

Smotlacha, V., Amy-Klein A., Bookjans E., Camisard E., Kronjäger J., Nogas P., Pottie P.-E., Quintin N., Radil J., Śliwczyński L., Tuckey P., Urbaniak R., Velc R., Vojtech J., Weinert A (2018): Best Practice Guide “Alien Wavelength Services” Version 1.0 of D1.3of the HORIZON 2020 project CLONETS. EU Grant agreement no. 731107.

Keywords optical fibre, time transfer, frequency transfer, T/F transfer, multi-point transfer, optical carrier, radio frequency, uni-directional, bi-directional, dark fibre, dark channel, DWDM channel, alien lambda, alien wavelength, optical clock, atomic clock, two-way comparison, T/F dissemination, active compensation, phase conjugation, optical comb, optical amplifier, bi-directional amplification, Raman amplifier, Brillouin amplifier, repeater laser station, White Rabbit, ELSTAB, clock network, clock synchronization, T/F link metrological model

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AD	Administrative Domain
ADEV	Allan Deviation
AM	Amplitude Modulation
AOM	Acousto-Optic Modulator
AOS	Astrogeodynamical Observatory in Borowiec near Poznan, Poland
APC	Angled Physical Contact
AW	Alien Wavelength
BER	Bit Error Rate
BEV	Bundesamt für Eich- und Vermessungswesen, Austria
bidi	bidirectional
BIPM	Bureau international des poids et mesures, France
CBF	Cross Border Fibre
CDG	Colourless/Directionless/Gridless
CEF	Customer Empowered Fibre
CERN	European Organisation for Nuclear Research
CLONETS	CLOck NETwork Services: Strategy and innovation for clock services over optical-fibre networks Project
CW	Continuous Wave
DCI	Data Centre Interconnect
DCN	Dynamic Circuit Network
DWDM	Dense Wavelength Division Multiplexing
EC	European Commission
EDFA	Erbium Doped Fibre Amplifier
ELSTAB	Electronically Stabilized
FEC	Forward Error Correction
FM	Frequency Modulation
GE	Gigabit Ethernet
GÉANT	Association of European NRENs
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRID	Global Resource Information Database
GUM	Central Office of Measure in Warsaw, Poland
HPC	High Performance Computing
IETF	Internet Engineering Task Force
IPE	Institute of Photonics and Electronics, Czech Republic
ISO	International Organization for Standardization
ISP	Internet Service Provider
ITU	International Telecommunication Union
KM3NET	Cubic Kilometre Neutrino Telescope
LAN	Local Area Network
LAN-PHYS	LAN Physical Layer
LSR	Label Switching Router
LDV	Link Design Value
LPF	Low Pass Filter
LPL	Laboratoire de Physique des Lasers, France
MAN	Metropolitan Area Network
MADEV	Modified Allan Deviation
METODE	MEasurement of TOtal DElay
MPLS	Multiprotocol Label Switching

NIL	Nothing in Line
NF	Noise Figure
NMI	National Measurement Institute
NMS	Network Measurement System
NOC	Network Operation Center
NREN	National Research and Education Networks
NRZ	Non Return to Zero
NTP	Network Time Protocol
OAM	Optical Add Drop Multiplexer
OAMP	Operations, Administration, Maintenance, and Provisioning
OADM	Optical Add-Drop Multiplexer
OEO	Opto-Electro-Optical
OFC	Optical Fibre Communication
OPLL	Optical Phase Locked Loop
OSI	Open System Interconnection
OTN	Optical Transport Network
PACS	Picture Archiving and Communications System
PM	Phase Modulation
PM-QPSK	Polarisation Multiplexed-Quadrature Phase Shift Keying
QPSK	Quadrature Phase-Shift Keying
PMD	Polarization Mode Dispersion
POS	Packet over SONET/SDH
PPP	Precision Point Positioning
PPS	Pulse per Second
PS	Photonic Services
PSEAR	Photonic Services Enable Advance in Research
PTP	Precision Time Protocol
QoS	Quality of Service
R&D	Research and Development
R&E	Research and Education
RF	Radio Frequency
RFC	Request for Comments
RLS	Repeater Laser Station
ROADM	Reconfigurable Optical Add Drop Multiplexer
RZ	Return to Zero
SATRE	Satellite time and ranging equipment
SDH	Synchronous Digital Hierarchy
SFP	Small Form Factor Pluggable
SNMP	Simple Network Management Protocol
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Networking
STM	Synchronous Transport Module
SPBA	Single Pass Bidirectional Amplifier
SS	Spectrum Sharing
SSaaS	Spectrum Sharing as a Service
SyncE	Synchronous Ethernet
SYRTE	Systèmes de Référence Temps-Espace, France
T/F	Time and/or Frequency
TDEV	Time Deviation
TIC	Time Interval Counter
TNC	TERENA Networking Conferences

TRL	Technology Readiness Level
TWOTT	Two Way Optical Time Transfer
TWSTFT	Two Way Satellite time and Frequency Transfer
UTC	Universal Time Coordinated
VLBI	Very Long Baseline Interferometry
VPN	Virtual Private Network
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WP	Work Package
WR	White Rabbit
WSI	Wavelength Selective Isolator
WPM	Cross Phase Modulation

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

REFERENCES

[1] ‘Global Lambda Integrated Facility’, https://www.glif.is/.

[2] L. Altmannová, T. Breach, M. Campanella, M. Carboni, M. Enrico, L. Fischer, R. Pekal, et al. ‘Final GÉANT Architecture’. Deliverable DS1.1.1,2. GEANT, 18 January 2012. https://geant3.archive.geant.org/Media_Centre/Media_Library/Media%20Library/GN3-10-279_DS1.1.1,2%20Final%20GEANT%20Architecture_v1.pdf.

[3] L. Altmannová, M. Altmann, M. Hažlinský, M. Hůla, O. Havliš, G. Korcsmáros, J. Kundrát, et al. ‘Photonic Services: Challenge for Users and for Networkers’. GN3 JRA1 T2 Activity. GEANT, 23 May 2013. https://geant3.archive.geant.org/Media_Centre/Media_Library/Media%20Library/GN3-13-110_JRA1-T2_Photonic-Services.pdf.

[4] Alberto Colmenero, Anna Manolova Fagertun, Daniel Camps Mur, David Schmitz, Frans Panken, Hao Yu, Ilker Demirkol, et al. ‘Blueprint of Services and Research Plan for Future Work’. GN4-1 JRA1 T2 Activity. GEANT, 29 April 2016. https://www.geant.org/Projects/GEANT_Project_GN4-1/Documents/D13-2_Blueprint-of-Services-and-Research-Plan-for-Future-Work.pdf.

[5] ‘Recommendation ITU-T G.698.1: Multichannel DWDM Applications with Single-Channel Optical Interfaces’, 2009.

[6] ‘Recommondation ITU-T G.698.2: Amplified Multichannel DWDM Applications with Single Channel Optical Interfaces’, 2007.

[7] Ruediger Kunze. ‘A Framework for Black Link Management and Control’. Expired Internet Draft. Internet Engineering Task Force, 3 January 2011. https://datatracker.ietf.org/doc/draft-kunze-black-link-management-framework/.

[8] ‘Cross Border Dark Fibre Triangle for Multiple 10 Gigabit Connection of Austrian, Czech and Slovak Research and Education Networks Enabled by Advanced Photonic Technology’. Press release. CESNET, 6 November 2006. http://archiv.ces.net/doc/press/2006/pr061106.html.

[9] ‘CZ-AT-SK Cross-Border Fibre Triangle Fundamentally Upgraded’. Press release. CESNET, 20 April 2016. https://www.cesnet.cz/cesnet/reports/press-releases/cz-at-sk-cross-border-fibre-triangle-fundamentally-upgraded/?lang=en.

[10] K. Slavicek, and V. Novak. ‘Introduction of Alien Wavelength into Cesnet DWDM Backbone’. In *2007 6th International Conference on Information, Communications & Signal Processing*, 1–5, 2007. https://doi.org/10.1109/ICICS.2007.4449739.

[11] 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. IEEE, 2008. https://doi.org/10.1109/OFC.2008.4528272.

[12] ‘Alien Wave Services in the NREN Community’. White Paper, 20 September 2013. https://geant3.archive.geant.org/Media_Centre/Media_Library/Media%20Library/GN3-13-164_MJ1.2.3_White-Paper_Alien-Wave-Services-in-the-NREN-Community_v3.pdf.

[13] Rob Smets. ‘Sharing of Spectrum and Alien Waves in and around SURFnet’. presented at the 3rd TERENA Network Architect Workshop, Copenhagen, 13 November 2014. https://www.terena.org/activities/netarch/ws3/slides/121114-alien.pdf.

[14] Guy Roberts. ‘GEANT Network Evolution - Sharing Fibre Infrastructure’. presented at the GEANT Symposium 2016, Vienna, 8 March 2016. http://slideplayer.com/slide/10744111/.

[15] ‘Recommondation ITU-T G.694.1: Spectral Grids for WDM Applications: DWDM Frequency Grid’, 2012.

[16] Pavel Skoda. ‘Efficient Spectrum Resource Sharing’. presented at the 9th CEF Networks Workshop 2017, Prague, 11 September 2017. https://www.cesnet.cz/wp-content/uploads/2017/05/5_Pavel_Skoda_Efficient-Spectrum-Resource-Sharing-amongst-NRENs-and-GÉANT.pdf.

[17] https://telecominfraproject.com/.

[18] Stephen Hardy. ‘Telecom Infra Project Intros Voyager White Box Open Packet DWDM Transponder’. *Lightwave*, 2 November 2016. http://www.lightwaveonline.com/articles/2016/11/telecom-infra-project-intros-voyager-white-box-open-packet-dwdm-transponder.html.

[19] ‘Lumentum Offers SDN Optical White Box Line’, 20 March 2016. http://www.lightwaveonline.com/articles/2016/03/lumentum-offers-sdn-optical-white-box-line.html.

[20] ‘The Case of Open Line Systems’. White Paper. Coriant, 2017. http://www.lightwaveonline.com/content/lw/en/whitepapers/2017/07/the-case-for-open-line-systems.whitepaperpdf.render.pdf.

[21] Eisenach, Randy. ‘Evolution to Flexible Grid WDM’. *Lightwave*, 26 November 2013. http://www.lightwaveonline.com/articles/print/volume-30/issue-6/features/evolution-to-flexible-grid-wdm.html.

[22] P. Munster, T. Horvath, O. Havlis, J. Vojtech, J. Radil, R. Velc, and E. Skaljo. ‘Simultaneous Transmission of Standard Data, Precise Time, Stable Frequency and Sensing Signals and Their Possible Interaction’. In *Optical Sensors 2017*, 10231:102312A, 2017. https://doi.org/10.1117/12.2266240.

[23] Horvath, Tomas, Petr Munster, Josef Vojtech, Radek Velc, and Vaclav Oujezsky. ‘Simultaneous Transmission of Accurate Time, Stable Frequency, Data, and Sensor System over One Fiber with ITU 100 GHz Grid’. *Optical Fiber Technology* 40 (1 January 2018): 139–43. https://doi.org/10.1016/j.yofte.2017.11.016.

[24] Vojtech, Josef, Jan Radil, and Vladimir Smotlacha. ‘Semiconductor Optical Amplifier with Holding Beam Injection for Single Path Accurate Time Transmission’. In *CLEO: 2015*, JTh2A.78. OSA Technical Digest (Online). Optical Society of America, 2015. https://doi.org/10.1364/CLEO_AT.2015.JTh2A.78.

[25] Terra, O., G. Grosche, and H. Schnatz. ‘Brillouin Amplification in Phase Coherent Transfer of Optical Frequencies over 480 Km Fiber’. *Optics Express* 18, no. 15 (19 July 2010): 16102–11. https://doi.org/10.1364/OE.18.016102.

[26] Josef Vojtěch, Vladimír Smotlacha, and Jan Radil. ‘All Optical Two-Way Time Transfer in Strongly Heterogeneous Networks’. In *Photonics Applications for Aviation, Aerospace, Commercial, and Harsh Environments V*, 9202:92020S–9202–6, 2014. https://doi.org/10.1117/12.2061346.

[27] Josef Vojtěch, Vladimír Smotlacha, and Jan Radil. ‘All Optical Two-Way Time Transfer in Strongly Heterogeneous Networks’. In *Photonics Applications for Aviation, Aerospace, Commercial, and Harsh Environments V*, 9202:92020S–9202–6, 2014. https://doi.org/10.1117/12.2061346.

[28] ‘The 9th CEF Networks Workshop 2017’. CESNET, Prague, September 2017. https://www.cesnet.cz/events/cef2017/?lang=en.

[29] https://www.geant.org/Networks/Pan-European_network/Pages/What-sets-it-apart.aspx.

[30] Altmanová, Lada, and Stanislav Šíma. ‘Development of the CESNET2 Optical Network’. In *TNC 2002 Proceedings*, 2002. https://tnc2002.terena.org/session3c.html.

[31] Sima, Stanislav. ‘Procurement and Lighting of Dark Fibre’. presented at the Workshop on CEF-Networks, CESNET, Prague, 25 May 2004. http://archiv.ces.net/events/20040525/.

[32] Smotlacha, Vladimir, and Alexander Kuna. 'Two-Way Optical Time and Frequency Transfer between IPE and BEV'. In *2012 European Frequency and Time Forum*, 375–78. IEEE, 2012. https://doi.org/10.1109/EFTF.2012.6502405.

[33] V. Smotlacha, and J. Vojtěch. 'Accurate Time Distribution Using Optical Fiber'. In *2015 International Association of Institutes of Navigation World Congress (IAIN)*, 1–5, 2015. https://doi.org/10.1109/IAIN.2015.7352265.

