Photonic Services: Challenge for Users and for Networkers

Last updated:	23-05-2013
Activity:	JRA1
Task Item:	T2
Dissemination Level:	PU (Public)
Document Code:	GN3-13-110
Authors:	L. Altmannová, M. Altmann, M. Hažlinský, M. Hůla, O. Havliš, G. Korcsmáros, J. Kundrát, M. Míchal, J. Nejman, J. Radil, K. Slavíček, V. Smotlacha, S. Šíma, M. Šimek, P. Škoda, M. Šlapák, R. Velc, R. Vohnout, J. Vojtěch (CESNET); E. Camisard (RENATER)

Table of Contents

Table of Figures

Table of Tables

Abstract

Photonic Services are able to provide unique features for new and innovative applications whose requirements cannot be met by conventional networks with OEO conversions. Simply using higher data transmission speeds (even 400 Gb/s and above) does not solve the issue of accurate time comparison or ultra-stable frequency transfer, which relies on a constant delay and minimal jitter within the transmission path. This document discusses the benefits and importance of these technologies and presents examples of their deployment. Actual challenges for the research management authorities, the networking community and responsible ICT experts of user projects are discussed.

Executive Summary

Photonic networks, i.e. setups utilizing all-optical equipment without intermediate conversion between light and electricity, are an interesting and novel concept. Eliminating the conversion process provides clear benefits: for example, there is no possibility of semi-random jitter being introduced to the transmission. To a certain extent, the value of the network as a whole is increased as it can transfer a wider spectrum of signals compared to conventional, OEO-setups. The concept of Customer Empowered Fibre networks can provide networkers with sufficient flexibility and a cost effective way of building such networks.

Modern scientific experiments are the driving force behind innovation in various fields and research is nowadays pushing for new features in networks. Emerging applications like timestamp transfer, highly accurate frequency transfer, or reproducible experiments using physically distant equipment were simply not considered when currently used networks were designed. Photonic Services might very well enable these innovations to happen.

The unique features of a purely photonic signal transfer enable innovative applications whose needs were not answered by conventional, OEO methods. In this study, we present current real-world applications of Photonic Services. The route between the Institute of Photonics and Electronics (IPE) in Prague and the Austrian national time and frequency laboratory in the Federal Office for Metrology and Surveying (BEV) in Vienna is used for an unprecedentedly accurate comparison of national, atomic clock standards. Another application is ultra-stable frequency transfer over on an existing DWDM backbone performed in the RENATER network in France. These two examples illustrate how to fulfil the potential of optical networks and hints at how the networks will be perceived by their users – especially by users from the Research and Education community. It is expected that the widespread implementation of Photonic Services will be inevitable in the R&E community and very probable even in commercial telecommunication networks.

However, as with any other emerging technology, there are also practical obstacles faced when deploying all-optical setups. The first step to climb might be a psychological one – whenever one is challenging industry standards, a significant resistance is to be expected, as people are often wary of the unknown. The dominant equipment vendors also approach the multi-vendor Photonic Services' deployments with a particular scepticism. That said, in this document we undertake to demonstrate that there are compelling reasons to consider deploying all-photonic networks. Some of the well-known transmission equipment vendors do offer systems which are sufficiently flexible and fully usable for PS deployment; the case studies presented offer a first-hand experience about such setups. During our tests, none of the frequently mentioned obstacles were encountered. Further experiments with additional heterogeneous equipment would be desirable in order to further explore and test these claims.

A case study presented in section 2.4.3 shows an example of how one can approach the task of designing a future-proof end-to-end link. The chosen mode of operation ensures that the line is ready to support future applications without a need for an expensive retrofit.

Feasibility studies have been made to show how Photonic Services enabled optical links can be built. A special focus of the feasibility studies was on showing how to design all-optical links using the Open DWDM equipment. The Open DWDM technology was chosen for its openness and the immediate availability of all the required technical data – a case which is not always present with proprietary equipment. Component pricing is also publicly available which is rather convenient for budgetary purposes. The Open DWDM is also fully transparent for any devices operating on higher network layers providing flexibility in network design that can lead to further cost savings.

The tests and real-world production setups described in this report have confirmed that fibre sharing works well and can be utilized even over heterogeneous networks. Successful deployments of Photonic Services over the same fibre spans as regular, n x 10G and 100G signals are discussed as well.

The examples presented in this document demonstrate how these new possibilities of using networks have changed the way how our partners think about their fibres. Photonic Services have manifested their potential for enabling customers to see the network as a crucial, innovative part of their offering.

The report concludes with real and significant challenges for the research management authorities, the networking community and responsible ICT experts from the end-user projects. The challenges are:

- To understand the nature of Photonic Services, to prevent uninformed decisions concerning dark fibre lighting, and to select an optimal long-term architecture of the network.
- To foster the development of dark fibre Lighting as a Service (LaaS) and to encourage vendor-independent, multi-domain E2E photonic service planning.

Testbed as a Service (TaaS) activity is proposed to be part of the GN3plus project and Open Calls are expected in order to support photonic research.

1 Introduction

The objective and purpose of the document is to foster innovation in Europe and beyond by developing Photonic Services and supporting long distance End-to-End Photonic Services (E2EPS) between user premises. The E2EPS are needed to satisfy new requirements of science, research and engineering.

The term Photonic Services was first coined by CESNET optical experts in 2010 and introduced in the GN3 Deliverable DS1.1.1,2 Final GÉANT Architecture [1], in 2011.

This document contains feasibility studies, description of successfully deployed, monitored and operated services, and references to publications and promotional titles useful in photonic service design and operation. In addition, global collaboration results are included.

1.1 Long Distance Photonic Services between User Premises

This document is based on results achieved in End-to-End Photonic service development in countries participating in the EU FP7 research project GN3. It is also aimed at promoting an understanding the limitations of legacy dark fibre footprint and transmission systems.

Lighting fibres for E2EPS requires very detailed information about fibre and all connected components. Things like the length of DCF, the length of erbium-doped fibre inside EDFAs or the design of the gain control loop in EDFAs become important. And for the most demanding applications, like frequency transfer, even the length of patchcords or connector types may be important. Many proprietary systems withhold such information from their users. For this reason, we have conducted our feasibility studies using the Open DWDM system. In the Open DWDM system, all required information is made public to the users. The system enables multi-vendor fibre sharing, a feature important for discussion of transmission in L band and for improved cost effectiveness. The Open DWDM system includes devices developed by CESNET which are manufactured under licence.

CESNET is able to help with fibre lighting for Photonic Services (PS), monitoring and supervision of PS as well as supporting other methods of E2EPS implementation for other projects. For example, the CzechLight Amplifiers are used in the Aurora testbed [2]. CESNET does not sell CzechLight devices, but the device prototypes are the result of CESNET research. The devices are produced under a non-exclusive licence and available from manufacturers. Deployment in production networks is usually carried out in the form of a service (see ‘Lighting as a Service’ in section 1.4).

In demonstrating E2EPS we were limited by available fibre lines and end users able to participate in deployment. Monitoring of multi-vendor E2EPS was made possible by the CLmon system developed by CESNET. CLmon can monitor optical equipment of multiple vendors, if a description of equipment functions is available and an interface module is written.

A dialogue of GN3 project participants (especially CESNET, DANTE and RENATER) with a world-wide community interested in Photonic Services was started in 2012. Significant feedback has been received from Australia (AARNET), Japan (SINET4), South America (RedCLARA) and the United States (ESnet), for example.

1.1.1 New Principal Requests from Science and Engineering

A few scientific experiments have emerged in recent years that have raised demands on the European optical infrastructure. For example, a group from Physikalisch-Technisechen Bundesanstalt (PTB) in a presentation by Predehl [3], demonstrated the possibilities and importance of accurate time and frequency comparison and dissemination. The joint research project (JRP) NEAT-FT ”Accurate time/frequency comparison and dissemination through optical telecommunication networks” [4], in Selected Research Topic SRT-s11 of the European Association of National Metrology Institutes (EURAMET) can only be achieved using Photonic Services. Other applications, such as robotic surgery, seismology, 4K (or stereoscopic) video conferencing, precise remote control of moving objects and other unique scientific experiments are also being developed.

Photonic Services constitute a crucial pillar for delivering the above mentioned tasks at a large, pan-European scale. The only economically feasible method is through sharing the optical spectrum of GÉANT and the NRENs’ fibre footprint.

The centrality of Photonic Services is nowadays being acknowledged in major projects. The REFIMEVE+ project [5], one of the 36 selected projects among 270 proposals from all disciplines, is another example. Involving cooperation between 21 partners and funding of 6.7M€ over eight years, the project involves the development, at the European level, of a fibre optic network to ensure the transfer of an ultra-stable clock signal without significant degradation. The project demonstrates a new concept of frequency reference from ultra-stable carrier distribution from an atomic source using the Internet.

The expected results are far-reaching, from earthquake risk reduction to the design of safer transport.

The R&E community demands and expects Photonic Services, not only in metrology but also in seismology and other fields: "Various scientific fields will benefit from the availability of the ultra-stable reference signal. For instance, time and frequency metrology, fundamental physics on earth and in space, precision spectroscopy… This instrument will also explore the possibility to realize a giant national-scale geophysical sensor sensitive to earth rotation, seismic and tidal phenomena", see additional information on REFIMEVE+ in [6].

The IDIL Company participates by development of Fibre Optic Systems and Components for Science and Industry [7]. The project is supported by The Network of Excellence FIRST-TF, see N. Dimarcq: Collaborative projects in Time and Frequency metrology in the context of the French program ‘Investissements d’avenir’, LNE-SYRTE, [8]. A good overview of the possibilities and expectations of high-accuracy frequency transfer in the Netherlands was given in J. Koelemeij’s presentation ‘Putting Optical Fiber Frequency Links to Work’ [9].

1.1.2 Principal Issues for Network Design and Operation

New principal requests of science and engineering bring significant new challenges for end users, for networkers and also for the industry involved in providing transmission equipment for research and innovation purposes, discussed below. Solving this issue should enhance the development of the 'Communication Commons', promoted in Europe by the Horizon 2020 programme (Commons is what we share: "resources that are collectively owned or shared between or among populations").

An almost ideal solution for ultra-stable time and frequency transmission is represented by dedicated underground fibres laid in an environment without mechanical or acoustic disturbances. However, this solution tends to be costly. Based on the GÉANT dark fibre footprint, we can estimate that European dedicated network will have to contain at least 15000km of fibre pairs. Based on the average rental price of 0.5 €/meter/year it yields the amount of 7.5M€/year just for fibre rental, [10].

We should also note that some fibre lines are not suitable for PSs transmitting ultra-stable frequencies because of present vibrations; this applies especially to aerial fibres or fibres in proximity of railways. Present compensation techniques stabilize only slow thermal effects. Without further testing we cannot be sure whether a fibre line is sufficiently protected against vibrations (for example, the Paris – London line is routed through the TransManche Link railway tunnel). Investigations of such effects on PSs would be very valuable.

Some legacy transmission systems are designed in a way that cannot easily support an all-optical transmission of so-called "alien wavelengths" (AW). As a result, these will not support transmission of Photonic Services either. In particular, this could prevent deployment of PS in some undersea cables, and might have implications to the availability of precise time and frequency transfer to research premises on islands, etc. Some of the existing AW systems can be used for fully-fledged PS deployments; others are only suitable for building the best effort (i.e. without real-time guarantees), digital setups over the analogue, photonic substrate. New vendors of lighting (transmission) equipment should enable multi-vendor fibre sharing instead of fibre occupation.

Another interesting point to mention is the coexistence of slow signals with OOK modulation (for example less than 1Gb/s) together with high speed coherent signals (100Gb/s). This is discussed rather frequently with transmission equipment vendors but there is no general agreement how deleterious these effects are and which slow speeds (i.e. 100M, 1G or 10G) are worst. Slow signals are said to have a negative effect on coherent ones (via nonlinear effects in fibre) but practical experience at CESNET shows that such effects are negligible. We tested the influence of slow (accurate time transfer) and 100G signals positioned on different ITU frequency grids and no BER degradation for 100G signals was observed [38].

Perhaps we should mention one new trend when building new optical backbone networks - DCM-free design - where there is no compensation for chromatic dispersion. This approach is valid when old methods of compensation are used and Dispersion Compensation Fibres (DCF) are deployed. DCFs have a negative effect on coherent 100G signals (the all-optical reach is shortened and an additional delay is introduced). A newer method of compensating for chromatic dispersion with new elements - Fibre Bragg Gratings (FBG) - is supported by research papers [11], and also practical experiments proving a positive influence of FBGs on coherent signals [12]. In Reference [12] it is shown that the application of FBGs can extend the all-optical reach of coherent signals from less than 3,000km to more than 12,000km.