[34] M. Cizek, L. Pravdova, V. Hucl, S. Rerucha, J. Hrabina, B. Mikel, J. Lazar, O. Cip, V. Smotlacha, and J. Vojtech. 'Transfer of Stable Optical Frequency for Sensory Networks via 306 Km Optical Fiber Link'. In *2016 European Frequency and Time Forum (EFTF)*, 1–4. IEEE, 2016. https://doi.org/10.1109/EFTF.2016.7477821.

[35] Josef Vojtech, Martin Slapak, Pavel Skoda, Jan Radil, Ondrej Havlis, Michal Altmann, Petr Munster, et al. 'Joint Accurate Time and Stable Frequency Distribution Infrastructure Sharing Fiber Footprint with Research Network'. *Optical Engineering* 56, no. 2 (2017): 027101-56–57. https://doi.org/10.1117/1.OE.56.2.027101.

[36] V. Smotlacha, J. Vojtěch, and A. Kuna. 'Optical Infrastructure for Time and Frequency Transfer'. In *2013 Joint European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC)*, 481–84, 2013. https://doi.org/10.1109/EFTF-IFC.2013.6702170.

[37] K. Turza, A. Binczewski, W. Bogacki, P. Krehlik, and L. Śliwczyński. 'Time and Frequency Transfer in Modern DWDM Telecommunication Networks'. In *2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS)*, 368–70. IEEE, 2017. https://doi.org/10.1109/FCS.2017.8088894.

[38] Krehlik, Przemyslaw, Lukasz Sliwczynski, Lukasz Buczek, Jacek Kolodziej, and Marcin Lipinski. 'ELSTAB—Fiber-Optic Time and Frequency Distribution Technology: A General Characterization and Fundamental Limits'. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 63, no. 7 (July 2016): 993–1004. https://doi.org/10.1109/TUFFC.2015.2502547.

[39] Łukasz Śliwczyński, Przemysław Krehlik, and Marcin Lipiński. 'Optical Fibers in Time and Frequency Transfer'. *Measurement Science and Technology* 21, no. 7 (2010): 075302. https://doi.org/10.1088/0957-0233/21/7/075302.

[40] Ł. Sliwczynski, P. Krehlik, Ł. Buczek, and M. Lipinski. 'Frequency Transfer in Electronically Stabilized Fiber Optic Link Exploiting Bidirectional Optical Amplifiers'. *IEEE Transactions on Instrumentation and Measurement* 61, no. 9 (September 2012): 2573–80. https://doi.org/10.1109/TIM.2012.2188663.

[41] P. Krehlik, Ł. Sliwczynski, Ł. Buczek, and M. Lipinski. 'Fiber-Optic Joint Time and Frequency Transfer With Active Stabilization of the Propagation Delay'. *IEEE Transactions on Instrumentation and Measurement* 61, no. 10 (October 2012): 2844–51. https://doi.org/10.1109/TIM.2012.2196396.

[42] Łukasz Śliwczyński, Przemyslaw Krehlik, Albin Czubla, Łukasz Buczek, and Marcin Lipiński. 'Dissemination of Time and RF Frequency via a Stabilized Fibre Optic Link over a Distance of 420 Km'. *Metrologia* 50, no. 2 (2013): 133–45. https://doi.org/10.1088/0026-1394/50/2/133.

[43] Ł. Śliwczyňski, P. Krehlik, M. Lipiňski, K. Turza, and A. Binczewski. 'Frequency Distribution in Delay-Stabilized Optical DWDM Network over the Distance of 3000 Km'. In *2015 Joint Conference of the IEEE International Frequency Control Symposium & the European Frequency and Time Forum*, 280–83. IEEE, 2015. https://doi.org/10.1109/FCS.2015.7138841.

[44] Ł. Śliwczyński, P. Krehlik, K. Turza, and A. Binczewski. 'Characterization of the Frequency Transfer over 300 Km of Aerial Suspended Fiber'. In *2016 European*

Frequency and Time Forum (EFTF), 1–3. IEEE, 2016. https://doi.org/10.1109/EFTF.2016.7477756.

[45] http://www.refimeve.fr/.

[46] Kéfélian, Fabien, Olivier Lopez, Haifeng Jiang, Christian Chardonnet, Anne Amy-Klein, and Giorgio Santarelli. ‘High-Resolution Optical Frequency Dissemination on a Telecommunications Network with Data Traffic’. *Optics Letters* 34, no. 10 (15 May 2009): 1573–75. https://doi.org/10.1364/OL.34.001573.

[47] Chiodo, Nicola, Nicolas Quintin, Fabio Stefani, Fabrice Wiotte, Emilie Camisard, Christian Chardonnet, Giorgio Santarelli, Anne Amy-Klein, Paul-Eric Pottie, and Olivier Lopez. ‘Cascaded Optical Fiber Link Using the Internet Network for Remote Clocks Comparison’. *Optics Express* 23, no. 26 (28 December 2015): 33927–37. https://doi.org/10.1364/OE.23.033927.

[48] Lopez, Olivier, Amale Kanj, Paul-Eric Pottie, Daniele Rovera, Joseph Achkar, Christian Chardonnet, Anne Amy-Klein, and Giorgio Santarelli. ‘Simultaneous Remote Transfer of Accurate Timing and Optical Frequency over a Public Fiber Network’. *Applied Physics B* 110, no. 1 (1 January 2013): 3–6. https://doi.org/10.1007/s00340-012-5241-0.

[49] https://www.orc.soton.ac.uk/distributedopticalfibresensors.

[50] P. Munster, T. Horvath, O. Havlis, J. Vojtech, J. Radil, R. Velc, and E. Skaljo. ‘Simultaneous Transmission of Standard Data, Precise Time, Stable Frequency and Sensing Signals and Their Possible Interaction’. In *Optical Sensors 2017*, 10231:102312A, 2017. https://doi.org/10.1117/12.2266240.

[51] Horvath, Tomas, Petr Munster, Josef Vojtech, Radek Velc, and Vaclav Oujezsky. ‘Simultaneous Transmission of Accurate Time, Stable Frequency, Data, and Sensor System over One Fiber with ITU 100 GHz Grid’. *Optical Fiber Technology* 40 (1 January 2018): 139–43. https://doi.org/10.1016/j.yofte.2017.11.016.

EXECUTIVE SUMMARY

This deliverable D1.3 reviews the CLONETS project partners experience with “alien wavelength” services, also known as “alien lambda” services, and provides a “best practice” guide. Related materials collected within the GÉANT GN3 and GN4 programs are also included in the review.

The capacity of optical fibres has significantly increased through the introduction of dense wavelength division multiplexing (DWDM) systems as this allows the propagation of multiple optical carriers or wavelengths through a single optical fibre. In the alien wavelength (AW) approach, a wavelength generated by a third party is introduced into and travels through such a DWDM transmission system. The infrastructure of the DWDM system is thus shared between the wavelengths of the fibre link operator and the introduced alien wavelength. Consequently, in order to guarantee the performance of the AW and to avoid interferences and cross talk, their deployment must be well planned and they must be well managed. It is crucial to ensure that the AW and the network are compatible.

AWs have been around for a little over a decade and have been successfully deployed in a number of European NRENs. The alien wavelength concept has also been applied to the transfer of time and frequency (T/F) signals and implemented in various different NREN networks, while the details of the implementation vary from network to network. For high precision T/F transfers, which require bi-directional transmission, the main challenge for implementation is the uni-directional nature of most networks. In the Dark Channel approach, the T/F signal, while sharing the spectrum in the fibre, bypasses all network equipment and thus allows for bi-directional propagation of the T/F signal in an otherwise uni-directional network. This deliverable describes the implementations of T/F transfer in the CESNET, PSNC and RENATER networks. The practical experience gathered by these NRENs leads to a set of recommendations or best practices for the implementation of T/F transfer as an AW service.

Important preconditions for a deployment of an AW in an optical data network that need to be considered include:

- The data channels usually have a higher priority than AWs and therefore must not be affected by the AW.
- The optical layer must implement spectrum sharing, typically as a DWDM system.
- The design of an interface between the vendor proprietary system and the AW application under own management in case the two are combined.

Consequently, certain factors that need to be managed, controlled, and constrained, for example:

- Modulation Techniques. Some modulation techniques (e.g. on-off keying) are likely to result in more crosstalk than others (e.g. a carrier wave for frequency distribution).
- Input power levels. The launch power of the light into an AW service needs to be held to within an agreed range. This is especially important for fibre links that include amplification.
- Power variations. The AW users should vary the optical powers at a slow rate in order to give other users of the system time to detect a variation in their pre-Forward Error Correction (FEC) bit error rate (BER), i.e. the error rate before error correction is applied.

1 INTRODUCTION

New possibilities in optical networking in real production networks – a short and generalized introduction

National Research and Education Networks (NRENs) have pioneered new networking concepts and strategies since the early days of their existence. A prime example is the shift from buying leased capacity services from telco operators to lighting (or renting) dark fibres (fibres which are not used for data traffic). This movement has proven to be crucial, especially in terms of saved money, independency, flexibility, and the emergence of new technologies. Despite some initial resistance to this new networking concept, the benefits of transitioning to dark fibres are now, after 20 years of implementation, uncontested. Almost all NRENs and many other networks across the world have consequently adopted this networking concept. The “bottom-up” approach provides the opportunity to explore new ideas, concepts, and applications offered by the optical layer and thus is also referred to as Customer Empowered Fibre (CEF) networking.

First dark fibre networks were based on Packet over SONET/SDH (POS) technology, utilizing rather expensive and very inflexible opto-electro-optical (OEO) regenerators, limiting transmission speed and blocking other types of traffic. Additionally, the first connections over dark fibre were limited to single lambdas connecting router interfaces (usually POS, later Gigabit Ethernet) without any dense wavelength division multiplexing (DWDM) equipment. However, by the mid-2000s, many NRENs had deployed DWDM systems with optical amplifiers and static multiplexers supporting 16/32 or even more DWDM lambdas or channels, with each channel operating at 2.5G or 10G speeds. On an international level, Global Lambda Integrated Facility [1], an international consortium promoting the paradigm of lambda networking, was established.

The race for higher speeds and more wavelengths continues and in 2018 almost all vendors offer 200 Gb/s speed in 50 GHz wide channels and more than 80 channels on a single fibre. Despite this exciting development, not all existing and emerging demands can be satisfied within these rough capacity barriers. New applications requiring new non-data optical signals, low jitter and/or constant delays have started to emerge and require support. In other words, we can draw an analogy between real-time networks and real-time operating systems.

These new ideas and developments have led to the initiation of the project Photonic Services Enable Advance in Research (PSEAR) led by CESNET within the pan European network GÉANT in 2012 ([2], [3]). The three main points of the project are:

1. There is fundamental desire to promote innovation in networking in the EU. The innovation in NREN projects (including GÉANT) have, in particular, focused on higher network layers. Such an approach is restrictive, as hardware technology (i.e. the lowest network layer) remains a fundamental source of innovation. The photonic network layer could therefore be an open and lower-cost approach for promoting innovation within the GÉANT transmission system.
2. A European Photonic Services network, in particular a real-time network with hard constraints on frequency and time services, has the ability to attract people/groups that have not previously been involved in networking and to solidify Europe’s leading position in advanced networking applications. By attending specialized conferences on suitable research fields (e.g. seismology or metrology), one can create an awareness of the possibilities provided by Photonic Services (PS) and identify new applications. A successful example of such a strategy is the medical application over R&E networks in the Czech Republic. A rarity just a few years ago due to a lack of awareness, medical applications of PS are now being demonstrated on a regular basis.
3. A simple upgrade to higher transmission speeds is not sufficient for low layer innovation and does not necessarily meet the demands of emerging cutting-edge technologies and

applications. CEF networks have initiated a low layer innovation by shifting from digital telecommunication services to dark fibres in order to remain independent from the transmission system technology development road map of a single vendor, which has been proven to be cost-inefficient and in the long run can potentially block new applications. GÉANT has decided to follow suit by adding the subtask "End to End Photonic services between user premises".

These ideas continue to be relevant and remain an important topic at workshops and conferences, e.g. CEF workshops and TERENA Networking Conferences (TNCs) organized by GÉANT. In the following paragraphs and chapters, we will, amongst other resources, refer to documents and results from the GEANT GN3 project, CEF workshops and TNCs. Results of the PSEAR activities have been summarized in the document [3] and Alien Wavelengths Services together with other relevant topics are described in the document [4].

Chapter 2 of this document gives a detailed presentation of Alien Wavelengths and related concepts. Chapter 3 briefly mentions vendor approaches to this question. Chapter 4 presents the experience with AW deployment by GEANT and NRENs, followed in Chapter 5 by the possibility of using AW services for remote sensing. Chapter 6 provides a set of recommendations on deploying AWs in optical fibre data networks. This is followed by the conclusion.

2 ALIEN WAVELENGTHS

2.1 Introduction

There are different approaches to so called Alien Wavelengths (AWs), also referred to as Alien Waves, Alien Lambdas, Foreign Wavelengths or Black Links. For example, ITU uses the term Black Links in ITU-T G.698.1 [5] and ITU-T G.698.2 [6]. To the best of our knowledge, a Request for Comments (RFC) document specifying AWs does not exist and we are aware of only one document mentioning them: an expired IETF draft [7]. Because there is no official standardization body defining the AW networking approach, the term Alien Wavelength has no single definition. The general principle behind AWs, however, is simple and intuitive. In a traditional approach, the vendor provides the source of the signals (transponder, muxponder, pluggable transceivers, etc.) and the transmission system including the equipment (multiplexers, demultiplexers, optical amplifiers, compensators of chromatic dispersion, optical switches etc.). An AW, in contrast, is a wave generated from a third-party light source and introduced into the transmission system. More precise specifications and more narrow definitions of AWs have been given by various different groups and projects, designed to describe the results and circumstances of the corresponding projects. As they are not relevant to CLONETS, they are not mentioned in this document.