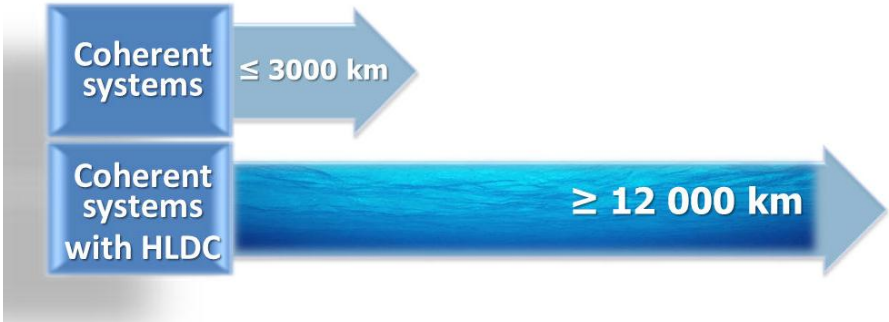

Figure 1.1 All-optical Reach Extension of Coherent Systems with help of FBG (from [12]).

Another problem may arise in future when the new generation of 400Gb/s or 1Tb/s line cards is introduced. It is acknowledged and mentioned in papers from prestigious conferences, like OFC and ECOC, that "the introduction of higher order modulation formats will bring significant reduction in reach", cited from [13]. This fact may change today's recommendations for DCM-free designs and networks because compensation of chromatic dispersion may be required again in the near future.

Unfortunately, the term DCM is often used both for DCF and FBG, even though DCF and FBG properties are completely different. So recommendations for so-called "DCM-free" designs should be evaluated very carefully because such designs can block new types of applications and networking services like future 400G or 1T, and of course any existing services utilizing both 10G and 100G signals.

1.2 Importance of Photonic Services for Users

Photonic Services have been demonstrated and will soon be available for the enhancement of research and innovation projects. Users will be able to transfer signals over long distances with a very accurate fixed delay to connect equipment, sensors or scientific instruments, as well as regular data transfer with transmission delays which are less stringent. PS utilization enables further progress in different fields of science and research: for example in time/frequency transfer, in the reproducibility of experiments or in remote control. Photonic Services are required by metrology and potentially by other applications (fundamental physics, geodesy, seismology, earth observation etc.) that benefit from ultra-stable transmission. For atomic clock comparison (or accurate time transfer) or even an accurate frequency transfer, a photonic (all-optical) signal transfer in optical fibres is the only option. Currently, no other technique meets the stringent requirements for such a high stability (typically in the order of 10^{-17}).

The Internet is slowly stepping up to a higher data transmission speed (even 400 Gb/s and above). But despite such an increase, these channels cannot provide an accurate, fixed end-to-end delay unless the whole path between user devices is all-optical (i.e. without the usual OEO conversion in network edges and nodes, etc.). This is because ordinary data transmission equipment is not designed for these tasks, and employs techniques with variable timing such as advanced digital signal processing (DSP), skew management and statistical multiplexing. These types of electronically-imposed limitations are discussed in Miyazaki's presentation [14].

1.2.1 Challenge for Users

In Photonic Services, an optical signal (i.e. a wavelength) is received from the user, transported across the transmission network and handed over to the recipient in almost the same form in which it was received ("almost" because of the optical noise and other effects on the signal; however, from a user's perspective, nothing else changes).

The interpretation of a signal in the PS setup depends only on the end users – they can use it as analogue or a non-standard or a standard digital signal. Nowhere along the transmission path is the signal converted or processed (by OEO conversion, for instance) in a way that would prevent recognition of the transmitted value.

The generation and interpretation of the signal is usually a responsibility of the R&E user's ICT experts, so it is unlikely that demand for PS will come directly from research users, at least initially. Even some ICT experts have been unaware of the potential and possibility of PS, but the message to them now is "the situation has changed, Photonic Services are coming" (if requested with sufficient lead time).

We expect that high-end users in leading-edge scientific research will continue to impose the most demanding requirements and will provide a testing ground for new innovations and services. Requests for more routine deployment (for example requests for frequency transfer from other telescopes) will be slower to arrive but the networking community in a given country should not conclude from this that there is no demand from users. It is too late to start replacing equipment when the first user asks for a service. The trend in high-end research is clear and it is only a matter of time before these value-added services are adopted by users outside of "big science".

What is now required is to make informed decisions in optical fibre lighting, including fibre to user premises. The following are examples of challenges to ICT experts preparing research and innovation projects in various application fields:

- In an on-going European Southern Observatory (ESO) project, the ALMA observatory will connect to the national research backbone. Approximately 150km of fibre over the desert will be constructed [15].
- The Pierre Auger Southern Cosmic Ray Observatory, partially funded by the EC, is located in Malargüe, 400km south of Mendoza in the Andes Mountains, and connected by fibre to Mendoza in the Buenos Aires-Rosario-Córdoba-Mendoza-Santiago link (1767km) travelling along the gas pipeline and providing a 5 x 10G DWDM system for RedCLARA and research projects. See Future Research Requirements in Latin America, [16].
- Other telescopes around the world may be future candidates for PSs.
- The Greek Nestor Institute for Astroparticle Physics, which hosts a deep sea high energy neutrino telescope, is preparing to install fibre under the sea (approx. 4000m) [17].
- The Observatorio del Roque de los Muchachos, La Palma, Canary Islands hosts a 10.4m telescope with a segmented primary mirror (as of 2010, the largest telescope in the world) [18]. Connection to the mainland is made via a 1500km submarine fibre line and 375km of inter-island fibre [19].
- Connection of The Czech polar station in the Ny-Ålesund research village on the Svalbard archipelago to continental Norway. This connection is operated by the University of South Bohemia in České Budějovice and is the subject of a project started by UNINET to deploy a submarine optical cable. Connection of the polar station by advanced network services enables innovative research methods in

fields such as Glacier and ecosystem dynamic monitoring, the impact of cosmic radiation on living organisms and year-long meteorological services [20].

Whereas Photonic Services bring new possibilities to science, research, industry and public services, it is not able to provide applications -for example accurate time or frequency transfer to their equipment - immediately. It is very important, however, to plan to provide PS on demand to avoid slow and expensive changes in fibre lighting, or even changes of undersea transmission equipment or cables.

The examples above might concern only large research projects, but mistakes can be made also in the fibre and lighting design inside or near to user premises. If long distance end-to-end optical paths are needed, multimode fibres (although less expensive) are almost unusable even in the local fibres to user desktops, laboratories, or to scientific and medical instruments inside the campus or building. Furthermore, significant difficulties in costs and flexibility can arise if the contract for the transmission system deployment allows the full fibre transmission spectrum to be tied to a single vendor. Both of these situations are, unfortunately, still common for many user premises.

There is a growing understanding of the need to control resources and equipment remotely, and to retrieve remotely collected data in real time. These datasets can be very large – prime examples are the 4K (Ultra HD) video signals and Gigapixel cameras or sensors whose data cannot be compressed without a loss of loss of information.

The report *Knowledge without Borders* [21], accepted by the EU, requires:

… high-speed bleeding edge services, using end-to-end optical aka photonic paths on demand, for serving unique large research instruments – such as those defined by ESFRI, the European Strategy Forum for Research Infrastructures [22]. It is based on the understanding that the current economy is a competition of and for talent. Talent is attracted by tolerance, technology and other talent. Excellent research depends notably upon world-class facilities and research infrastructures, including remote access to resources and equipment [23]. The overall context can be seen in Horizon 2020 as instrument implementing the Innovation Union, a Europe 2020 flagship initiative aimed at securing Europe's global competitiveness [23].

In summary, we suggest that “using end-to-end optical paths” does not go far enough; new network designs need to be enhanced to allow the transfer of signals with a known and very accurate fixed delay (usually in addition to the parallel data transfer).

1.2.2 Challenge for Networkers

R&E users (such as metrologists and physicists) have recognized that getting access to dedicated fibre is difficult and/or expensive. However, getting access to a dark fibre or to Photonic Services is simple and affordable if you are a CEF network designer, a designer of lighting equipment, or if you deal with vendors open to new ideas.

The idea of Customer Empowered Fibre networks has proved to be very useful in terms of cost effectiveness and flexibility. Interested networkers were able to use cost-effective single fibre bidirectional DWDM transmission (a DWDM transmission suitable for connections to user premises), for a multi-vendor environment in cross-border fibre connections between NRENs. The two key points of success were the development of the CzechLight family of optical equipment by CESNET (and their non-exclusive production licensing to industry partners), and the procurements of dark fibre lighting services designed by the customer (in this case by CESNET rather than by an equipment vendor).

Moreover, the idea of Customer Empowered Fibre networks now has a strong potential to enhance the intent of Communication Commons, as presented by the EU document *Knowledge without Borders* [21].

CEF Networks require:

- A dark fibre connection to end users (Customers), which can be user desktops, laboratories or scientific instruments.
- Allowing Customers to decide what end-to-end transmission they need for their research and innovation projects.

The above requirements are widely accepted by the networking community for data transmission. We should, however, keep in mind the case of a more general signal transmission (including non-digital signals) needed, for example, in the comparison of atomic clocks or for the transfer of frequency, even though such requirements cannot be realized in all locations.

We have also recognized that the strict separation of network fibres into the production and experimental footprint is harmful and expensive, because:

- It is useful to enable experiments on the production network (for specialists) while maintaining high reliability and availability for legacy traffic.
- It is also useful to allow production traffic on experimental lines: it is an effective use of leftover bandwidth.

We can speak about an Integrated Facility instead of a separated production network and Experimental Facility. Networkers should develop an Integrated Facility for:

- Production traffic.
- Scientific discoveries.
- Experimentation and engineering.
- Control of external processes (including hard real-time control).

In summary, PS are suggested as a means to enhance services and goals as described in the report *Knowledge without Borders* [21], written before requests for time and frequency transfer were first made. The authors noted that:

- Eighteen of the EU/EFTA NRENs currently offer dedicated wavelengths (lambdas) to their customers, and another is planning to do so. In addition, at the pan-European level the GÉANT lambda service provides private, transparent 10 Gbps wavelengths between any two NRENs connected to the GÉANT dark fibre cloud.
- By 2020 the European networks will require terabit backhauling together with multi 100-gigabit flexible lambda management across NREN territories and local domains.

- The European R&E networks have performed well and have notable achievements. They are world leaders in many areas; an innovation environment and ideas generator, helping to drive the development of new networking technologies and services.
- Open innovation and open learning are two increasingly interesting paradigms. The research networks tend to be at the most innovative end of the spectrum, and new technologies and services are often discovered in academia where the early adopters are most frequent. The networks provide European industry with a testbed for advanced hardware, software and applications, while also offering an increasingly important market for the supply of advanced technology and services.
- The current generation networks must evolve into service-enabled infrastructures that provide a platform for innovation by users. This service provision spans, and requires interaction across, three levels: advanced networking R&D, testbeds, and production services. It is the co-existence of these three levels, in unique combination, that constitutes a European communications commons and distinguishes the research and education networks from commercial service provision.
- NRENs should become living labs, providing live testbeds for future technologies and connecting researchers and others to the market.

1.3 Milestones of Previous Developments

The development of all-optical services was launched at CESNET in January 2000 by the 311km dark fibre lease Praha – Brno. CESNET's Optical Networks research team initiated the development of CzechLight Optical Amplifiers, enabling the cost-effective lighting of dark fibre lines by the NIL (Nothing-in-Line or 'hut skipping') approach. After extensive lab testing, a 189km NIL dark fibre line Praha – Pardubice has been continuously operating in the CESNET2 production network since May, 2002. Our experience with lighting was presented at the Terena Networking Conference in 2002 [25] and was further discussed with a global audience in the first Customer Empowered Fibre Networks workshop in 2004 [26].

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

Following the above successes, our Optical networks research team developed the Open DWDM photonic system based on the CzechLight family of devices. The system is capable of multi-vendor, all-optical transmission over fibre pairs and also supports bidirectional, all optical transmission over a single fibre. Our motivation was mainly cost savings, but this approach also allowed us to verify the quality of our own R&D results, provide flexibility for the DWDM photonic connection of remote R&D premises in the Czech Republic and allow interoperability with other transmission equipment. The all-optical interconnection with Cisco DWDM lines is operated in the CESNET2 network, and interconnection to Brocade XMR 8000 is operated in the PIONIER network on Poland's side of the Cross Border Fibre: Ostrava (CZ) – Bialsko – Biała (PL). CESNET2 was able to provide end-to-end Photonic Services (all-optical lambdas) between user premises prior to the metrologists' requests for the transfer of highly accurate time or frequency.

CESNET has 5340km of leased fibres now and more than 50% of them are lighted by the Open DWDM photonic system based on CzechLight optical devices, manufactured under CESNET's non-exclusive licence; see the presentation [27].

CESNET commenced offering its CESNET2 network as a large-scale integrated facility for the European R&E community, to support both medium- and long-term research on networks and services, at an EU event held in Poznań in October, 2011 [28]; see the presentation [29].

In 2010 CESNET tested precise time transmission over PS between Prague and Vienna. This PS carries signals generated from special adapter over two different transmission systems. In 2011, comparison of atomic clock scales in Prague and Vienna went into operation. The six-month statistics of IP traffic in the Praha – Brno – Wien route can be viewed at:

http://www.ces.net/netreport/CESNET2_IP_MPLS_backbone_utilization/Praha%20-%3E%20Brno/index.html (lighted by Cisco DWDM), and

http://www.ces.net/netreport/CESNET2_IP_MPLS_backbone_utilization/Brno%20-%3E%20ACONET/index.html (lighted by CzechLight DWDM), where IP traffic flows in parallel with photonic (all-optical) service between Prague-Vienna.

These statistics show that the PS have no negative operational influence on lambdas (transmitting IP traffic) running in parallel to PS on the same fibre pair. The PSs themselves are monitored by the CLmon system. No education or training of operational staff at CESNET or ACOnet was needed.

RENATER showed a possible way on how to transmit special PS (ultra-stable frequency) on an existing DWDM backbone. They created a loop around the Paris Observatory with an achieved length of 540km, including 70km of dark fibre and sharing 470km of fibres with commercial transmission equipment. Important results included:

- No perturbations on RENATER traffic.
- Good behaviour of scientific signal: less than 10 fs jitter in optical signal transmission (fixed signal delay given by the fibre length is 0.1s in 20,000km of fibre) [30].

These findings are detailed in 'Transmitting ultra-stable optical signals over public telecommunication networks' [31].

SURFnet and NORDUnet conducted a demonstration of multi-vendor AW, transmitting a 40G coherent wave over 1056km of fibre between Amsterdam and Copenhagen. Two different transmission systems were used: one DCU based, and the second DCU free. For details see [32].

As mentioned above, the idea of Photonic Services was described in the report *Final GÉANT Architecture* [1] in 2010, but has not yet been used for the GÉANT production network. Feasibility studies and deployment in European-wide dark fibre testbed are discussed in [33].

In the second quarter of 2012 CESNET obtained support for the GN3 project subtask: "E2E Photonic Services between user premises", leading to a feasibility study on a Europe-wide scale, and "Photonic Services enable advances in research”, oriented to the world-wide dissemination of our results among research and scientific communities. Our collaboration with RENATER, which developed a method of frequency transfer on the production network backbone, was also very useful.

1.4 Contributions to Cost Effectiveness

The economic situation demands that we look for economies of scale and integration.

Cost savings and leading edge services in the R&E networking are brought about by the creative use of advanced technologies. From a cost-savings point of view, four main innovations were identified and have been successfully demonstrated:

1. Fibre acquisition and lighting instead of buying telecommunication services (achieved by some NRENs in 2000, achieved by GÉANT in 2004).
2. Single fibre bidirectional transmission is often sufficient, leading to savings of up to 25% of annual network expenditure compared to a fibre-pair transmission. This estimation takes into account small differences in equipment costs; savings on single fibre renting itself are usually 40% compared to renting of fibre pairs. OpenDWDM can offer ROADMs for single fibre lines.
3. Independency on transmission equipment technology development roadmap of a single vendor (buying Lighting as a Service – LaaS). Buying lighting as a service was referenced in CEF network workshop many years ago [26] by CESNET; LaaS is only a new term in popular style for an old practice.
4. Open DWDM transmission systems based on leading-edge photonic components can be used on most lines (saving about 30% of equipment costs) if the transmission system is designed by the user (i.e. Customer) before the procurements of LaaS.

1.5 Suppliers for Photonic Service Implementation

The request of Photonic service availability changes the relationship between the R&E Community and the transmission system vendors. The main goal of transmission system vendors is 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 (called “Alien Waves” in the rather parochial view of individual vendors). The situation will probably not change significantly in the future because service to ISPs will continue to be the main source of each vendor’s revenue. The market segment of advanced and specialized transmission systems for the R&E Community is significant, but may not be sufficiently lucrative for established transmission systems vendors.

The required end-to-end Photonic Services are multi-domain and multi-vendor in nature, so interoperability on a low layer is required. This means that for each end-to-end Photonic service between user premises, we need one common project and the participation of multiple vendors in the implementation. This is a difficult request for vendors relying on the design of the transmission system mostly from their own simulation tools which are unable to deal with “alien devices” sharing the same fibre or connected in the edge. There is probably a new open market segment and an opportunity for newcomers. Detailed discussions with five representatives of well-known transmission equipment vendors took place during the preparation of the CEF Networks workshop in

2012, and directly in our workshop in Prague [34], so we expect to see future developments. More information is provided in Section 4.1.

In CESNET, the situation was solved by the development of the CzechLight family of devices and by non-exclusive licensing contracts with three manufacturers. PS-enabled transmission system projects have been designed and implemented by CESNET after procuring of LaaS by one of six lighting service providers. CESNET also offers remote setup and monitoring of CzechLight devices.

In RENATER, a request for frequency transfer was solved by bypassing the line amplifier nodes by special OADMs and bidirectional EDFA amplifiers. These devices are produced by the IDIL Company, a participant in the REFIMEVE+ project.

1.6 Early Adopters of Photonic Services

Photonic Services based on an Open photonic DWDM system were available internally at CESNET a few years ago [56]. These were used for field testing new transmission devices. All-optical lambdas were also available at country-wide distances in a Cisco DWDM backbone. Cross-border connections in Brno and Ostrava to CBFs linking Bratislava, Vienna and Bialsko – Biała are lighted by an Open photonic DWDM system which provides international, all-optical lambda connections. In the beginning of 2010, CESNET and ACOnet agreed on a Photonic Service, as noted in the Press Release “A new method of accurate time signal transfer demonstrates the capabilities of all-optical networks”, [35]. This was the start of Photonic Services offered now in CESNET to the Research and Education Community, [36]. The Photonic service Praha – Brno – Vienna has been operated in parallel with the 100 Gb/s data transfer between Praha – Brno in one fibre pair since the 8 February 2013 [37]. This is probably the first deployment of Photonic service in a 100 Gb/s production backbone world-wide [38].

In the spring of 2010 and 2011, the ultra-stable frequency transfer tests were carried out by RENATER for the REFIMEVE+ (Metrological Fibre Network with European Vocation: MEFINEV+ in English) project, with no noticeable influence on live data traffic [39].

Photonic Services are now requested in a European-wide scale by metrology in the new EU project NEAT-FT with the participation of CESNET. More information can be found in the presentation of the NEAT-FT leader, H. Schnatz in Prague [40].

1.7 Expected Adopters of Photonic Services

Various scientific, engineering and technical fields are expected to benefit from the Photonic Services. These include:

- Time and frequency metrology.
- Fundamental physics on earth and in space.
- Precision spectroscopy.

- Geophysics (sensors sensitive to earth's rotation, seismic and tidal phenomena).
- Surveying and oil/mineral exploration.
- Essential timing backup for vital systems (e.g. mobile telecom network, power grids) in the case of GPS outages.
- Next-generation network synchronization.

From an engineering point of view, Photonic Services are expected to activate new requirements of users, for example:

- Network Aided Design.
- Network Aided Manufacturing.
- Network control of Instruments and processes.
- Demanding real-time applications.

In a broader sense, the development and deployment of Photonic Services will extend the R&E networks' ability to offer the full potential of a global system of interconnected computer networks to users. For example:

- Network applications running in parallel to the Internet.
- Development of experimental networks and services.
- Environmental research work.
- Using resources (especially fibre footprint) more efficiently.

Photonic Services consume much less power than the equivalent services based on multiple OEO conversions and electrical switching. This difference will be even greater once data rates increase to the next level.

1.7.1 Photonic Services in Real-time Network Applications

Some applications are expected following on from real-time network applications. Contemporary network services are usually non-real-time services, i.e. no timeliness constraints are defined. Photonic Services are an exception, so these can be incorporated in a hard real-time service (where missing a deadline constitutes a total system failure).

Real-time network services are needed for the interaction with external processes running outside of the network, when the timing of interaction limits quality or even the acceptability of network application. For example, values from sensors must be collected during the availability and deadlines for sending data to actuators. In other words, a Real-time network service should respond to an event within a predetermined time (i.e. there are "real-time constraints" - operational deadlines from event to system response). The timeliness constraints or deadlines are generally a reflection of the physical process being monitored or controlled. Networks should provide all real-time services satisfying their time constraints even in the worst case (maximal requirements of all monitored or controlled external processes). A real-time deadline must be met regardless of the system load. More details are given in: 'Research Networking for new applications' [41].

Photonic Services will improve some remote network applications, for example:

- Real systems control in industry and transport, vehicle control.
- Signal processing (signal from radio locator, sonar, etc.).
- Remote instrument control, telescope control.
- Ultra HD videoconferencing and multicast with guaranteed performance.

2 Photonic Services Provisioning in RENs

2.1 Photonic Services as a Transmission Services Innovation

As described in Section 1, Photonic Services allow new applications to be carried over optical networks, although they may have quite demanding requirements on network resources. This brings both innovations and challenges into optical networking. Innovation allows trials of new network applications, as described in Section 2.3. On the other hand, there are some challenges connected with new applications, although many NRENs are well positioned to overcome most of them. NRENs provide connectivity for the majority of Photonic Service users: they also adapt the latest network architecture and still have free bandwidth to accommodate PS. Specific challenges are discussed in points below.

- Application requirements on network architecture – generally a more complex application has higher requirements on network parameters and resources. End users of complex applications need a state-of-the-art network infrastructure that satisfies their application needs.
- Network cost effectiveness – it seems feasible for the End user to use a part of the NRENs infrastructure that is not generally fully utilized and to find a way to share it with standard internet traffic. One way is to deploy two transmission systems on the NREN's infrastructure. Such an example is considered in a feasibility study discussed in section 3.1.2, in which transmission systems are separated into C and L bands. The end user may also use the PS that takes advantage of an NREN's already deployed network equipment, given that the end user's application does not influence other traffic.
- PS interoperability with standard traffic – because PS is just a network tool for end-to-end application, the interoperability depends mainly on a complex application. Every application should be tested via trial experiments to verify its influence on other network traffic. Such testing was also done prior to launching the time transfer experiment that is described in section 2.3.

2.2 Multi-vendor Environment of European NRENs

The GN3 project and GÉANT community is partially funded by participating European NRENs that manage and operate their national networks directly connected to the GÉANT pan-European network. The actual size and complexity of each network reflects the needs and budgets of those particular NRENs. The fact that each NREN builds its network independently and with different considerations is reflected in the diversity of the networks transmission systems throughout Europe. Figure 2.1 shows the multi-vendor environment of European NREN backbone networks from information publicly available in presentations from NRENs. It is easy to see that multinational end-to-end (E2E) services may have to pass through several different transmission systems (network domains) to reach its destination. A useful implementation of photonic E2E services in this multi-vendor and multi-domain scenario is the alien wavelength (AW) concept that allows a kind of bypassing of multiple network domains to reach its destination. The AW concept is already used by a few European NRENs, for example in CESNET, SURFnet and NORDUnet [42].