For purpose of this document, we use the following definition:

"An Alien Wavelength is a photonic signal carrying user information, which is transported transparently without OEO conversion through a Wavelength Division Multiplexing (WDM) network or networks running equipment under a possibly different administrative control than the ingress/egress end-points."

We note here that PS introduced by CESNET in the GN3 project can be thought of as AW service [2].

2.2 The AW approach

Alien Wavelengths have been around for a little over a decade and have been deployed in a number of European NRENs. These NRENs have access to the photonic layer of their networks, i.e. the ability to control their own (D)WDM infrastructure, a prerequisite for being able to offer an AW service. Additionally, the deployment of AWs in Cross Border Fibres (CBFs) between different NRENs allows for mutual infrastructure sharing and extension of the (transparent) reach of the network operators.

An early implementation of AWs, which describes a real deployment, i.e. the transmission of DWDM signals generated outside the active DWDM transmission system, established the transmission of AWs in 2006 over two CBF links (Brno-Bratislava and Brno-Vienna) deployed by Czech Light^{TM} DWDM systems. The overall experience with these two CBF links has been very good and the fundamental upgrade of this CBF triangle to include the additional CBF link Vienna-Bratislava confirms the utility of the AW approach ([8], [9]). One of the first use cases of an AW service, was established in 2007 over a traditional vendor DWDM system. CESNET applied the concept of AWs to the CESNET2 backbone network with the goal of transmitting sensitive medical data for hospitals. AWs were set up connecting the Thomayer hospital in Prague to the regional Picture Archiving and Communications System (PACS) archive in Brno [10].

The deployment of AWs in the DWDM infrastructure of the telecommunications company Embratel has been demonstrated [11] and further examples of their deployment in NRENs can be found in ([12], [13], [14]). In Section 4, the NRENs CESNET, PSNC and RENATER and their experience with AWs are described in more detail.

2.3 AW Services classified by Administrative Domains traversed

AWs have been investigated and classified as part of the GN4-1 JRA1 T1 activity [4]. Here, we briefly present and summarize the classification of AWs provided by the GN4 team. They classify an AW service into three fundamental categories based on the different administrative domains (ADs) involved in the transmission of the AW:

The light signal carried by an AW service:

1. is generated in the provider's AD domain,
2. is generated in the customer's AD,
3. transits the ADs of multiple providers.

For each of the three types of AW service described here, the signal being carried can be either data or analogue signals, including T/F signals and depending on the customer's application.

Alien Wave type I: "Own alien wave"

In the case of an AW type I, the optical signal is formed within the same network (administrative domain) as the DWDM equipment, but not within the optical network layer. A typical example of this is where coloured (C-band tuneable) optics are installed in a router and the light is launched into the DWDM equipment without OEO.

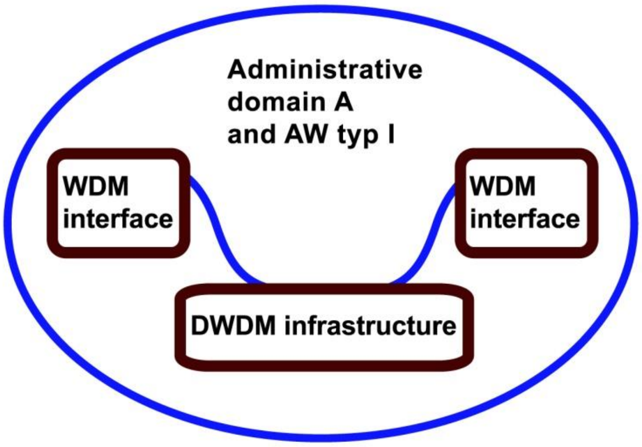

Figure 1. Alien Wave Type I.

Alien Wave type II: "Customer's alien"

In the case of an AW type II, the optical signal originates in the customer’s network and is then passed to a single provider’s network (AD) to be carried on the DWDM equipment without any OEO conversion.

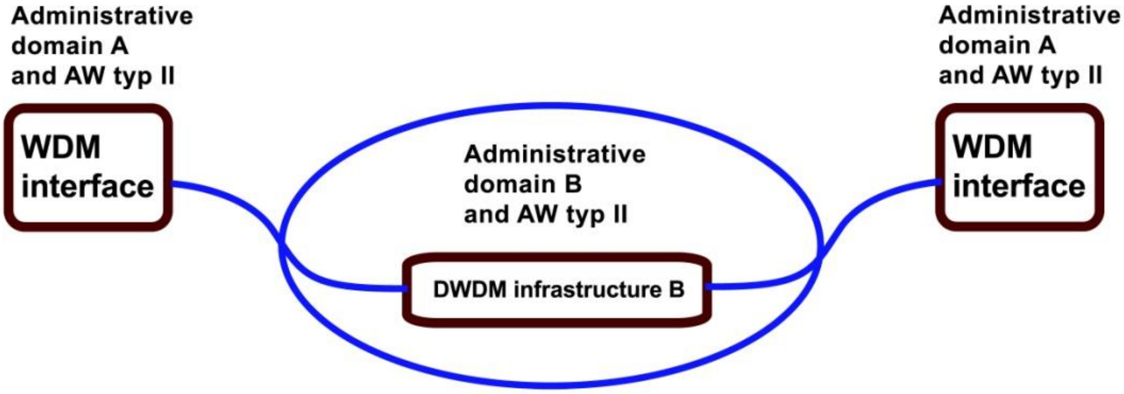

Figure 2. Alien Wave Type II.

Alien Wave type III: “Multi-domain alien”

In the case of an AW type III, the optical signal transits the optical networks of two or more providers. Therefore an AW type III is generally more complex than an AW type II. For instance, additional transition optical equipment may be needed in order to equalize the different optical powers required by the different DWDM systems.

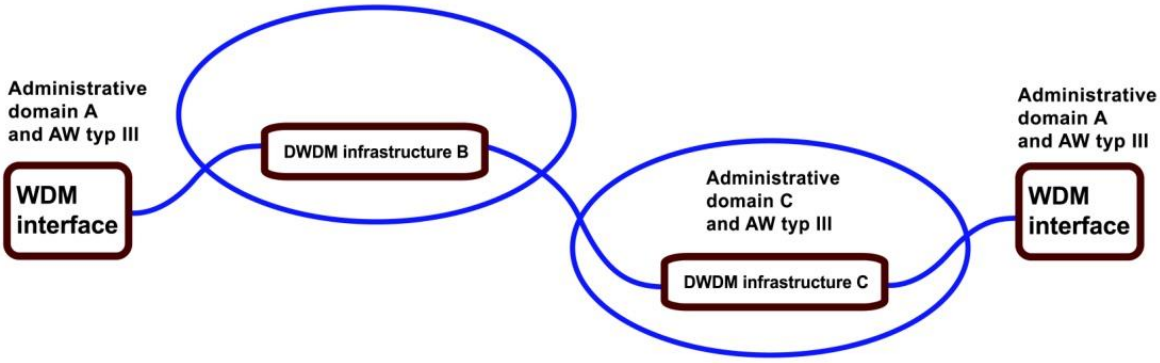

Figure 3. Alien Wave Type III.

2.3.1 Other Categorizations of AW Services

According to GN4 documents, AWs can also be categorized by features other than just the ADs transited. Other factors that can vary between different AW services and should be taken into account include:

- The management of the AWs. Commonly the light source (transponder) for the AW is managed by a third-party network management system. However, it is possible that a unified management system is employed to manage both the DWDM-system (e.g. amplifiers, multiplexer, demultiplexer) and the transponder on third-party equipment. This case is often described as ‘Friendly Waves’ in order to make a distinction from unmanaged alien waves [7].
- Obligations on the AW client performance. An AW service may impose some obligations on the client to operate within a range of performance measures. This may restrict the modulation scheme, the launch power or the optical spectrum. For example, the client equipment will be required to comply with the DWDM C-band and an agreed modulation format such as PM-QPSK. This contrasts with the ‘alien spectrum’ approach that can share spectrum with no constraints on the light signal.

2.4 Spectrum Sharing

As with AW, different definitions can be found for the newer term Spectrum Sharing (SS) and the closely related term Spectrum Sharing as a Service (SSaaS). In general, a DWDM system carries approximately 80 wavelengths in the C-band (1525–1565 nm), which is split into 50 GHz spectral grids [15]. While an AW consists of one slice or grid, SS contains multiple contiguous slices or grids. An SSaaS could therefore potentially serve as a resource for an AW service ([13], [14], [16]).

Here we define several differences between SSaaS and AW services:

- An AW service is defined on a single ITU-T grid. This will typically be 50 GHz, but with the introduction of flex-grid (see Section 2.7) this could be other larger amounts of spectrum. A SSaaS will split the optical spectrum in to larger ‘slices’ of the spectrum than just a single grid.
- The AW service generally includes gain control. The loss/gain along the path will be monitored and adjusted by the DWDM equipment to keep the power level optimum for the amplifiers and keep the gain spectrum flat. This may not be the case for SSaaS, for which the optical power levels may need to be independently and manually monitored and adjusted for each part of the spectrum. For this reason, a true SSaaS may constitute a more complex engineering problem than an AW service.
- In general, constraints are placed on the optical parameters of the client’s AW signal in order to ensure that the service works correctly. This may not be the case for a SSaaS.

2.5 The Dark Channel Approach – an independent AW without DWDM equipment sharing

The Dark Channel technique is quite similar to the AW approach, even though it is not an AW service. With this technique, an alien optical signal propagates in the same fibre, however all telecom or network equipment (such as amplifiers or access points) is bypassed by the alien optical signal and thus is excluded from the signal’s path, e.g. through optical bandpass filters. This type of AW only shares the fibre itself, while its optical spectrum is included in a channel of the DWDM grid. The Dark Channel technique employs its own amplifiers and/or other network equipment. In general, a bidirectional propagation inside the fibre is implemented in contrast to usual telecom and data signals and infrastructures, which are uni-directional. The Dark Channel technique has been proven to be compatible with DWDM networks and has successfully been tested with the REFIMEVE+ signals in the RENATER network in France and with T/F signals within the T/F infrastructure of CESNET in the Czech Republic. Both REFIMEVE+ and the T/F infrastructure of CESNET are described in more detail in Sections 4.4 and 4.2, respectively.

2.6 Open Systems

As described in [3], the demand for PS or AW service availability is changing the relationship between the R&E Community and the transmission system vendors. The main goal of transmission system vendors has been to deliver equipment and services to Internet Service Providers (ISPs) for digital data transmission. They do not usually offer “Black links” ITU-T G.698.2 (aka our AWs) [6], which require all-optical equipment and networks. While the market segment for advanced and specialized transmission systems for the R&E Community is significant, it may not be sufficiently lucrative for established transmission systems vendors, whose main source of revenue continues to be the service to ISPs.

Despite a potential resistance to open multi-vendor AW services, equipment sufficiently flexible and fully usable for AW deployment is available. The trend towards more flexible and open systems originated from higher layers (e.g. Ethernet or Internet Protocol) with so called white boxes. These white boxes have been useful for many companies, including large international companies such as Facebook, Google or Amazon. A good example is the Telecom Infra Project [17], which released the Voyager Open Packet DWDM transponder platform [18]. Other vendors, e.g. Lumentum [19], are following this trend of open optical networking and are offering optical white boxes, i.e optical equipment which is customizable and suitable for new applications with AWs or SS requirements. New vendors of lighting (transmission) equipment with regards to the rise of Open Line Systems [20] should, in principle, enable multi-vendor fibre sharing instead of remaining limited to a single-vendor occupation of the whole fibre. In practice, however, some traditional vendors might apply an additional license fee for the support of each individual AW over their system. To avoid any potential blocking of AWs, it is important to be informed of the practices of the vendor in question.

It is important to note that some legacy transmission systems are designed in such a way that they do not easily support an all-optical transmission of AWs. In particular, this might have implications on the availability of accurate Time and/or Frequency (T/F) transfers to certain remote research premises e.g. on islands, etc.

2.7 Flexible Grid

DWDM networks started with fixed frequency grids defined by ITU [15]. The typical channel spacing was defined as 200 GHz, with 100 GHz and 50 GHz variants adopted by all DWDM vendors. Other spacing grids were also defined, going down to 12.5 GHz or 33 GHz and used for special applications (e.g. submarine optical systems), but 100 GHz has de facto been the norm for many years with 50 GHz being used when more DWDM channels/lambdas are needed. For example, older transceivers such as XENPAKs are available with 100 GHz spacing only. These older transceivers may still be employed in today’s networks, together with 100 GHz grid multiplexers and demultiplexers.

As it has become apparent that a fixed grid could potentially block certain innovative and high speed signals, a new multiplexing scheme, not tied to any particular channel spacing, was proposed and thus the idea of a flexible grid was born. An introduction to the flexible grid WDM is available online [21] explaining the different reasons for the move towards flexible grid schemes, the main motivation being high speed coherent signals, such as 100 Gb/s using a QPSK modulation and so-called superchannels with speeds up to 1 Tb. These high speed signals cannot fit into the older channel spacings. The shift towards flexible grid WDM systems has implications for the employed multiplexers. New equipment, such as reconfigurable optical add-drop multiplexers (ROADMs), must be able to support flexible grids, as evidenced by the fact that terms such as colourless/directionless/gridless (CDG) are now in the portfolio of all optical equipment vendors.