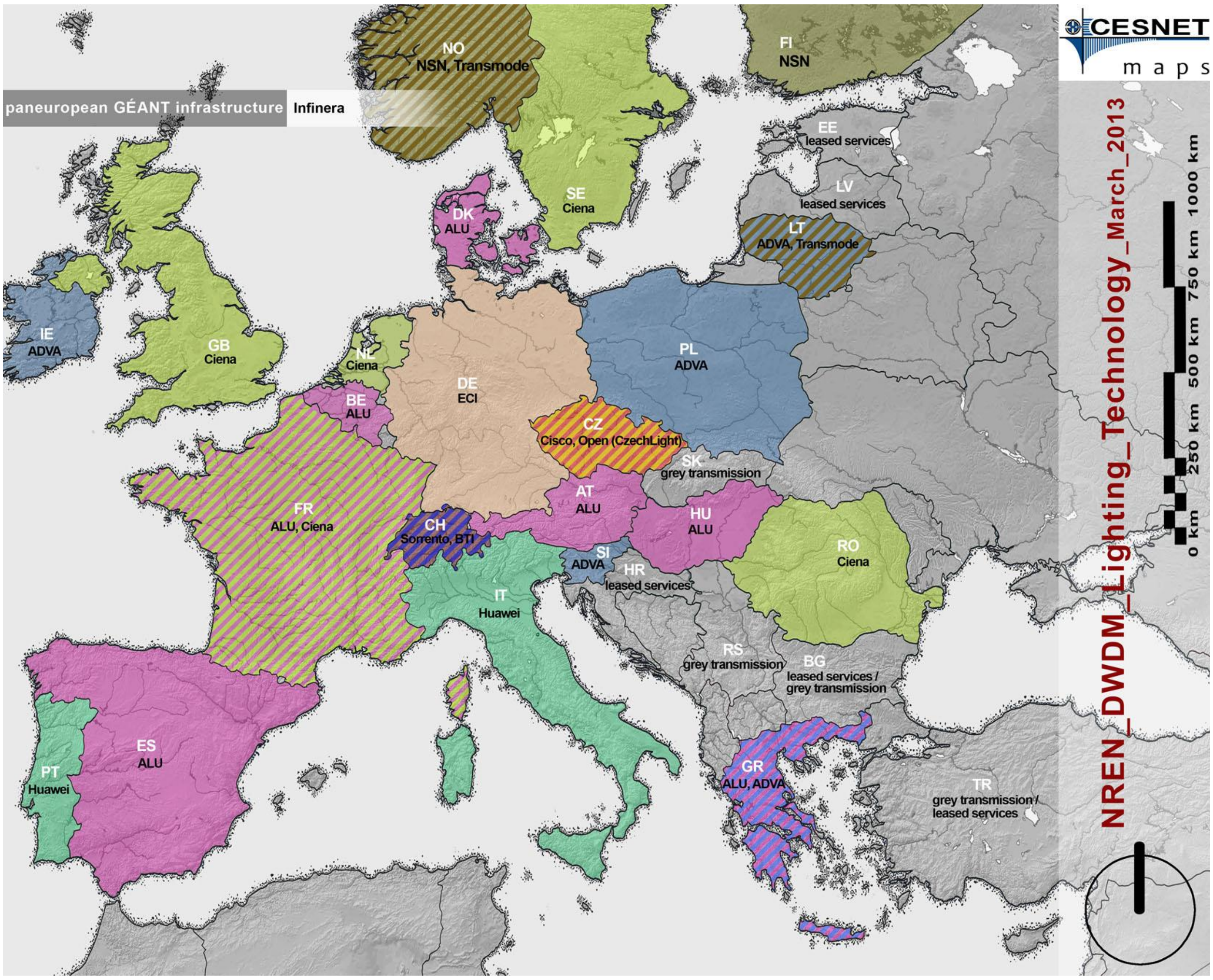

Figure 2.1: Optical Transmission Systems of European NRENs

2.3 Photonic Service IPE-BEV

This section describes the time transfer between the Czech Laboratory of the National Time and Frequency Standard of the Institute of Photonics and Electronics (IPE) in Prague, and the Austrian national time and frequency laboratory in the Federal Office for Metrology and Surveying (BEV) in Vienna.

Comparison of the time scales generated by the national time and frequency laboratories is an important task for time metrology. Very accurate methods based on two-way satellite links are available; however, such solutions are very expensive. Alternative methods based on GPS receivers are more common, but provide a much lower accuracy.

Dedicated optical fibres have been used to link atomic frequency sources between nearby laboratories - such links are typically a few tens of kilometres - and thus create a local point-to-point network. The increasing number and coverage of all-optical networks used mainly in telecommunications opens the possibility for using these networks for a time and frequency transfer at a distance of several hundred kilometres.

2.3.1 IPE-BEV Optical Path

In 2011, a bidirectional optical path between the IPE in Prague and the BEV in Vienna was set up by combining dark fibre and a dedicated DWDM channel in the CESNET production network. Since February 2013, part of the network core, the optical DWDM lines Hradec Králové – Prague – Brno – Olomouc runs at 100Gb/s. The optical path IPE – BEV uses part of the Prague – Brno core, see Figure 2.2.

This path is heterogeneous (i.e. multi-vendor) from the technological viewpoint, since part of it is equipped by a Cisco ONS 15454 MSTP and another part by a CzechLight open transmission system. Figure 2.2 shows the path deployed, with highlighted monitoring points. An analysis of data from the measuring points provides information on the availability of optical connections. See section 3.2 'Vendor independent monitoring' for information about OAMP and all-optical path supervision.

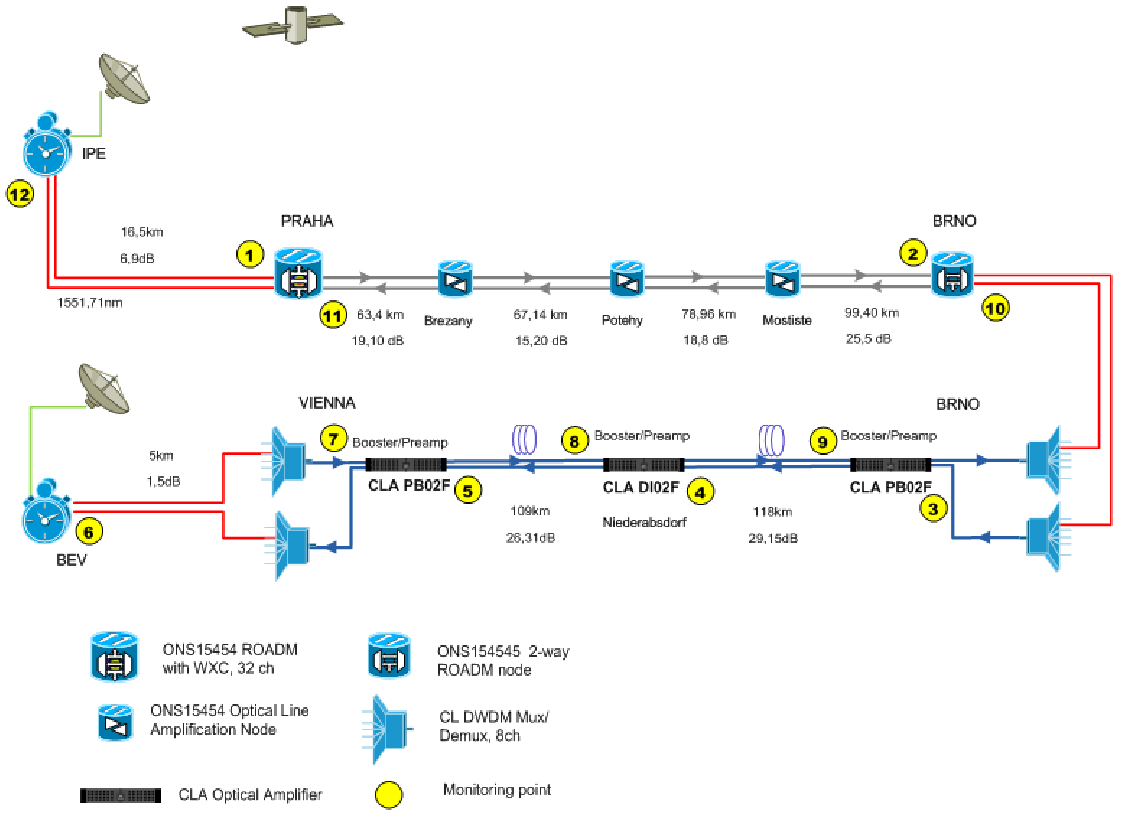

Figure 2.2: IPE – BEV Deployment with Monitoring Points

Two end user devices are connected by a bidirectional all-optical link without OEO conversion. Each of these devices has a 1 Pulse per Second (PPS) signal from a local clock at its input and produces an optical pulse sequence representing the 1 PPS signal. The time interval counter measures the interval between the local and remote 1 PPS signals.

Details for logical segments of Photonic Service are given in Table 1; total length is 557km.

Segment	Country	Length	Attenuation	Technology
IPE CESNET PoP Prague	CZ	16km	8.9 dB	Dedicated dark fibre pair
CESNET PoP Prague Brno University	CZ	309km	78.6 dB	Cisco ONS (DWDM channel)
Brno University Vienna University	CZ – AT	227km	55.5 dB	Open DWDM CzechLight (DWDM channel)
Vienna University BEV	AT	5km	1.5 dB	Dedicated dark fibre pair

Table 1: Details for Logical Segments of Photonic Service

The Photonic Service of accurate time transfer between IPE and BEV has been operating continuously since August 2011 without any significant problems. A network monitoring history of the largest sections, Prague –

Brno and Brno – ACOnet (Vienna) is available for up to six months in arrears at http://www.ces.net/netreport/. The map of the line is shown in Figure 2.3.

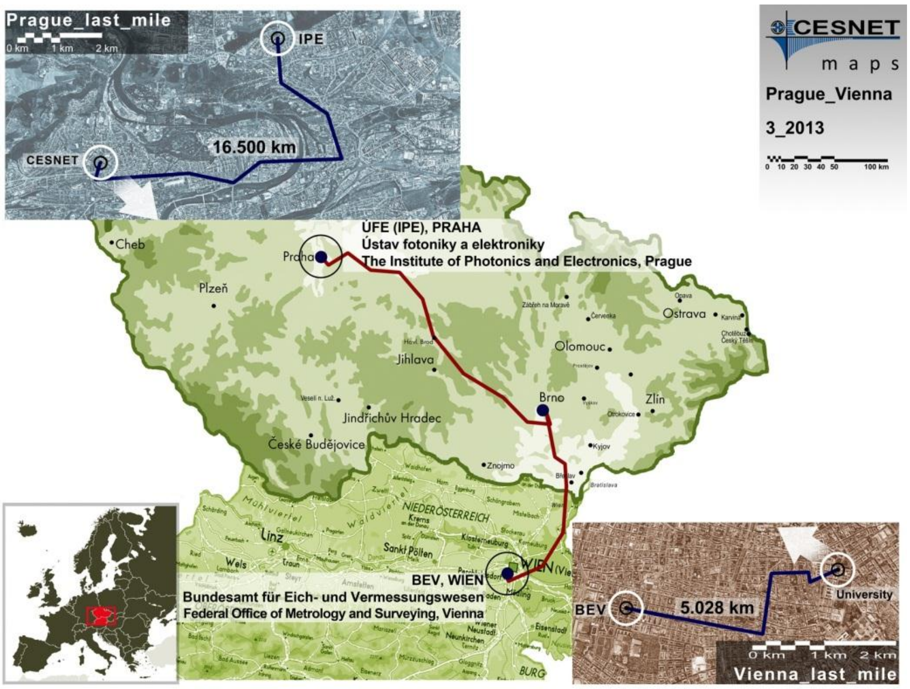

Figure 2.3: The Physical Line IPE (CZ) - BEV (AT)

This method of accurate time signal transfer demonstrates the capabilities of an all-optical network. More information about both advanced applications of time transfer and network solutions by Photonic Service can be found in [43] or [44]. Both of the time and frequency laboratories involved are also equipped with metrological GPS receivers that allow the evaluation of the offset of local time to the Coordinated Universal Time (UTC) time with the accuracy of a few nanoseconds, using the GPS Common View method. Compared to the GPS Common View, CESNET's PS of accurate time transfer improves both short and long time stability. The end user devices have been specially designed for this application by CESNET and are able to transfer 1 PPS from a local atomic clock to the remote site. The setup is symmetrical: time is also transferred in the opposite direction and therefore transport delay variation, caused mainly by temperature changes, is cancelled out.

Although the optical path is bi-directional, it is implemented as a pair of unidirectional fibre segments and therefore it is not absolutely symmetrical. This advanced application successfully runs over two optical transmission systems – an open DWDM CzechLight system and a Cisco DWDM. Therefore, it is a fully operational Photonic Service over a multi-vendor network. The path from Prague through Brno to Vienna is all-optical, as shown in Figure 2.3. This PS is well suited for other advanced network applications.

2.4 Photonic Service to User Premises in the Czech Republic

Many R&E institutions in the Czech Republic upgrade their connection for providing advanced E2E services (Photonic Services, lambdas, etc.). The upgrade is mostly realized by lighting the last mile fibres by CzechLight OpenDWDM equipment and by the addition of physically diverse optical fibre lines for very high availability. This connection enables the full participation of R&D premises in national and international research collaborations using advanced services.

2.4.1 Some institutions which have recently upgraded, prepared or are being prepared for advanced Photonic Services

- Institute of Photonics and Electronic AS CR
- Czech Metrology Institute in Prague
- Astronomical Institute AS CR Ondřejov, The Department of Geodesy and Geodynamics of the Research Institute of Geodesy, Cartography and Topography and the Geodetic Observatory Pecný
- National Library of the Czech Republic
- Municipal Library of Prague
- Extreme Light Infrastructure (ELI) and High average power pulsed lasers (HiLASE) in Dolní Břežany
- Biomedicine Centre of the Academy of Sciences and Charles University in Vestec (BIOCEV)
- IT4i, National Centre of Excellent Research under IT sphere in Ostrava
- International Clinical Research Centre (FNUSA-ICRC) in Brno
- Nuclear Physics Institute AS CR + Sustainable energy (SUSEN) centre in Řež
- Academy of Sciences, Library premises, Jenštejn
- Science and Technology Park (STP) in Roztoky. Josef Božek Research Centre of Combustion Engine and Automotive Engineering of the Faculty of Mechanical Engineering of the Czech Technical University in Prague
- Centre of Excellence, Institute of Theoretical and Applied Mechanics AS CR Telč

Some Institutions prepared for advanced Photonic Services in 2013 and 2014 are shown in Figure 2.4.

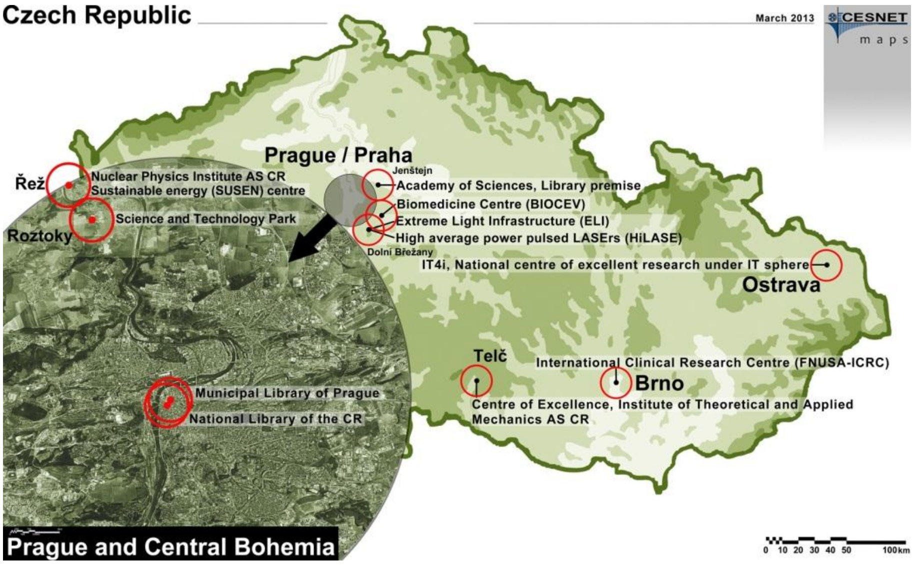

Figure 2.4: E2E Photonic Services Potential Users

2.4.2 Time and Frequency Transfer Infrastructure

Based on ACOnet and CESNET's previous experiences with time transfer between Czech and Austrian national time and frequency laboratories (from August 2011), CESNET decided to design and build the national infrastructure for time and frequency transfers.

Time and frequency transfer users in the Czech Republic are shown in Figure 2.5.

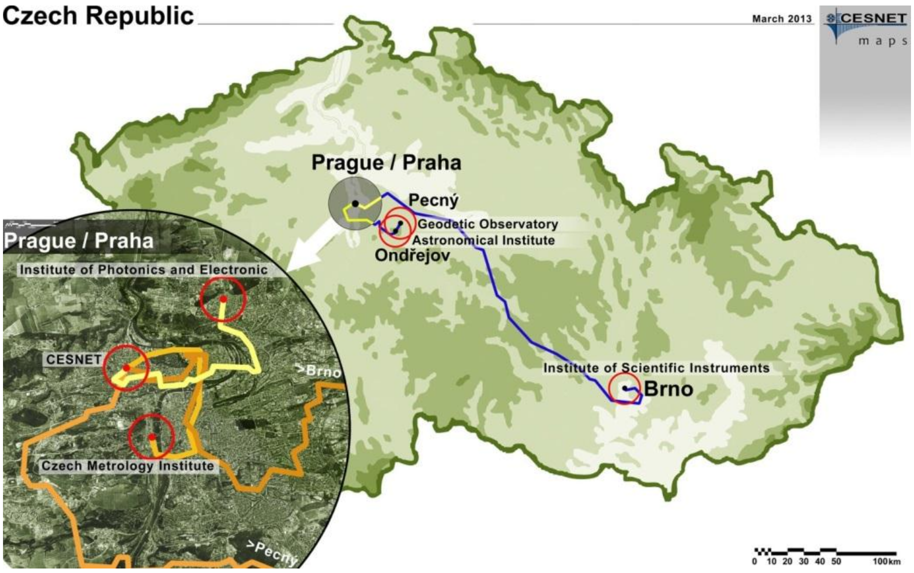

Figure 2.5: Time and frequency transfer users

2.4.3 CESNET (Prague) – Geodetic Observatory (Pecný)

Significant users of the time and frequency transfer infrastructure are CESNET and the Geodetic Observatory in Pecný, approximately 30km from Prague. The following text describes the technical solution of this line, which terminates at the Astronomical Institute in Ondřejov.

The main part of the line is represented by single fibre span from CESNET Prague, Zikova to Pecný, 78km, it represents about 21.2 dB of attenuation. This first span is operated by the bidirectional open transmission system CzechLight. Both ends look symmetrically: DWDM signals are multiplexed, amplified by booster EDFA (part of CLA PB01F) and through a band splitter launched into line. The incoming DWDM signals are divided from the line by this band splitter, amplified in an EDFA preamplifier (part of CLA PB01F) and finally demultiplexed. The second fibre span is very short (attenuation of only 1.2 dB) and thus is deployed by passive mux/demux only, without amplification. As these building blocks are naturally capable of bidirectional operation, there is no need to use band splitters.

Deployment of the line is shown in Figure 2.6.

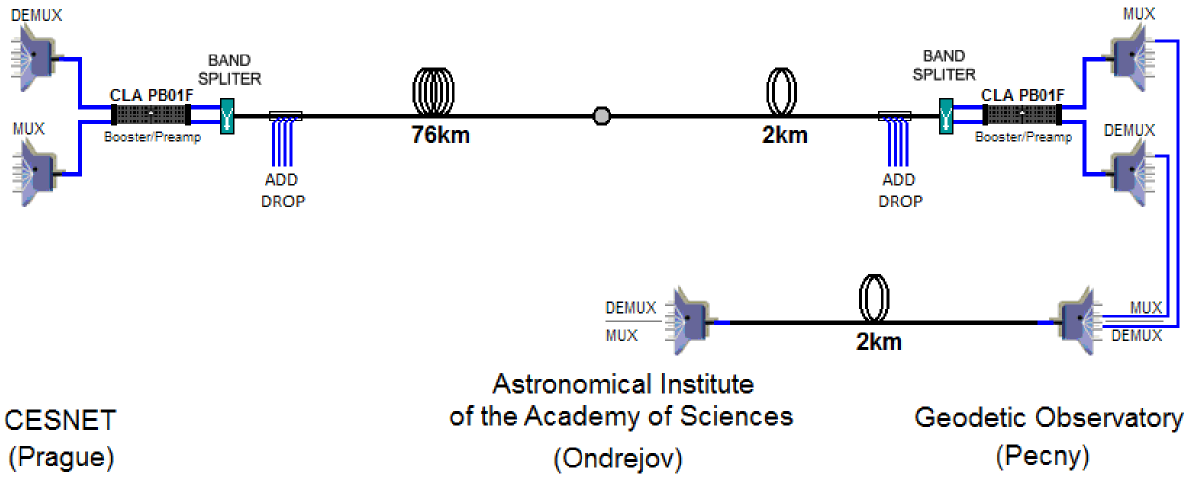

Figure 2.6: Line CESNET (Prague) – Geodetic Observatory (Pecný) – Astronomical Institute (Ondřejov) prepared for bidirectional PSs

The last mentioned bi-directionality is an important precondition for special transmission types, e.g. some of the Photonic Services. A propagation delay of light within the optical fibres is temperature dependent, as both the fibre length and refractive index are temperature dependent. Also, optical fibres exhibit weak birefringence where the refractive index is dependent on light polarization which can be changed, e.g. by mechanical stress.

For the transmission of basic quantities, such as frequency and time, fibre links can improve on traditional satellite links in terms of stability. However, to achieve such a stability, it is necessary to compensate almost all disturbances (propagation delay change), and this is not possible if transmission is through a different fibre in each direction. This set up works perfectly for data transmission, but in order to compensate disturbances, it is necessary to transmit these quantities bi-directionally within a single fibre.

The line Zikova – Pecný is prepared for PS transmission of basic quantities. It is deployed in the first span by an ADD/DROP filter that allows for the addition and removal of bidirectional Photonic Services. The second span is naturally bidirectional.

2.5 Photonic service REFIMEVE+

2.5.1 Project overview

Since 2010, the LNE-SYRTE (Laboratoire national de métrologie et d'essais – Système de Références Temps-Espace) and the LPL (Laboratoire de Physique des Lasers) laboratories have been working with the French NREN RENATER, to realize ultra-stable frequency transfers on the RENATER-5 live network by using a dedicated ITU-T DWDM wavelength. In 2012, they applied successfully for funds to launch the REFIMEVE+ project (in English, Metrological Fibre Network with European Vocation). The purpose of this project is to build a national infrastructure on RENATER fibre, capable of disseminating ultra-stable frequency signals to scientific laboratories that need to work with high-accuracy instruments. European interconnections by cross-border fibres will also be studied within this project.

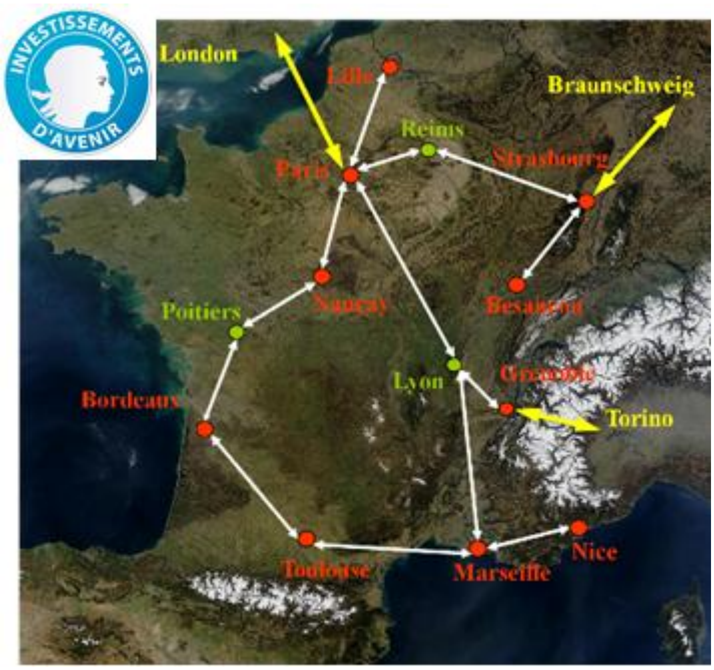

Figure 2.7: REFIMEVE+ project infrastructure

Within this project which continues until 2019, the following scientific institutions should benefit from the Photonic Service with end-to-end connections to the Paris Observatory:

- Laboratoire Kastler Brossel – LKB
- Laboratoire Charles Fabry de l'Institut d'Optique – LCFIO

- Institut des Sciences Moléculaires d'Orsay – ISMO
- Astroparticule et Cosmologie - APC
- Laboratoire de Physique Moléculaire pour l'Atmosphère et l'Astrophysique - LPMAA
- Laboratoire Aimé Cotton – LAC
- Physique des Interactions Ioniques et Moléculaires – PIIM
- Laboratoire Collisions Agrégats Réactivité – LCAR
- Univers, Transport, Interfaces, Nanostructures, Atmosphère et environnement, Molécules - UTINAM
- Franche Comté Electronique Mécanique Thermique et Optique - Sciences et Technologies - FEMTO-ST
- Station de Radioastronomie de Nancay - USN
- Laboratoire de Physique des Lasers, Atomes et Molécules – PhLAM
- Laboratoire Photonique, Numérique et Nanosciences - LP2N, Géosciences Azur - GEOAZUR
- Astrophysique Relativiste, Théories, Expériences, Metrologie, Instrumentation, Signaux - ARTEMIS
- Laboratoire interdisciplinaire de Physique – LIPhy
- Centre Spatial de Toulouse - CNES-CST

2.5.2 Transfer method

Unlike legacy DWDM systems where modulated data is carried, data carried in REFIMEVE+ is a particular frequency, that is, an ultra-stable wavelength within the light spectrum. This frequency is sent by a thin, constant and low-powered laser beam emitted from the Paris Observatory to the laboratories. To ensure the spectral stability of the frequency at destination, a control loop is built by sending the frequency back to the Observatory. Hence, the main feature of this PS is its bidirectionality, a fact that makes it non-compliant with legacy DWDM systems that require isolators most of the time.