2.8 Management and Deployment of AWs

Factors that need to be constrained, in order to guarantee the performance of an AW (as studied in GN4), include:

- Modulation Techniques. Some modulation techniques (e.g. on-off keying) are likely to result in more crosstalk than others (e.g. a carrier wave for frequency distribution).
- Input power levels. The launch power of the light into an AW service needs to be held to within an agreed range.
- Power variations. The AW users should vary the optical powers at a slow rate in order to give other users of the system time to detect a variation in their pre-Forward Error Correction (FEC) bit error rate (BER), i.e. the error rate before error correction is applied.

Because data traffic generally has a higher priority over AWs in production networks, interference or cross-talk between the signals remains a concern. For example, amplitude modulated signals (the vast majority of 10 Gb/s transmission and also time transmission) can potentially interfere with phase modulated signals (almost all coherent 100+ Gb/s transmission, and optical carrier frequency transmission) via the nonlinear effect of cross phase modulation

(XPM). Coexistence of such signals is rather frequent nowadays but may be of less significance in future when only coherent systems are deployed.

This topic has often been discussed with different transmission equipment vendors during various face to face meetings and professional networking events, such as conferences (e.g. OFC or ECOC (European Conference on Optical Communication)). However, there is no general agreement on how deleterious these effects are and which slow speeds (i.e. 100M, 1G or 10G) are worse. Slow signals are said to have a negative effect on coherent ones (through the effect of XPM), but the practical experience at CESNET shows that such effects are negligible. It has been found that more critical effects are related to different insertion losses in different DWDM channels in DWDM multiplexers and demultiplexers. Even a small, 0.5 dB difference in insertion loss had a larger degradation effect than the close 100 GHz spacing of slow and coherent signals. These tests showed the influence of slow (accurate time transfer) and 100G signals positioned on different ITU frequency grids. No BER degradation for the 100G signals was observed provided that the power levels were kept sufficiently low ([22], [23]). However with flexible grid networking, such XPM-induced effects still need to be investigated and verified properly in real production networks to avoid any degradation effects on broadband signals with rates 400 Gb/s and above, especially since high order modulation schemes used for 200, 400 and 600 Gb/s are more sensitive to any disturbance effects such as XPM or optical noise.

When designing accurate time adapters, it is advisable to use non return to zero (NRZ) coding, i.e. to stay close to standard data transmission modulation schemes because almost all non-coherent transceivers for lower speeds (i.e. 100 Mb/s, 1 Gb/s, 10 Gb/s) use NRZ modulation. Accurate time signals are just pulses and represent slow data signals and should ideally use industry standard modulation schemes. Of course it is possible to use alternative coding schemes, such as return to zero (RZ). However, RZ signals have broader spectra and it is safer to avoid them because such issues with RZ coding are, for example, known from Passive Optical Networks.

2.9 Amplification of AWs

2.9.1 Erbium Doped Fibre Amplifiers (EDFAs)

EDFAs are well known and have been used in optical networks since the early 90s. In principle EDFAs can be used both for conventional data AWs and accurate time signals, but there are a few issues to consider. For data AWs, the set-ups are relatively straightforward as for any other data signal. One EDFA is used for one direction (or fibre) and the same goes for the other transmission direction. A uni-directional set-up can also be used for an accurate time transfer, however it can introduce asymmetries between the two transmission directions (e.g. lengths, noise), which can be difficult to determine and therefore potentially limit the accuracy and the stability of the time transfer. To eliminate such problems, applications utilizing a bi-directional transmission in one fibre generally employ bi-directional EDFAs. In this case, it is important to avoid reflections as much as possible. It is therefore recommended to either splice junctions or, if this is not possible, to use angled (green APC) connectors throughout the fibre link. Sometimes optical index-matching gels are require for achieving better performances.

Bidirectional (bidi) EDFAs must be deployed carefully because they are prone to transmission instabilities (or degradation effects) arising mainly from light scattering, so that usable optical gains are low, i.e. less than 20 dB. In comparison, standard EDFAs can achieve gains of more than 27 dB for longer fibre distances and a higher DWDM channel count. This poses an immediate problem for upgrading standard data fibre links from uni-directional to bi-directional transmission. Longer spans may be difficult (or potentially impossible) to amplify with bidi EDFAs. In such situations, additional bidi EDFAs must be deployed within the length of such long spans.

There are two possible approaches to amplifying bidirectional transmissions over a single fibre. One approach is one (real) bidi EDFA deployed together with one fibre, the other approach uses two standard (uni-directional) EDFAs connected through optical circulators to provide an effective 'bidi' mode of operation. From an operational point of view, the latter 'bidi' configuration is not as demanding, but the bi-directionality and its advantages are sacrificed.

2.9.2 Semiconductor Optical Amplifiers (SOAs)

Another option suitable for bidirectional transmission is SOAs. It is interesting to note that while SOAs were studied in the 1960s, when semiconductor lasers were invented, their deployment in optical networks has been rather delayed. Even nowadays, SOAs are not deployed frequently. The advantages of SOAs are their already mentioned bi-directionality and their ability to provide gain for a very broad range of spectra. Unfortunately, some SOA drawbacks, such as nonlinearities with fast transients, rather high noise figures, and polarization sensitivity, can be seen as the major factors preventing a wider deployment. Some of these issues can be reduced, for example fast transient effects can be mitigated [24].

2.9.3 Distributed Raman and Brillouin Amplification

Both EDFAs and SOAs can be described as 'lumped' in contrast to 'distributed' Raman and Brillouin amplification. Brillouin amplifiers are used rather rarely because of their very narrow amplification window. Such amplifiers are suitable for ultra-stable frequency transfers, for which the frequency signals are not modulated and therefore have a very narrow spectrum [25].

Raman Amplifiers and Bi-Directional Signals

GIP-RENATER (France) and other extensive telecommunication networks use their fibres in a uni-directional way, i.e. the data signals propagate only in one direction in the fibre. This is indeed the most common way to structure an optical network because it prevents interactions between two signals propagating in opposite directions, which could potentially disrupt the traffic. On the contrary, ultra-stable metrological signals necessitate bi-directional propagation, i.e. the signals propagate in both directions in the same fibre, for noise-cancelling purposes. These combination of these two architectures may lead to interference between them, and we propose here some best practices to prevent this from happening.

As an example, we consider the REFIMEVE+ signals (ultra-stable optical frequency signals) propagating in the GIP-RENATER network, as drawn in blue in Figure 4. This frequency reference uses a signal @ 194.4 THz (wavelength 1543.2 nm) and propagates from West to East. The data signal (red) @ 194.0 THz (wavelength 1546.4 nm) propagates from East to West and is amplified over the last 10 km thanks to high power Raman pumps. Spontaneous Rayleigh (same frequency) and Brillouin-Stokes (shifted by -11 GHz in frequency) signals that are created by the REFIMEVE+ signal propagate opposite the Raman pump. The risk is that the amplification can be so strong that these signals become powerful enough to, in turn, create their own Rayleigh and Brillouin-Stokes induced signals, consequently generating a comb with the signals overlapping neighbouring channels (see Figure 4). In order to prevent the generation of second and higher order signals leading to the creation of a comb, it is recommended to:

- inject a low metrological signal power into the fibre (< 5 dBm), such that the first order Brillouin-Stokes signal is low and is not sufficiently amplified with the Raman pump to generate a second order Brillouin-Stokes signal and to
- if possible, lower the Raman output power restricting the gain, so that the first order Brillouin-Stokes signal cannot be sufficiently amplified to generated a second order Brillouin-Stokes signal.

The implementation of distributed Raman amplifiers for a precise time transfer in a bi-directional fibre line has been investigated in [27].

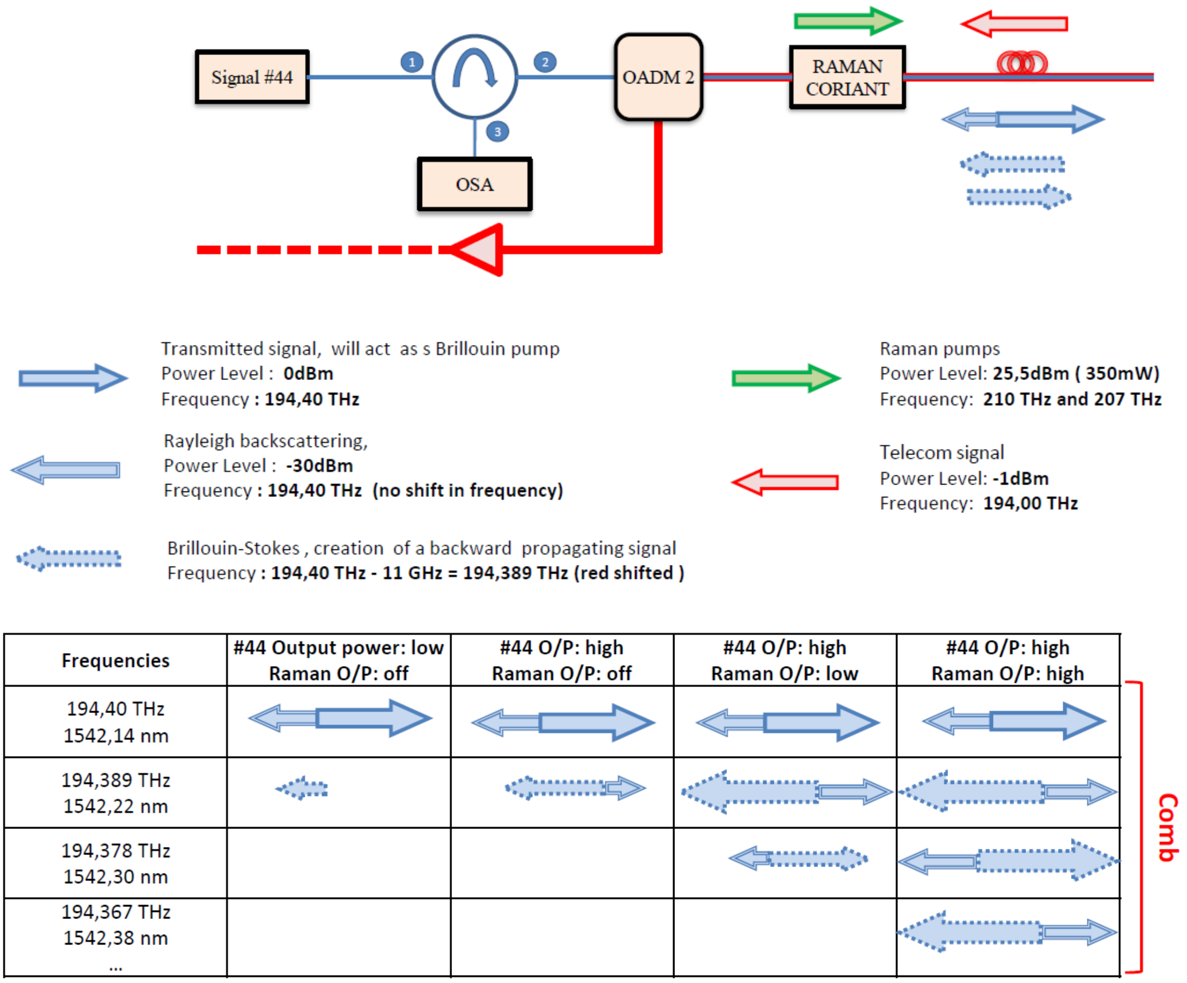

Figure 4. REFIMEVE+ signals propagating on Raman amplifier equipped fibres.

2.9.4 Summary

We have described different types of lumped optical amplifiers (EDFAs and SOAs) and distributed amplification techniques (Raman and Brillouin). Their advantages and disadvantages are summarized in Table 1. The mentioned values are recommendations and should be considered as safe ‘upper’ limits.

EDFAs are very mature and have very good noise properties, however the amplification window is limited. SOAs can be customized to almost any amplification window, however noise figures are rather high and the optical powers are limited. Raman amplifiers typically use high power, which can pose issues with eye safety. Brillouin amplifiers are suitable for very narrow signals only.

Amplification	**Bidi EDFA**	**SOA**	**Raman**	**Brillouin**
Output power	< 20 dBm	15 dBm	< 27 dBm	5 dBm
Gain	20 dB	20 dB	< 20 dB**	> 50 dB
Noise figure (NF)	4 dB	8 dB	Similar to EDFA*	Similar to EDFA
Fibre length	N/A	N/A	> 25 km	< 25 km
Amplification window	1530-1565 nm 1565-1620 nm	Can be customized to 1300-1600 nm	Can be customized to 1300-1600 nm	Can be customized to 1300-1600 nm
Bi-directional gain	Yes	Yes	Yes	No

* Some calculation methods may even provide NFs for Raman amplification in the negative figures, however noise theories agree on the quantum noise limit to be 3 dB for any optical amplification technique.
** Distributed Raman gain is limited in standard fibres due to low pump penetration and low gain coefficient.

Table 1. Comparison of different optical amplification techniques.

3 VENDOR APPROACHES

As can be seen from the previous chapters, accurate T/F transfer must be supported by the transmission equipment. It is therefore important to find vendors that are willing to handle AWs and other specific requirements, e.g. bi-directional propagation of the signals. While this was nearly impossible 15 years ago, the situation started to change approximately 10 years ago and nowadays it is no longer difficult to find a vendor supporting AWs and all optical end to end connections. Unfortunately, some vendors support AWs but with significant restrictions including licensing. In this scenario, AWs are supported but licensing fees must be paid. For some vendors the licensing fee is equal to the price of DWDM transponders needed to light such a fibre. In other words, some vendors use open AWs to compensate for lost profits of closed solutions. As such restrictions are usually available under a non-disclosure agreement or part of confidential contracts, they are not widely known. However, some information is available and has been discussed at special events such as CEF network workshops. The last, 9th CEF (September 2017) revealed interesting facts from some NRENs [28]:

- SWITCH (CH) deployed an Apollo platform (from ECI Telecom Ltd.) providing AW support including future spectrum sharing.
- SURFnet (NL) also chose ECI.
- PSNC (PL) presented existing time and frequency fibre infrastructures and future visions, clearly indicating that AWs must be supported.
- RNP (BR) presented plans for future years, with many projects having specific requirements for new applications, such as connecting radio telescopes.
- KREONET (KR) presented many achievements, including an optical T/F transfer testbed and radio telescopes used for worldwide eVLBI activities.
- AARNet (AU) presented very interesting results on AWs, where specific problems related to lightning disturbances had to be solved.
- GARR (IT) is active in new trends and AWs have been used in their optical network.
- CESNET (CZ) has been using AWs for many years both over proprietary systems and the open system Czech Light™ for different applications; T/F transfers are the most challenging.
- RENATER (FR) has been working with REFIMEVE+ AWs since 2009. Promising state of the art measurements have led to international measurements with NPL and PTB. Best practices were adopted and Dynamic Circuit Network (DCN) managing scientific equipment is being tested.

- The pan-European network GÉANT is involved in the Telecom Infra Project and considers AWs vital for future activities.

4 ALIEN WAVELENGTHS IN NRENS

Many NRENs and GÉANT have been using dark fibres and operating their own DWDM transmission equipment for many years. It is clear that the situation with data transmission has changed and new signals (non-data, non-digital) with new applications are here and must be supported by a new generation of optical networks. The technology used for lighting dark fibres should be vendor independent and focused on the photonic layer and all possibilities this layer can offer, without any restrictions imposed by closed and proprietary transmission systems.

NRENs and GÉANT are generally pioneers of AWs deployment, however there are significant differences between particular NRENs due to network operation models (own fibre infrastructure vs leased fibres vs purchased data services), existing in-house research, funding model, etc. All NRENs directly involved in the CLONETS project have long term experience with AWs and their utilization for time and frequency services.

4.1 GÉANT

GÉANT is a pan-European network, terabit-ready and connecting 50 million users at 10000 institutions across Europe serving research and education. The qualities of GÉANT that set it apart from commercial operators include robustness, total reliability, flexibility, capacity and rapid upscale, efficient operations and services [29]. The network is built on dark fibres and in some parts of Europe on leased wavelengths. The transmission layer integrates optical networking together with Optical Transport Network (OTN) switching with an Infinera DTN-X platform. The packet layer is a converged layer supporting Ethernet (Layer2) and IP (Layer3) services with help of a Juniper MX platform.

GÉANT is also very active in new trends in optical networking and participating in TIP and testing new Data Centre Interconnect (DCI) boxes. The support of AWs, CBFs and SSaaS is also actively being investigated and employed throughout the GÉANT and NREN ecosystem. Such activities are challenging because they are essentially multi-domain and multi-vendor, requiring the resolution of many issues.

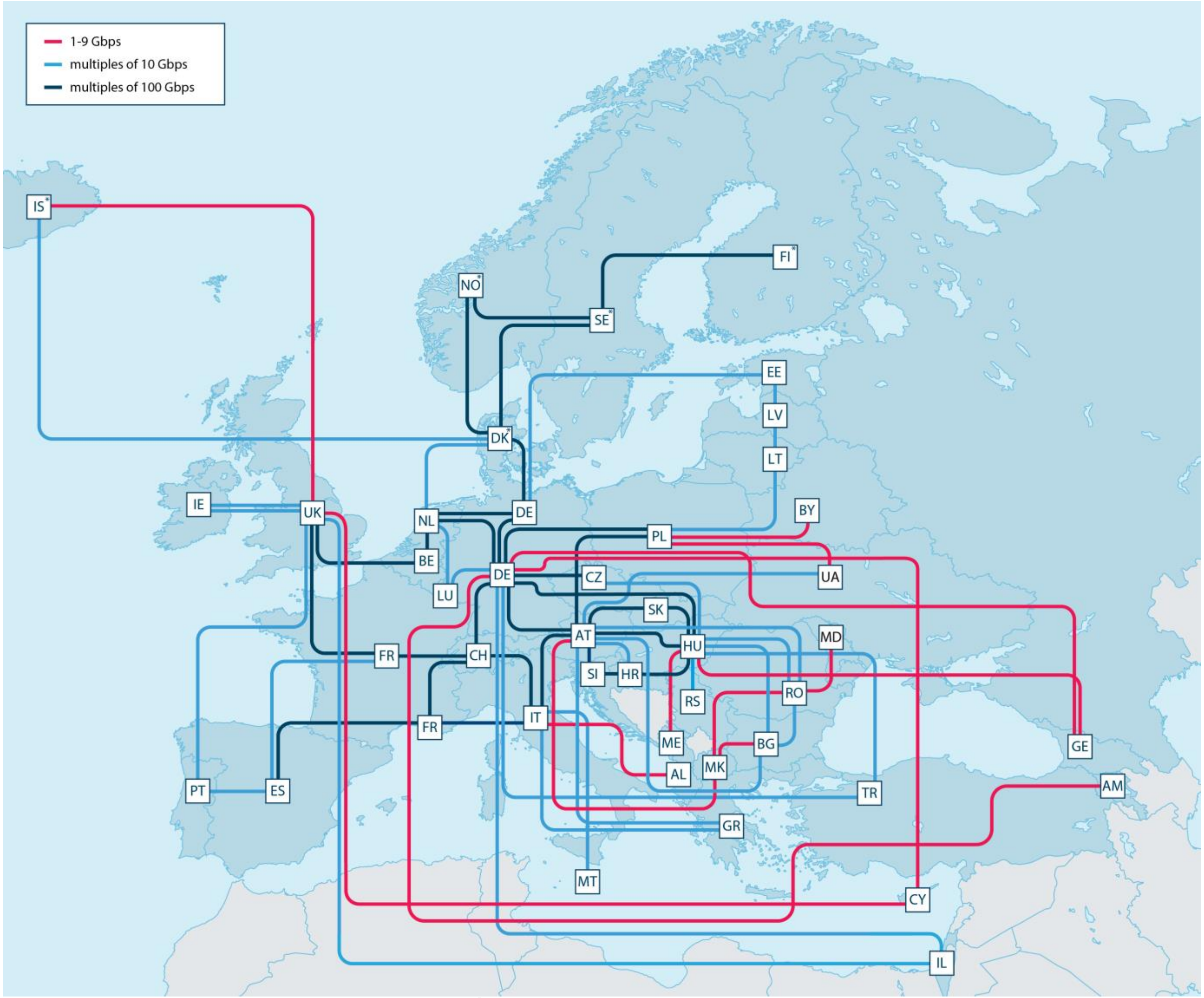

Figure 5. The GÉANT backbone network (August 2017).

GÉANT has selected two dark two routes (London – Paris and Vienna – Torino) as testbeds for end to end PS and provided optical designs for these routes based on the Open DWDM systems Czech Light^{TM} [3]. Important aspects of such links are vendor independent monitoring (OAMP), automatic light power balancing, monitoring of different light path segments and responsibilities of all involved partners.

4.2 CESNET

4.2.1 The Optical Network

The development of all-optical services was launched at CESNET in January 2000 through the 311 km dark fibre lease Praha – Brno. CESNET’s Optical Networks research team initiated the development of Czech Light Optical Amplifiers, enabling the cost-effective lighting of dark fibre lines through the NIL (Nothing-in-Line or ‘hut skipping’) approach. After extensive lab testing, a 189 km NIL dark fibre line Praha – Pardubice was established and has been continuously running in the CESNET2 production network since May 2002. CESNET’s experience with lighting was presented at the Terena Networking Conference in 2002 [30] and was further discussed with a global audience in the first CEF Networks workshop in 2004 [31].

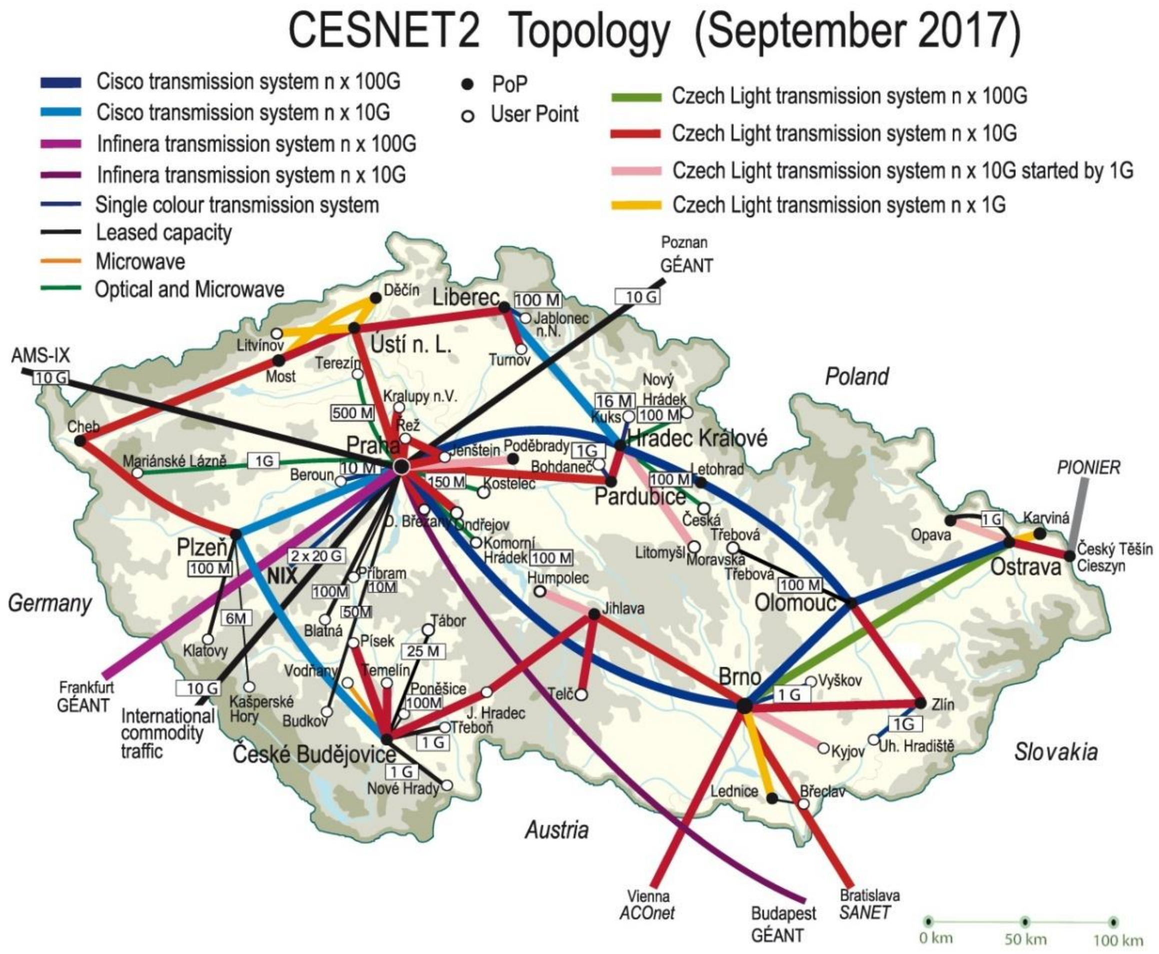

Figure 6. CESNET optical fibre network.

In 2004, CESNET introduced the usage of AWs over an Open DWDM system developed in-house. This system was also used for PS. The first PSs provided over the CESNET network were an uncompressed 4K video transmission in 2007, followed by high quality stereoscopic transmissions. The signals were generated from custom, in-house-developed video processing cards and were transmitted over two different DWDM systems using multi-vendor PSs.

Following the above successes, CESNET’s Optical networks research team developed the Open DWDM photonic system based on the Czech Light^{TM} family of devices. The system is capable of both a multi-vendor, all-optical transmission over uni-directional fibre pairs and an all-optical transmission over a single bi-directional fibre. While the main motivation was cost savings, this approach was also adopted in order to allow for the verification of the quality of the R&D results, to provide flexibility for the DWDM connections of remote R&D premises in the Czech Republic and to allow interoperability with other transmission equipment. CESNET2 was able to provide end-to-end Photonic Services (i.e. all-optical lambdas) between user premises prior to the metrologists’ requests for the transfer of highly accurate time or frequency.

4.2.2 T/F-infrastructure

In 2010, CESNET for the first time tested an accurate time transmission between Prague and Vienna. The optical signal generated through a special adapter is carried over two different transmission systems. In 2011, the comparison of atomic clock time scales in Prague and Vienna went into operation [32]. The construction of the T/F-infrastructure started in 2010 after a 550 km long link (Figure 7) between the Institute of Photonics and Electronics (IPE) Prague and Federal Office for Metrology and Surveying (BEV) in Vienna was established. These institutes keep national approximations of UTC; the Czech time scale UTC(TP) and the

Austrian time scale UTC(BEV). This link has been in operation since August 2011, and to the best of our knowledge, has been the world's first optical time transfer between two NMIs. This link utilizes two independent fibres in the same optical cable and is planned to be upgraded to a single bi-directional fibre, in order to improve the time transfer uncertainty and to avoid the need of recalibration after any optical fibre path changes due to maintenance.