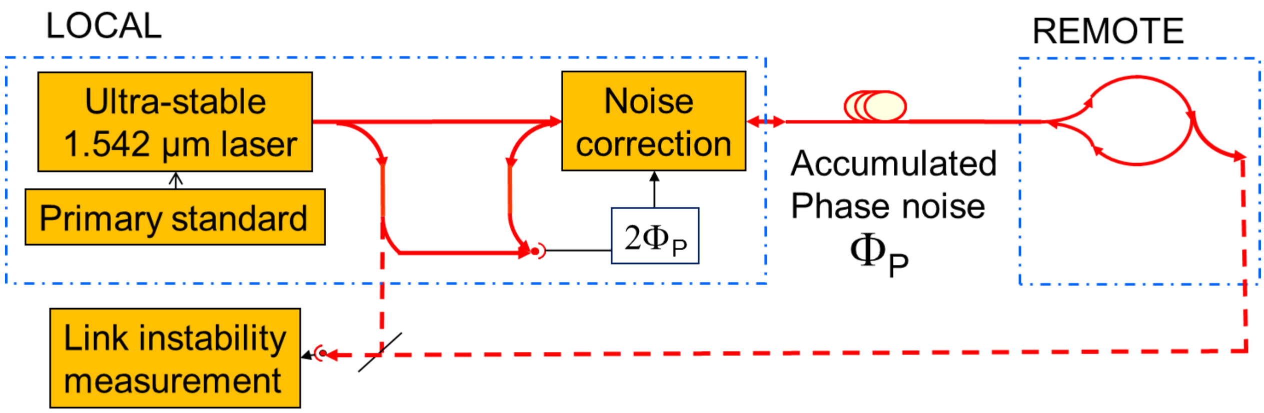

Figure 2.8: Method of ultra-stable frequency transfer

When such a PS is deployed on an existing NREN backbone built on dark fiber, the ultra-stable signal is transmitted simultaneously with IP data by using different DWDM wavelengths and a solution to bypass the NREN DWDM equipment must be found.

The technical solution chosen in RENATER was to dedicate a single DWDM channel to REFIMEVE+ (Ch. #44 : 1542.14 nm) on the whole backbone and to insert dedicated Optical Add and Drop Multiplexers (OADM) in each fibre segment between RENATER optical devices already in production, as depicted in Figure 2.9:

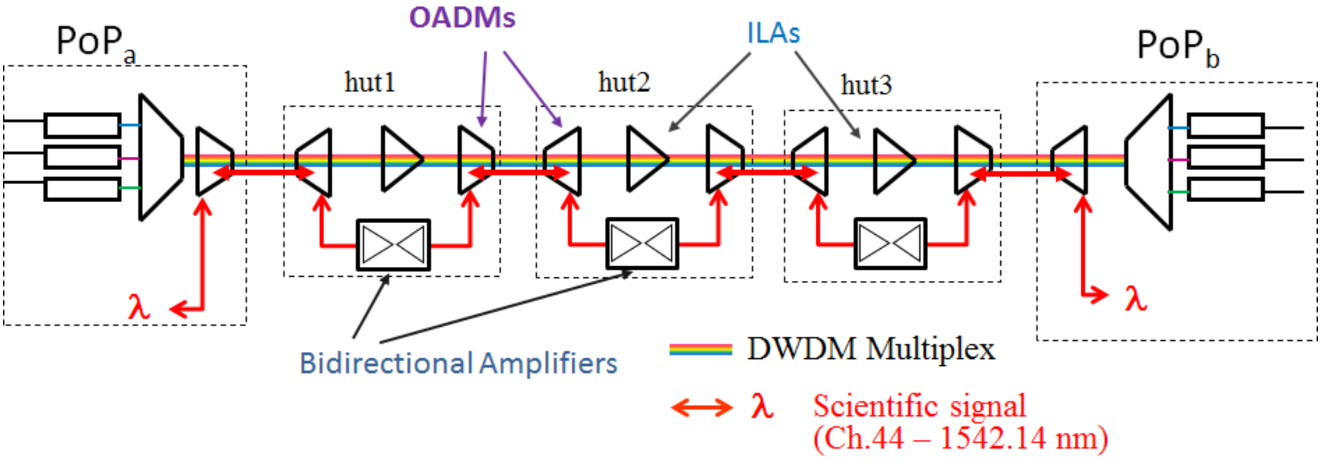

Figure 2.9: Principle of bypassing NREN equipment in REFIMEVE+ project

This equipment insertion requires slight network changes as channel equalization, link architecture and wavelength capacity checking.

2.5.3 Achieved deployments

A first transmission test was conducted in 2009 on 90km of urban dark fibre in the Paris area to validate the stabilized laser system used for photonic service.

The path then was extended in 2010 to 193km between the Paris Observatory and Nogent l'Artaud [39], to validate the process of bypassing RENATER optical devices in the national backbone. Repeater prototypes were also evaluated.

In 2011, a frequency signal was transmitted on 540km from Paris to Reims using 468km of RENATER fibre and bypassing two in-line amplification sites. In the Reims point of presence, the ultra-stable signal coming from one of the fibres was looped back to the other fibre to the LPL. The circuit is shown in Figure 2.10. In this way, both link end points were located in LPL, making it easier to evaluate the transmission and stability performance of the optical link. Stability and accuracy of the transmitted clock signal was 10^{-19} throughout one day. This result is beyond requirements and demonstrates the feasibility of the architecture deployed to achieve a long-haul circuit. Moreover, no perturbation between RENATER traffic and the REFIMEVE+ frequency was noticed on the DWDM backbone.

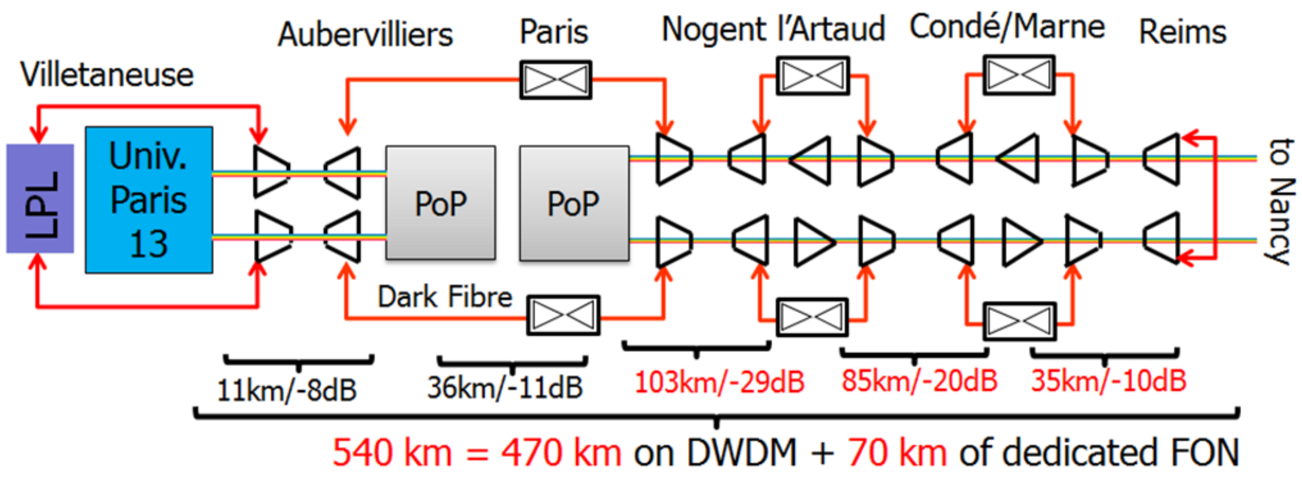

Figure 2.10: Circuit deployed in RENATER in 2011

A new circuit extension is already deployed to Nancy (1100km) and bidirectional amplifiers will be installed on the Paris – Nancy link in 2013. The next step is to complete the deployment of the REFIMEVE+ national infrastructure to ensure the capacity of the project partners to develop a scalable solution:

- In Spring 2013, the Kastler Brossel Laboratory (LKB) in Paris should be the first one to receive and to exploit the ultra-stable frequency from the Paris Observatory. This first experience will be significant in defining the user interconnection process to REFIMEVE+.
- A middle term goal (end of 2013) is to reach the German border to connect REFIMEVE+ to the PTB Photonic Service deployed between Braunschweig – Kehl, in order to compare French and German atomic clocks. It is also planned to extend the REFIMEVE+ PS to the FEMTO-ST Laboratory in Besançon this same year.
- The major part of REFIMEVE+ infrastructure should be completed in 2014-2015.

2.6 Photonic Services provisioning in dark fibre test-beds

A dark fibre (DF) testbed means an experimental network consisting of fibres designated for testing. On such a network it is possible to run potentially disruptive experiments involving the lower layers of a networking model down to the physical infrastructure consisting of fibres themself. This gives researchers and network designers open access to the basic building blocks of networks, and allows for the development of new types of services.

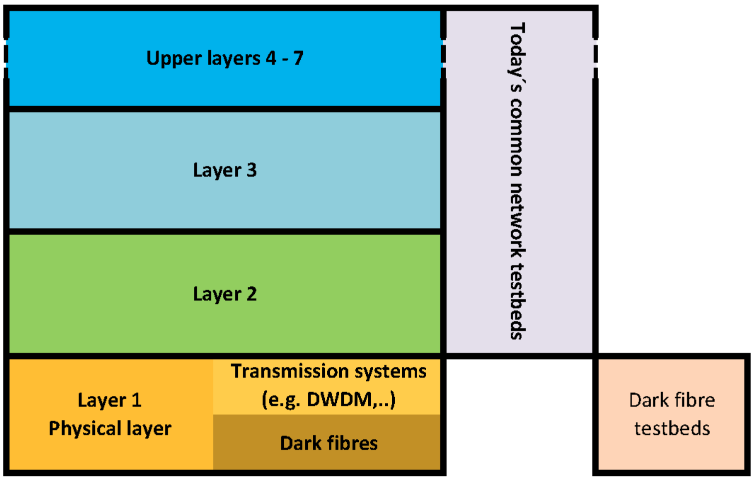

Figure 2.11: Dark Fibre testbed inclusion in network layers in relation to other types of testbeds

Direct access to fibres allows for the building of all optical networks in which Photonic Services became possible. There are no limitations like decisions, requests, technology development road maps of equipment vendors or software providers, operation and maintenances rules, etc. Open DF testbeds are also called multipurpose and multi-vendor experimental facilities.

Many European NRENs are big promoters of the Customer Empowered Fibre (CEF) Networks concept, based on network operators renting dark fibres and installing their own technology in them. Open access to dark fibres and lighting equipment enables services which are not available in legacy production networks (e.g. all-optical lambdas). Moreover, traditional production data services may run in parallel to Photonic Services in a single shared fibre or a fibre pair (see PS IPE-BEV in section 2.3.1). Thus PS can be a reliable way of supporting innovative applications and allowing the creation of facilities where traditional applications and trials of new applications can coexist in a common fibre footprint. By operating such facilities – so-called Integrated Facilities - NRENs can provide new services that would otherwise need an isolated dark fibre testbed, as the complement to traditional data services using common fibre infrastructure. As a consequence, various scientific fields (e.g. metrology, astronomy, physics) can take advantage of the full potential of optical fibre networks.

The proposal to build an European Open DF testbed has been presented within GN3, with the potential to continue as part of GN3+. This planned testbed could use the dark fibres which became available after the current GÉANT network migration and interconnect existing DF experimental facilities in Europe (e.g. CESNET EF, Aurora in Janet). There are five DF lines which will become available after March 2013 and they are:

- London – Paris
- Frankfurt – Geneva
- Amsterdam – Frankfurt
- Amsterdam – Brussels
- Milan – Vienna

The London – Paris line and the Milan – Vienna line are described in section 3.1.

3 Photonic service design and operation

3.1 Feasibility studies of E2E Photonic Services between user premises

We have selected a few GÉANT routes and some leased fibres to undertake feasibility studies of E2E Photonic Services.

After GÉANT migration, there will be a few dark fibre routes which will become available for use as a dark fibre testbed: two of them were selected for feasibility studies of E2E Photonic Services. These were chosen because they can be used by the NEAT-FT project and we have already succeeded in collecting preliminary last-miles parameters.

The objective of the NEAT-FT project is to transfer accurate frequency over the optical fibre between endpoints without OEO conversion. The proposed solution reflects CESNET's experience on the field of accurate frequency and/or time transfer.

- The first fibre line is between the National Physical Laboratory (NPL) in London and the Laboratoire National de Métrologie et d'Essais - Système de Références Temps-Espace (LNE-SYRTE) in Paris, a distance of 792km, last miles included. Figure 3.1 shows the topographical fibre route between London and Paris. The fibres are mostly G.655+ with G.652 in the last miles.
- The second fibre line, between Bundesamt für Eich- und Vermessungswesen (BEV) in Vienna and The Istituto Nazionale di Ricerca Metrologica (INRIM) in Torino is 1367km long, last miles included. The fibres are mostly G.655+with G.652 in the last miles. Figure 3.2 shows the topographical path of the fibre.

Table 2 shows the parameters of the individual fibre routes.

Fibre line	Fibre Type	Length [km]	Loss [dB]	CD [ps/nm]
London (NPL) – Paris (LNE-SYRTE)	G.655+ and G.652	792	220	6361
Vienna (BEV) – Torino (INRIM)	G.655+ and G.652	1352	331	8930

Table 2: The parameters of optical routes (last miles included)

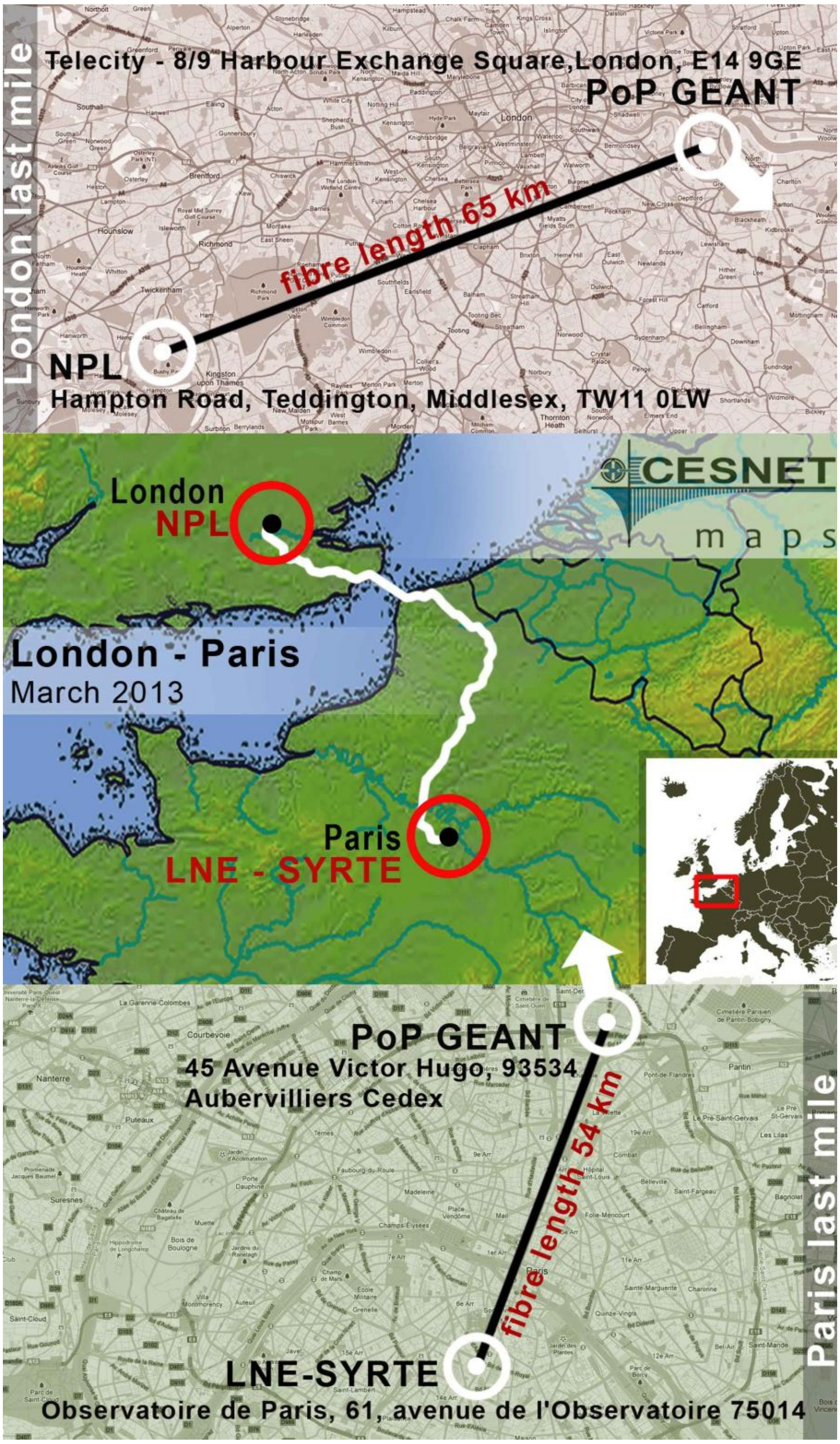

Figure 3.1: Topographical fibre route between London and Paris

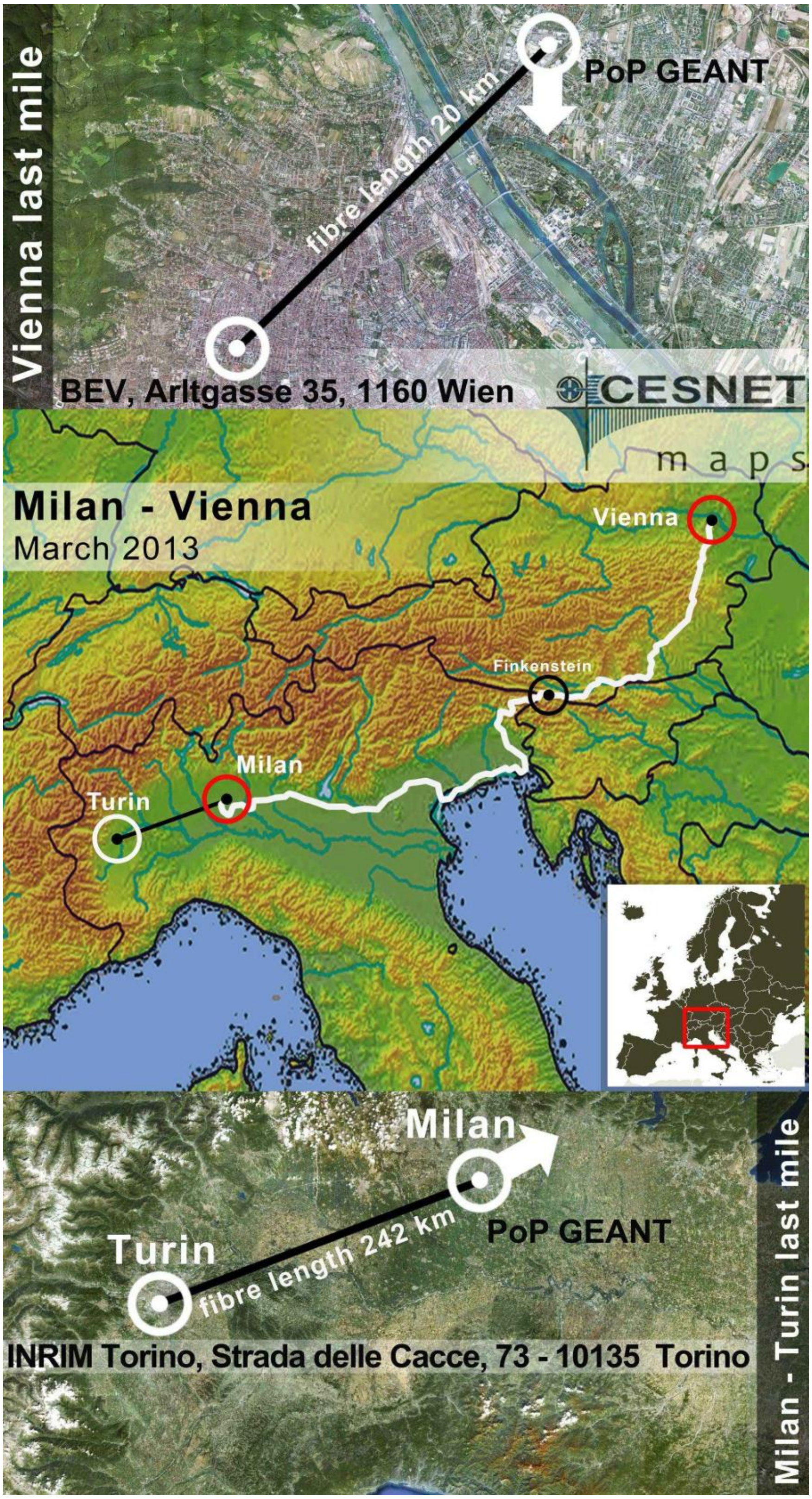

Figure 3.2: Topographical fibre route between Vienna and Torino

3.1.1 Lighting by OpenDWDM

The project covers lightning of two fibre pairs (London – Paris and Vienna – Torino) by Open DWDM technology. This technology aims to be vendor independent and is focused on the pure photonic layer only. The use of Open DWDM is not a requirement, however, since every device can be replaced using appropriate parameters.

OpenDWDM has been chosen because of its flexibility, economic advantages and its lack of hardware and software restrictions, making it ideal for supporting new and challenging applications like PS.

The calculation has been done for 40 DWDM channels with 100GHz channel spacing, without OEO conversion, along the whole fibre length. It covers the deployment of amplifiers and chromatic dispersion compensation elements in huts and variable multiplexers in the end points. The project contains in-band management for all active devices. In Figure 3.4 you can see the schema of DWDM line London – Paris. Chromatic dispersion is compensated by a Dispersion Compensation Fibre (DCF) in this case. This design is intended to allow for native transmission of 10Gb/s waves. These modules would not be necessary if the line was intended only for carrying signals up to 2.5Gbps or coherent signals. Omitting dispersion compensation (for DCF, not FBG) would benefit accurate frequency transfer and coherent signals.

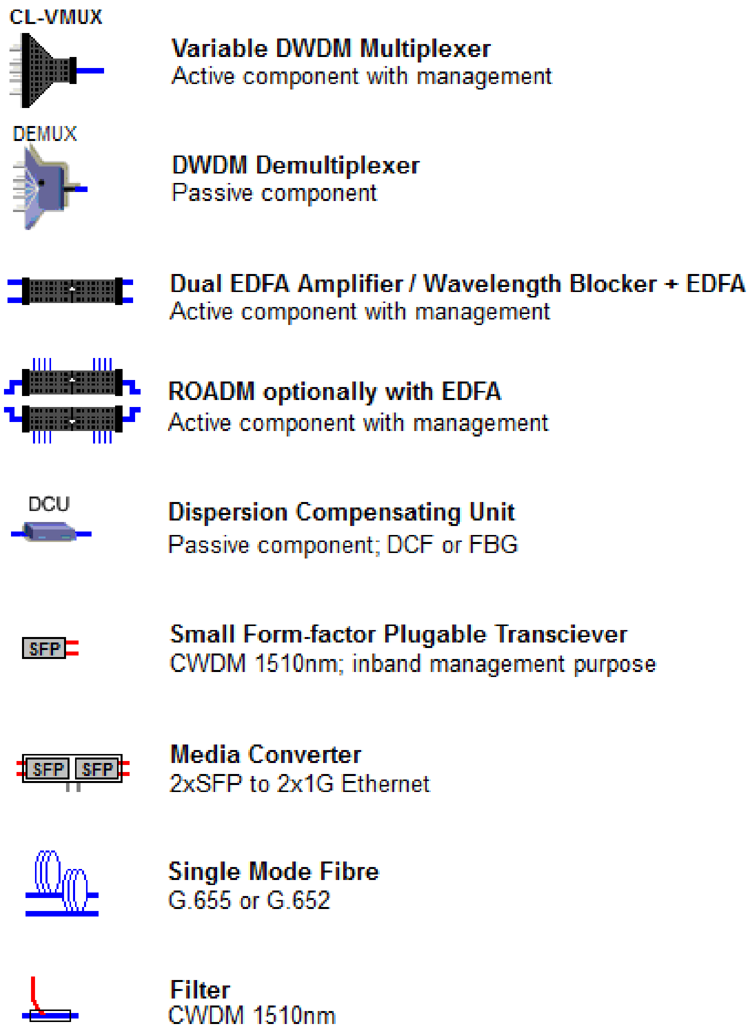

Figure 3.3: OpenDWDM base schematic components key

Figure 3.4 shows a lighting schema of the London – Paris line. Fibre spans represent the present distribution of fibre/huts.