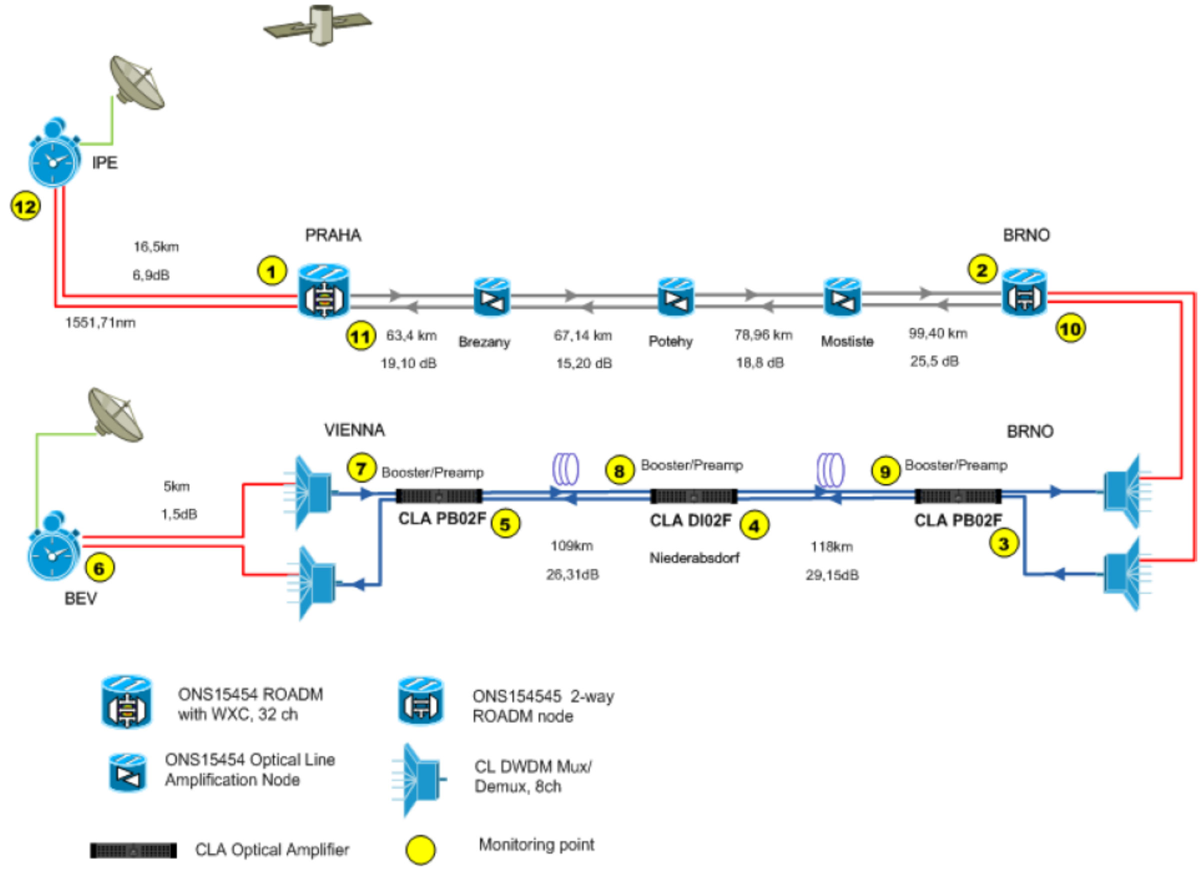

Figure 7. Optical link between Prague and Vienna comparing the time scales UTC(TP) and UTC(BEV).

There is a fibre link between Prague (CESNET headquarters) and Brno (ISI), which is running both a time transfer and an experimental phase coherent optical frequency transfer. While data on the link channels utilizes a pair of uni-directional fibres, the T/F transfer is implemented in a single bidirectional fibre within a reserved 800 GHz bandwidth with dedicated bi-directional amplifiers. The structure of the link is illustrated in Figure 8. The comparison of independent time and frequency transfer is described in [34].

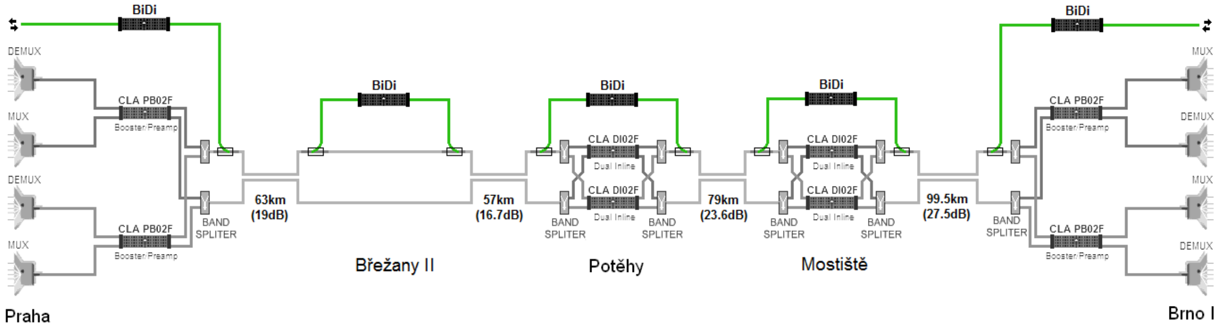

Figure 8. Fibre link between Prague and Brno, with dedicated bidi amplifiers.

The time transfer system utilizes in house adapters capable of transmitting a 1 PPS signal modulated on a 400 MHz carrier and receiving identical signals from the remote site. The system operates symmetrically and without active stabilization on a single bi-directional fibre (either a dark fibre or a DWDM channel) or a pair of uni-directional fibres. The achieved accuracy on a 306 km long field deployed fibre with terminals in same lab is better than 10 ps [33]. The Phase coherent optical frequency transmission uses a highly-coherent laser Koheras Adjustik working at 1540.56 nm with a linewidth < 100 Hz. The laser is frequency stabilized to the Acetylene ($^{13}C_2H_2$) P(13) transition with a saturation absorption spectroscopy technique [34]. The Doppler frequency shifts of the coherent transfer induced by the fibre link are suppressed using a closed loop control system with AOMs in the phase coherent transfer scheme [35].

The deployment of the CESNET T/F-infrastructure started in 2012 [36]. Now, in 2017, it operates seven lines with time transfer and two lines with frequency transfer. There is also a new, ready to use line to the Polish border prepared for connecting the CESNET T/F-infrastructure with the Polish infrastructure OPTIME. Additionally a line from Brno to Temelin (a nuclear power plant site in the Czech Republic) is in planning and partially built. The current state of the CESNET T/F-infrastructure is shown in Figure 9; more than 1660 km of T/F transfer lines have been deployed [35].

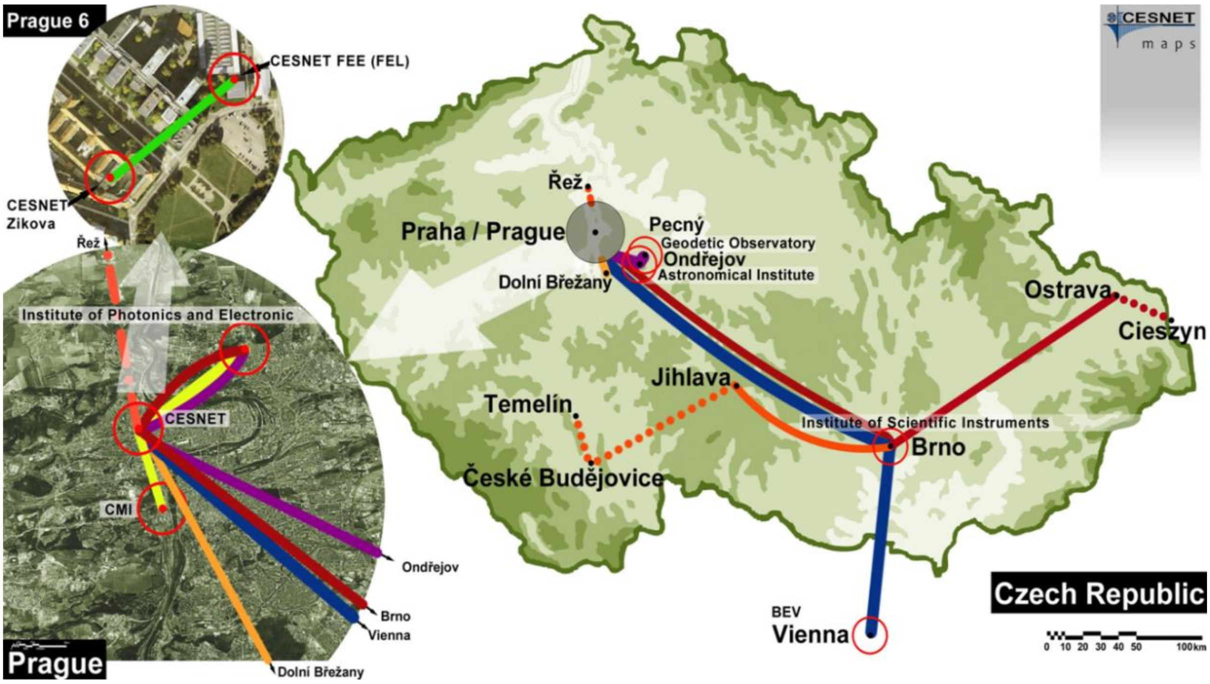

Figure 9. The CESNET T/F infrastructure (2017).

Other designs are implemented for lighting both C- and L-communication bands and are also being employed by CESNET in 2017, including the T/F transfer infrastructure connecting scientific and research institutes, with prime examples being the Geodetic Observatory Pecný, the Astronomical Institute Ondřejov and the Institute of Scientific Instruments in Brno.

An example of a single bi-directional fibre AW used for time transfer between 3 institutes is demonstrated in Figure 10. The AW signal travels through three different background technologies: dark fibre, DWDM system and CWDM transport system.

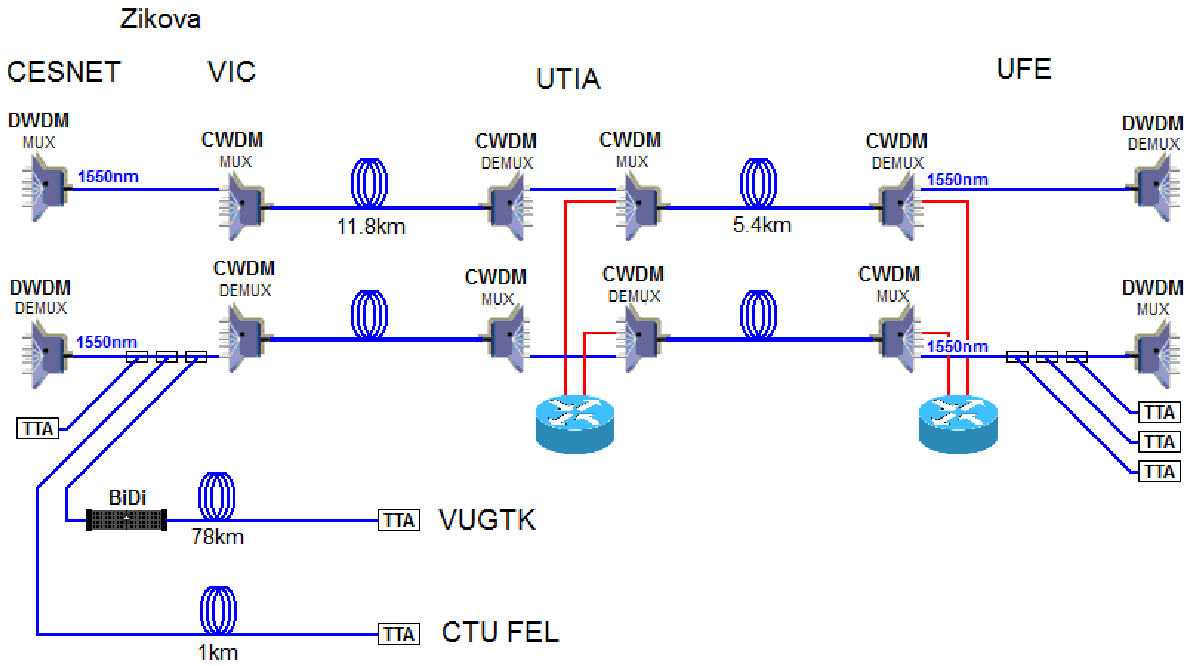

Figure 10. A single bi-directional fibre AW for time transfer.

4.3 PSNC

4.3.1 The PIONIER Network

The PIONIER network was created within the confines of the programme of the Ministry of Science and Higher Education in Poland under the name of 'PIONIER: Polish Optical Internet – Advanced Applications, Services and Technologies for Information Society'. The ultimate goal of the programme is the delivery of modern, technologically-advanced infrastructure and applications for the Information Society. This programme resulted in the realisation of PIONIER - Polish Optical Network for assisting and supporting science. The PIONIER network is managed and supervised by a Consortium consisting of representatives of all Metropolitan Area Networks (MANs) and High Performance Computing (HPC) centres. The operator of the PIONIER network is the Poznan Supercomputing and Networking Centre (PSNC).

PIONIER is a nationwide broadband optical network and represents a base for research and development in the area of information technology and telecommunications, life sciences computing (grids, cloud-computing, etc.) and applications and services for the Information Society. PIONIER network includes 21 Academic MANs and 5 HPC Centres providing access to global resources and a dedicated Internet connection between research centres in Poland and centres abroad (e.g. universities, research institutes, supercomputing centres, libraries, etc.).

The basic transmission mediums used in PIONIER network are own fibre cables of types G.652 and G.655. The PIONIER network owns 6479 km of fibre cables in Poland and 2453 km of fibre lines from the Polish-German border to Hamburg in Germany and from the Polish border to CERN (Geneva) in Switzerland. Additionally, the PIONIER network has external connections to the European Research Network GÉANT and the Internet and cross-border connections to NRENs in Europe. Figure 11 presents the current optical fibre infrastructure of the PIONIER network including external and cross-border connections to European NRENs.

Figure 11. Optical fibre infrastructure of the PIONIER network.

The network connects all Academic MANs and HPC Centres with the DWDM transmission system ADVA running on all fibre lines. The system is equipped with cards for one or two 10 Gb/s optical carrier wavelengths. Each of the wavelengths can carry either STM-64 or 10 Gigabit Ethernet (GE) LAN-PHY signals. On each link one wavelength is used for Internet traffic while the other is used for direct interconnections between HPC Centres and for experiments.

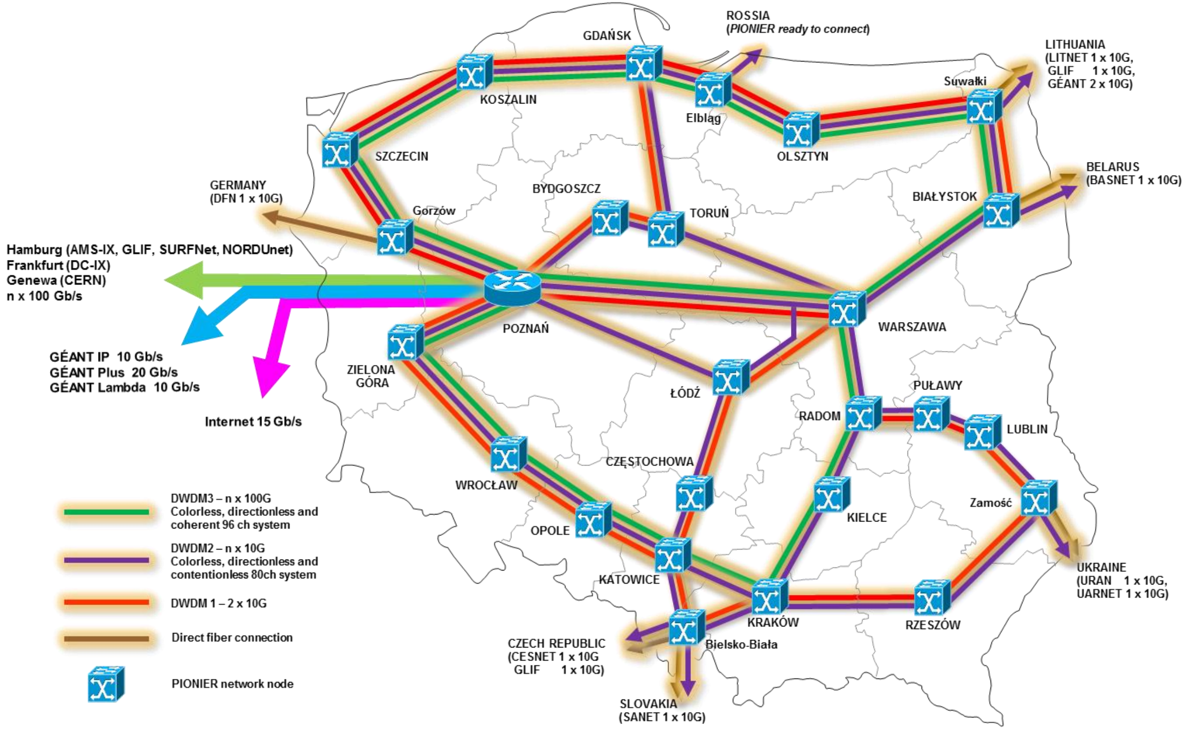

Figure 12. Schematic of the interconnections in the PIONIER network.

The DWDM system has been extended with ROADM support (colourless, directionless, contentionless) and additional transponder modules. In each of the university cities PSNC has a Multiprotocol Label Switching (MPLS) Label Switching Routers (LSRs) (Foundry NetIron XMR 16000/8000, Juniper MX960) equipped with 10GE and 1GE interfaces. The connections between the backbone switches are always 10GE (LAN-PHY or WAN-PHY) over ADVA DWDM links. Figure 12 shows the interconnection scheme implemented in the PIONIER network.

The proper functioning and operations of the PIONIER network are under surveillance 365/7/24 by the PIONIER Network Operation Center (NOC) located in PSNC (Poznań) and by the IP-NOC located in the Computer Center of the Technical University of Lodz.

The PIONIER NOC provides the following services:

- PIONIER international links monitoring,
- PIONIER network monitoring,
- Handling of network problems,
- Handling of service problems,
- Handling of security incidents,
- Handling of scheduled maintenance works,
- Problems troubleshooting.

The PIONIER network resources include:

- Fibre network infrastructure,
- Network services:
  - Wavelength-on-demand,
  - Large Data Transmission,
  - Virtual networks,
  - Guaranteed access to world research networks (QoS),
  - Broadband Internet access,
- Global Resource Information Database (GRID) infrastructure supervised by 5 HPC Centres

4.3.2 AWs in the PIONIER Network

Currently, two types of DWDM systems are used in the PIONIER network. The first one is implemented only in the Polish part of the PIONIER Network and is based on the 80-channel DWDM system FSP3000 from ADVA. This system is dedicated to non-coherent signals (mostly 10Gps) and therefore is equipped with in-line chromatic dispersion compensation modules. This system is directly connected to PSNCs neighbouring NRENs, such as DFN, CESNET, SANET, UARNET, LITNET. This system enables the transmission of the AWs in strictly defined 50GHz channels.

The second DWDM system is dedicated to coherent signals (mainly 100Gps) and does not include in-line chromatic dispersion compensation modules. The chromatic dispersion has to be compensated for in receiver or transponder. This system is implemented both on the Polish territory of the PIONIER Network and on the Poznan (PL) - Hamburg (D) - Frankfurt (D) - Geneva (CH) link. This system allows transmitting all 96 of the 50 GHz channels. It also has Flex Grid functionality, so it is possible to flexibly define the width of the transmitted bandwidth.

PSNC has implemented AW connections in the PIONIER network and uses such connections in foreign networks. An example is the bandwidth exchange between PSNC and SURFnet networks on the Hamburg-Geneva link. PSNC provides the Hamburg-Frankfurt-Geneva link and receives from the Hamburg-Amsterdam-Geneva link.

Moreover, both types of DWDM systems in the PIONIER network are being tested for their ability to transmit T/F signals using ELSTAB systems (provided by AGH). Results of these experiments were presented at the conference EFTF 2017 [37].

4.3.3 ELSTAB

The system ELSTAB [38], developed by AGH University of Science and Technology, is a solution for transferring of time (1 PPS) and frequency (5/10/100 MHz) via optical fibre. The technology exploited in ELSTAB relies on an active stabilization of the propagation delay of a fibre link connecting the local terminal with the remote one using variable electronic delay lines. The stabilization mechanism used in ELSTAB requires the transmission of optical signals bi-directionally between the terminals in order to cancel noise picked up by optical fibre due to temperature fluctuations and mechanical vibrations. This is in fact a general requirement exploited in many kinds of fibre optic time and frequency transfer links (see deliverable CLONETS D1.5 "Fibre Time and Frequency Techniques"). The greater the symmetry between the two counter-propagation conditions, the higher is the correlation between the delay/phase fluctuations picked up by signals. This translates directly into a better stability of the signal received at the remote end of a fibre link.

The best ELSTAB performance can be achieved using a dark fibre operating bi-directionally. Typical performances proved by laboratory and field tests show an ADEV around $2 \ldots 4\times10^{-13}$ @ 1 s, rolling down to a few 10^{-17} @ 1 d, with a slope inversely proportional to the probe time [40] [41]. The accuracy of the time transfer, verified in experiments with local and remote terminals collocated in the same laboratory, show values 5…35 ps, depending on the length of the fibre and the accumulated chromatic dispersion [42].

The operation of ELSTAB is also possible on DWDM AW links (a dark channel operated uni-directionally) with a degradation in performance depending on the asymmetry between the forward and backward directions. A time transfer is possible but because of this asymmetry its auto-calibration (i.e. performed accordingly to the methods described in [42]) cannot be performed. A calibration is only possible with the help of an external time transfer system, e.g. GPS-based techniques.

Many experiments have been performed with ELSTAB operating over distances of up to approximately 3000 km, reaching an ADEV around 10^{-12} @ 1 s, decreasing to 10^{-16} @ 1 d. The obtained performance strongly depends on the length and type of the DWDM system implemented in the optical network ([43], [44]).

4.4 RENATER

RENATER, the French NREN, was deployed in the early nineties of the last century in order to federate telecommunication infrastructures for research and education in France. RENATER equips the community with fixed and mobile high-speed broadband infrastructures capable of supporting exchanges in the best possible conditions in terms of speed, quality, security and integrity. It offers national and international connectivity and evolves with improvements in technology and the available capacity of the infrastructure.

In 2005, dark fibres and DWDM technology were introduced in the national backbone network with the RENATER-4 version: a "project network" dedicated to scientific & grid computing projects was deployed in parallel to traditional leased lines for IP connectivity. This first DWDM infrastructure was designed with a capacity of 16 channels at 10 Gb/s and was provided by Alcatel 1696 Metro Span and 1626 Light Manager.

In 2006, the DWDM usage was progressively extended within the Paris and the Cadarache (ITER) areas and subsequently, during the RENATER-5 roll-out in 2009, was extended to the French metropolitan territory in order to transport IP traffic and replace POS on previously leased lines. Ciena CN4200 equipped 4/5 of this new network, while the former RENATER-4 Alcatel was re-deployed on the remaining fifth of the backbone. The link capacity was multiplied by 4, with a 40-wavelength architecture and a 10 Gbps throughput per wavelength.

In 2013, RENATER and the French Ministries agreed on a fibre mutualisation for the transport of RENATER and Ministry IP traffic. The solution of an optical VPN (i.e. dedicated

DWDM channels) was consequently deployed on RENATER’s existing DWDM infrastructure in order to transport these new circuits, called RIE: inter-ministerial government network.

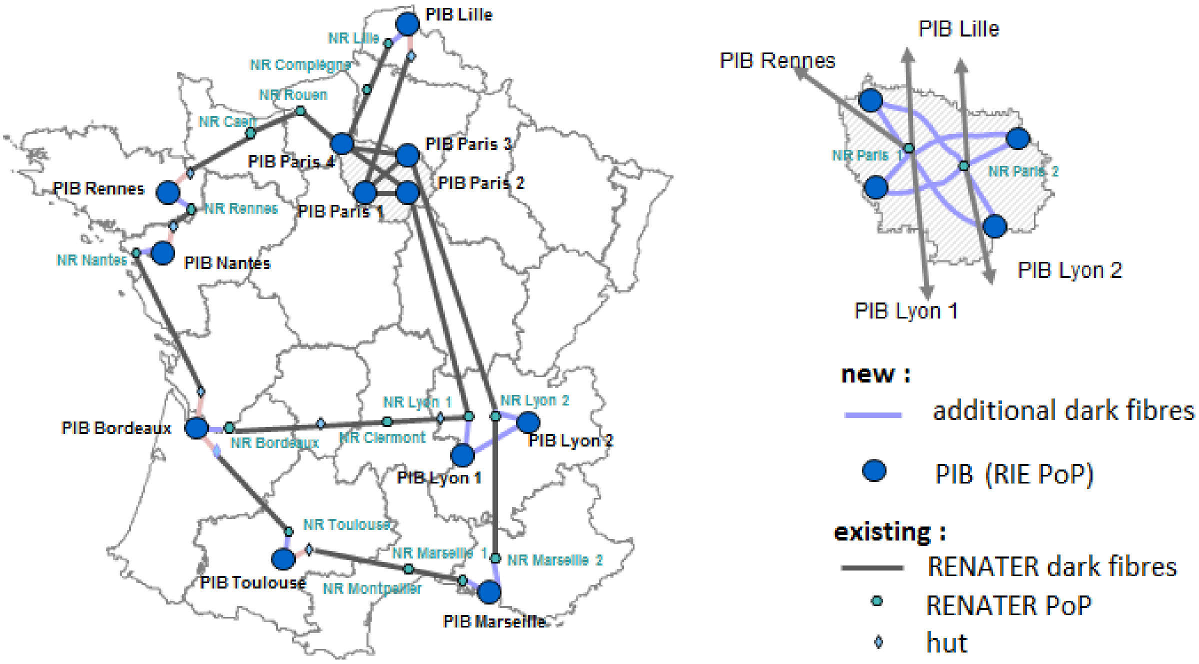

Figure 13. Optical VPN dedicated to the inter-ministerial government network (RIE).

In 2015, the RENATER-6 roll-out began with the deployment of new DWDM devices (Coriant hiT7300 and mTera) enabling a new generation of optical technology: 100Gbps coherent wavelengths, OTN switching and protection, ROADMs.

As depicted in Figure 14, the 2017 RENATER architecture is mainly composed of:

- RENATER-6 links equipped with 100G DCU-free systems provided by Coriant (combination of hiT7300 and mTera with static DWDM filters),
- RENATER-5 links equipped with 10G Ciena system, not yet replaced by new generation materials,
- RENATER-5 links equipped with a 10G-legacy system, but also transporting 100G alien waves emitted by Coriant devices.

4.4.1 100G AWs on a legacy 10G-Network

Due to the complexity of traffic migrations, the RENATER-6 roll out has been planned for geographic areas which are progressively transformed with coherent equipment. However, in order to cope with the rise of traffic demand on areas not immediately upgraded, a temporary solution has consisting of 100G AWs (generated by Coriant equipment) transported on the RENATER-5 photonic layer (Ciena) been deployed. These are type-I AWs as explained in Section 2.3. This solution consists of the spectrum sharing of an 8-channel band dedicated for 100G AWs and physically realized through RENATER-5 band splitters at each PoP.

Figure 14. The RENATER-6 DWDM backbone (End of 2017)

4.4.2 REFIMEVE+

RENATER has been working closely with OBSPARIS and LPL on T/F experiments since 2009 and is a member of the REFIMEVE+ consortium, which aims to disseminate a metrological ultra-stable frequency to French scientific laboratories and perform comparisons with European NMIs through the RENATER DWDM network and CBFs [45]. With its commitment to provide more than 10,000 km of dark fibre infrastructure, RENATER is a key partner of this project.

To make the transport of an ultra-stable frequency possible, RENATER was required to adapt its network because the REFIMEVE metrological signal is not compliant with conventional DWDM technology. The REFIMEVE signal is actually transmitted bi-directionally through each dark fibre and therefore cannot pass through standard DWDM equipment such as EDFA amplifiers with isolators. While the ultra-stable optical signal propagates in the same fibre, all telecom or network equipment (such as amplifiers or access points) are bypassed. Thus the AW only shares the fibre with its optical spectrum being included in a channel of the DWDM grid. This technique was first demonstrated in 2009 in the RENATER network on a short 11 km fibre link using CWDM propagation [46]. Consequently, this technique was demonstrated on longer spans with simultaneous data traffic on the neighbouring channels of the 100 GHz DWDM grid. The ultra-stable frequency transfer from Paris to Reims and back (540 km) is in operation since 2012 and the transfer from Paris to Strasbourg and back (1500 km) since 2014 [47]. The fibre link uses a cascaded link of 4 spans with 40 OADMs to extract or insert the ultra-stable signal from the data traffic, and 16 bi-directional EDFAs, as displayed in Figure 15. Repeater Laser Stations (RLSs) are used to regenerate the ultra-stable signal. This Dark Channel technique uses its own amplifiers and repeaters (Figure 16). The AW propagates, in contrast to usual telecom infrastructure, fully bi-directionally inside the fibre and uses its own bi-directional amplifiers. It has been proven to be compatible with a DWDM network. Only one problem has been reported since 2009, when Raman amplifiers weren't correctly set-up on the RENATER network.

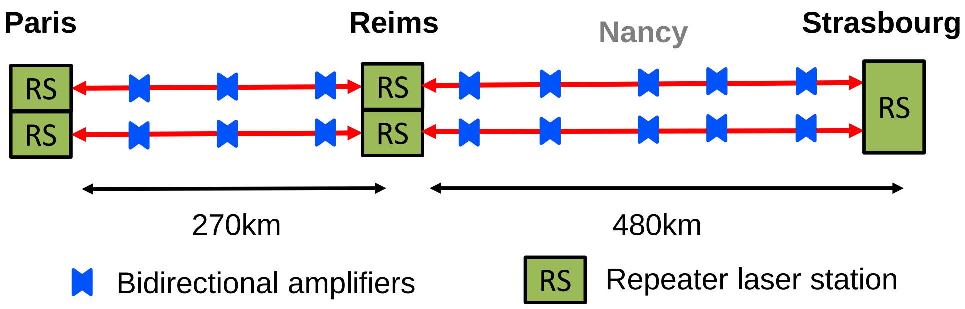

Figure 15. Schematic of the cascaded link between Paris-Strasbourg and back.

In 2012, a timing signal was also transferred on the RENATER network, simultaneously with a frequency transfer, using the Dark Channel technique on the 540-km long span between Paris and Reims and back [48].

The 'Nancy-Reims' link of the RENATER Network, which is equipped for REFIMEVE+ transmission, is depicted in Figure 16. To avoid the isolators, dedicated OADMs are installed at each PoP and ILA, such that the metrological signal (depicted in red) by-passes the DWDM equipment. Once extracted at the ILAs, the signal is re-amplified separately from the remaining NREN signals. The insertion of an OADM causes an extra-attenuation of 1.6 dB on each span.

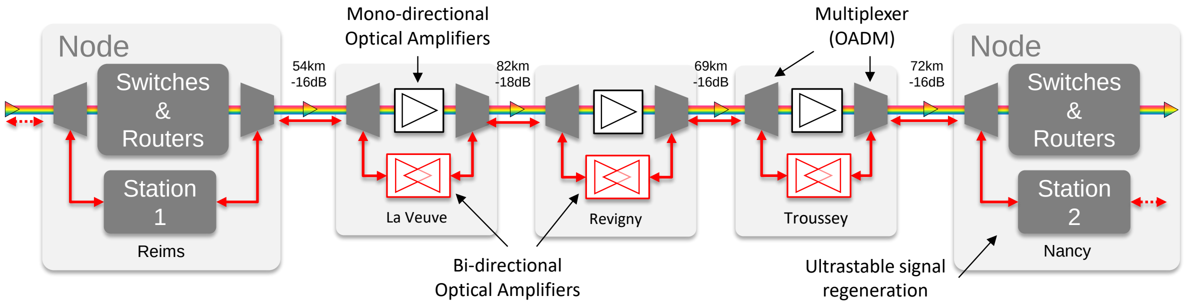

Figure 16. Detailed schematic of the Reims - Nancy fibre link.

This is a typical example of spectral sharing, where the spectrum is opened and waves from other equipment and/or entities are injected into a system.

Figure 17 presents the target infrastructure of REFIMEVE+. The Paris-Strasbourg branch of the network is operational since 2014 and is connected to the German infrastructure of PTB in Strasbourg, where both OBSPARIS and PTB perform atomic clock comparisons. Work on the Paris-Lille and Strasbourg-Besançon extensions has started mid-2017.

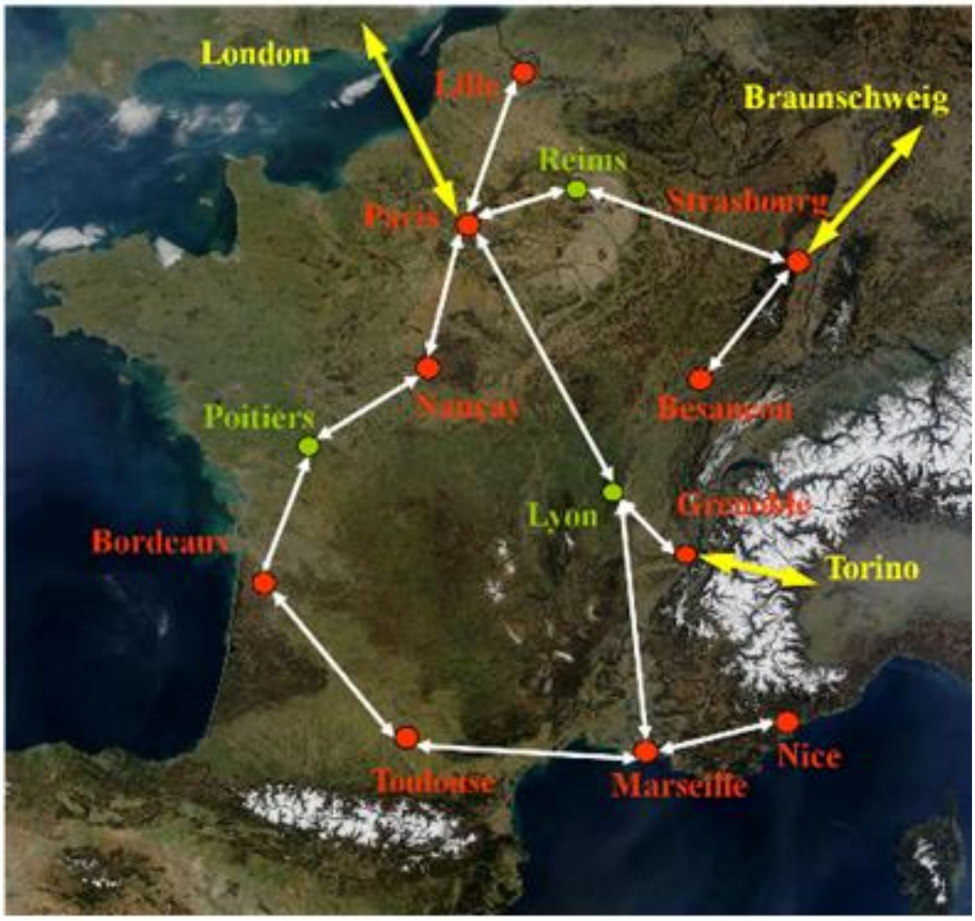

Figure 17. Target REFIMEVE+ infrastructure in the RENATER network.

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

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

5 AW SERVICES IN FIBER SENSING APPLICATIONS

AWs have been successfully used by many NRENs and commercial operators and this trend seems to be gaining popularity, especially within the data centre world. As described in the Introduction, PS represent a generalised end-to-end all-optical path between two end points and serve as an enabler for non-data transmissions. Although this deliverable focuses on T/F signals and services, there exist other applications that can benefit from PS, for example, fibre sensing applications. Optical fibres are sensitive to temperature, vibrations, mechanical stress and other environmental phenomena, which on the one hand is problematic for standard data transfer applications, but on the other hand is the basis for a new kind of sensor. Fibres can therefore serve as distributed sensors providing the possibility to monitor a large variety of quantities, such as temperature, seismic disturbances, strain or acoustic perturbations. The practical utilization is usually based on propagating a specific wavelength, either as a continuous wave or RF modulated, through the fibre sensor and observing changes in the signal. AWs could potentially be employed for the interconnection of these sensors. More information on fibre sensing can be found, for example, on the web pages of the University of Southampton [49], a university where EDFAs were extensively studied in 1980s and distributed optical fibre sensors have been studied since the 1990s. Fibre sensors and their applications are also studied at CESNET, with the focus on integrating time, frequency, data and sensing applications in one fibre [50].

6 RECOMMENDATIONS

According to the practical experience gathered in RENATER, PSNC, and CESNET, we have summarized a set of general preconditions for the deployment of AWs in an optical data network:

- The data channels usually have a higher priority than AWs and therefore must not be affected by the AW.
- The optical layer must implement spectrum sharing, typically as a DWDM system.
- The design of an interface between the vendor proprietary system and the AW application under own management in case the two are combined.

AW requirements that should be considered are:

Bi-directional versus uni-directional AWs

For the specific case in which a bi-directional AW shares the fibre with a uni-directional data channel, potential interferences between the data channel and the "backward" AW due to backscattering must be considered and avoided. This is particularly critical if Raman amplification is used. In the case of a Raman amplification at the data receiver end being shared with a bi-directional AW, the AW power should be less than 5 dBm and the Raman gain set as low as possible.

An AW alongside data traffic

Even if the AW originates from equipment outside the AD, it needs to be controllable by all ADs it passes. An AW should never be allowed to propagate alongside data traffic, if there is no way to shut down an AW that would degrade the BER of an operating fibre link. A basic recommendation is to force all AWs to pass through a bi-directional variable optical supervised attenuator at the entrance and at the exit of every AD. As this is an "all or nothing solution", it is desirable to implement a more sophisticated solution to have a better control of AW, if possible, such as a dedicated DCN integrated within a global supervision.

Optical amplification

In case of shared amplifiers, the power of the AW and the data channels should be similar. When an AW is RF modulated, the modulation should have duty cycle of about 50% (i.e. similar to NRZ). Signals with amplitude and phase (or none) modulation should be separated by an unused spectrum gap, i.e. a guard-band. The width of a guard-band is not defined by any standard, as optical equipment may have different tolerances to different impairments. For example experiments performed in the CESNET2 backbone network showed that a 100 GHz band is sufficient for the simultaneous transmission of 100 Gb/s coherent signals and RF modulated time signals [51]. Another option is the deployment of dedicated amplifiers for AWs including channel or reserved bandwidth filters. This approach also solves the problem of bi-directional AWs in an otherwise uni-directional fibre.

Required bandwidth

Several applications require only a few separated DWDM channels, however, it is often more convenient to reserve a wider bandwidth. Systems utilizing the whole optical band (e.g. the S-band that is amplified by an SOA) also exist.

The signal source: standard transmitters versus lasers

The utilization of standard transmitters (e.g. Small Form Factor Pluggable SFP/SFP+) significantly improves their compatibility with the rest of the optical layer as they assure the required wavelength, spectrum line bandwidths and power. If a laser is being used, it is the responsibility of the AW designer to meet these parameters.

Sensitivity to occasional fibre owner maintenance

Rented fibre is subject to maintenance by its provider. AW applications must be resistant to temporary disconnections, replacements of dispersion compensating fibre, changes of amplifier gain and other events that may occur. Data transmission is more robust to such issues and therefore it is important that the fibre owner is aware of bi-directional and non-standard protocol transmissions.

7 CONCLUSIONS

There exist new optical layer applications, which do not primarily focus on very high terabit speeds or a large number of DWDM channels but instead require direct access to the optical channels. Although the vendors’ support for these kinds of applications, including the AW approach, was reluctant some 5 years ago, the situation has recently started to change. NRENs and other advanced optical networks are benefiting from this shift. New open optical trends and equipment has been brought to the market, and it has become possible to test, verify, design and deploy them. Ultimately, the new and open technology might enable the implementation of new services in production networks. Use cases of AWs exist within NRENs, e.g. CESNET, RENATER, PSNC, NORDUnet, SUNET, UNINETT, SURFnet, GARR and others.