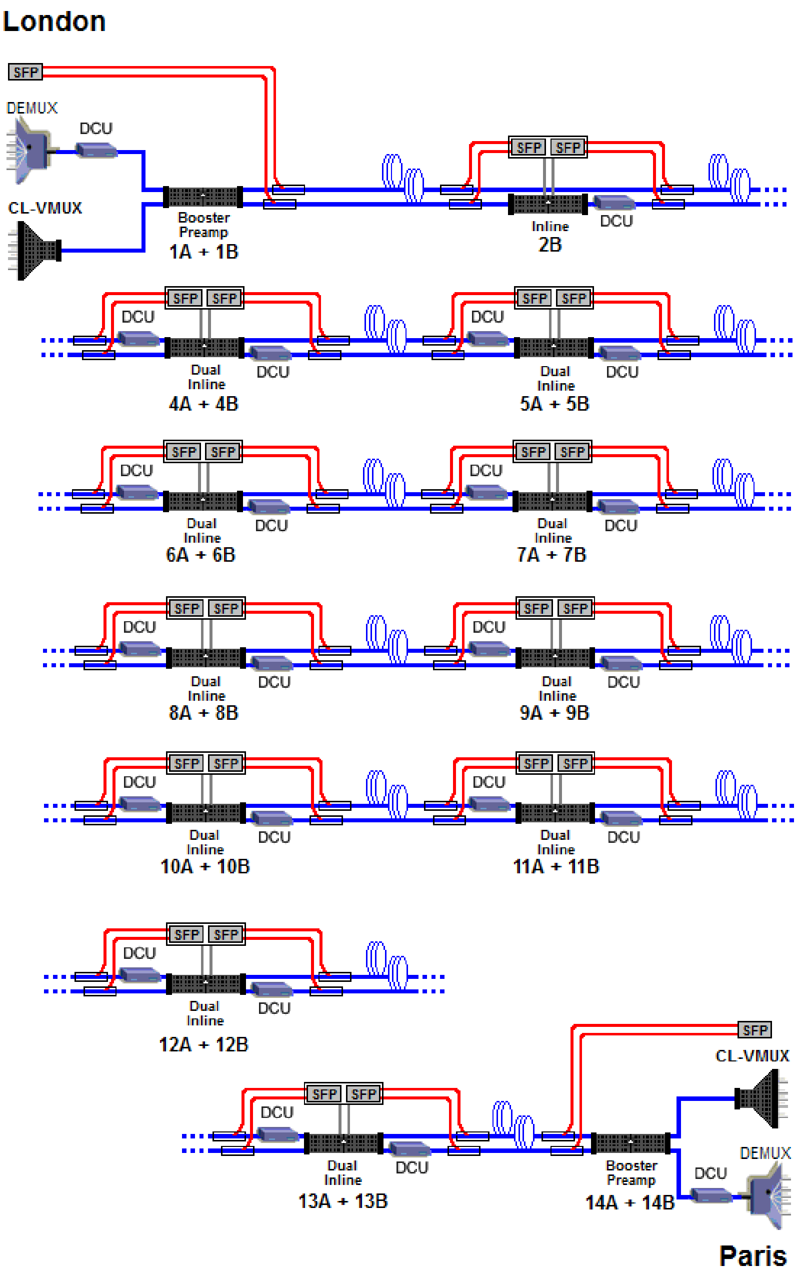

Figure 3.4: Schematic line between London and Paris

The second line between Vienna and Torino is almost twice as long as London – Paris and contains 24 in-line amplifiers, compared to 13. Because of the considerable length of this DWDM line, additional devices for the improvement of EDFA gain flatness must be used. The gain characteristic of an EDFA amplifier is not inherently absolutely flat and in long cascades of amplifiers these inequalities multiply, resulting in significant inequalities. Because of this, devices for channel power re-equalisation must be used. Wavelength blockers are suitable for that, as well as ROADMs, and both are used. For CD compensation, Fibre Bragg Gratings (FBG) are used. Figure 3.5 shows the schema of the line. For simplicity, in-band management components are not shown, but they are same as in the London – Paris line.

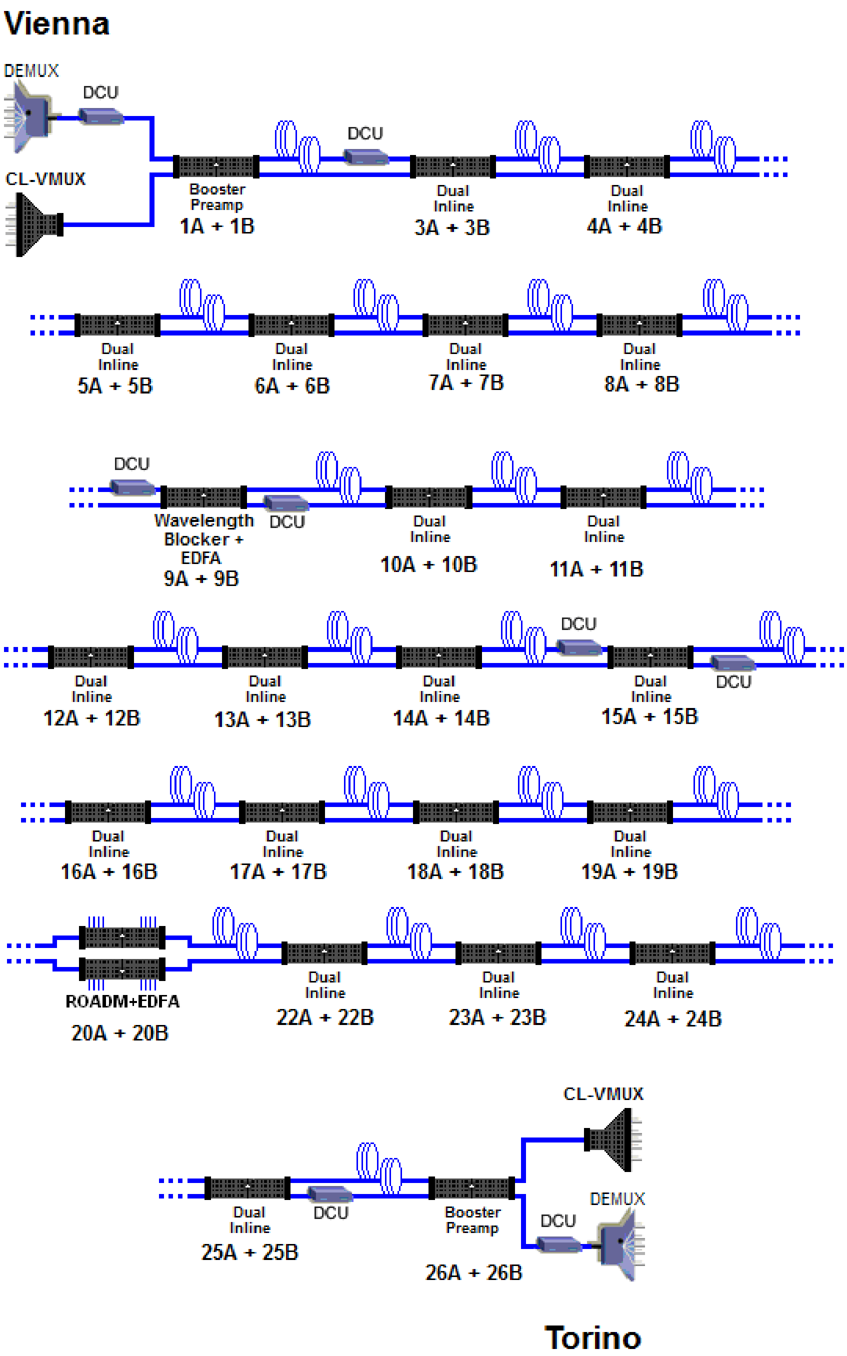

Figure 3.5: Schematic line between Vienna and Torino

3.1.2 Lighting of both C and L communication bands

In the days of the DWDM introduction the capacity of conventional transmission band (1530-1565nm) seemed inexhaustible. However, massive increase of traffic carried over fibre networks gradually filled all eighty channels available in the C band (with 50GHz grid). Further logical growth of bandwidth targets the L band

(1570-1610nm), where the attenuation coefficient is comparable with the C band - especially where well-known EDFA amplifiers can offer reasonable operational parameters.

This principle raises the possibility of leaving the L band uncompensated. The C band may then be used for ordinary 10G data transfer channels with the L band dedicated to PS, or vice versa.

Lighting of two fibres by the OpenDWDM technologies includes 40+40 DWDM channels with 100GHz channel spacing with no OEO conversion along the whole fibre length, in both the C and L bands. The lighting is very similar to the previous one, adding the necessary components for the L band. In terminals, dual VMUXes and DEMUXES, dedicated to the C and L bands respectively, will be deployed. In this case, amplifiers are dual for both bands; internally, amplifiers contain two branches with a band splitter and a coupler inside. The DCUs are also dedicated for each band and they are connected directly to the amplifiers. This lighting requires about 1.2 dB more of amplifier gain in each segment to cover the splitter losses. The in-band management remains the same as in the previous case. The lighting of the Vienna – Torino line also requires a dual ROADM (containing a branch dedicated to the C and L bands) at point number 20, with the dual power level equalizer at point number 9 - see Figure 3.5.

3.1.3 Experiments and services requiring full fibre spectrum

Dark fibres can be used for many different experiments, some of which may affect neighbouring optical channels. For example, experiments with new techniques of optical signal amplification can generate spurious events, potentially disrupting the surrounding optical transmission channels. There can be initial difficulties in providing a dark fibre end-to-end service because there is no way to troubleshoot it in operation without causing network outage: on the other hand, this approach provides a guaranteed and very low-latency signal that is a constant throughout its lifetime. Such experiments include:

- Low-latency networking. The transfer of ultra-stable accurate frequency or time over long distances remains an interesting research area [45].
- Using new modulation techniques with classic optical fibre (which is incompatible with DWDM grid spacing).
- Fibre sharing using spatial division multiplexing techniques in standard fibres. This technique can increase the data carrying capacity of optical fibres by orders of magnitude. The orthogonal modes of the multi-mode fibre can in principle be utilized to form a multi-input multi-output (MIMO) system [46].
- Dynamic optical switching or likely optical burst switching. The purpose of optical burst switching is to create logical units of optical waves, called bursts. These bursts can then be separately processed and switched, according to the wavelength in the part of the optical end-to-end path [47].

Optical signal processing has recently come to the forefront as a promising candidate for OEO substitution [48]. This kind of signal processing might use various nonlinear optical effects for the desired result. This all-optical approach, combining nonlinear effects and implementing them into photonic devices, allows a reduction in both the size of the devices and overall energy consumption. On the other hand, most of these nonlinear optical effects can have a negative impact on neighbouring optical channels, so for now, confining such experiments to dark fibre is recommended.

- One of the basic nonlinear effects in fibre optics is the self-phase modulation inducing a nonlinear phase shift, resulting in chirping and spectral broadening of the optical pulses.
- Another optical pulse shaping method is cross-phase modulation, which is suitable for light switching or pulse modulation. Cross phase modulation considers at least two optical signal pulses, which are able to interact in the nonlinear medium. Pulses belonging to different channels travel at different speeds and pass through each other at a rate that depends on their wavelength difference, just as a faster moving pulse belonging to one channel collides with and passes through a specific pulse in another channel.
- Four-wave mixing is also a well-known nonlinear intermodulation phenomenon, where the interaction between two wavelengths creates two more wavelengths.

CESNET proposes using dark fibre lines available after the GN3 migration as a dark fibre testbed by two methods. The Paris – London and Vienna – Milan routes should be lighted by all-optical DWDM transmission equipment managed by SA2 activity within the GN3plus project and shared among the user projects in parallel by the dedication of lambdas to projects or subtasks. The remaining dark fibre lines: Frankfurt – Geneva, Brussels – Amsterdam and Amsterdam – Frankfurt will be fully dedicated to user projects or subtasks for some period of time (for example six to 12 months) carrying out experiments that are incompatible with regular data transmission.

3.1.4 Automatic Light Power Balance

For optimal transmission of an optical signal, it is important to improve certain of its parameters, such as the signal-to-noise ratio or chromatic dispersion and also to produce a sufficient output power from the in-line amplifiers. Pump diodes in amplifiers suffer from the material aging, so the driving current of the pump diodes has to be increased over time. Optical pumps last longer by being driven by the minimal required current, so an automatic power balance is one method to achieve both these goals.

The solution presented is a general one: it can be deployed not only for backbone parts of network, but also for specific E2E PS applications.

We focused on an agent approach because agents are an efficient way to deal with distributed problems. An agent is a computer system situated in some environment that is capable of autonomous action in this environment in order to meet its design objectives. Autonomy means that agents are able to perform actions without the intervention of humans or other systems. Agent’s important features are the ability to adapt to changes in the environment and collaborate with other agents. Interacting agents join together in more complex groups called multi-agent systems (MAS). This concept provides several advantages, such as the ability to work in a distributed system by delegating sub-problems to other agents, and lends flexibility to the software system proposal.

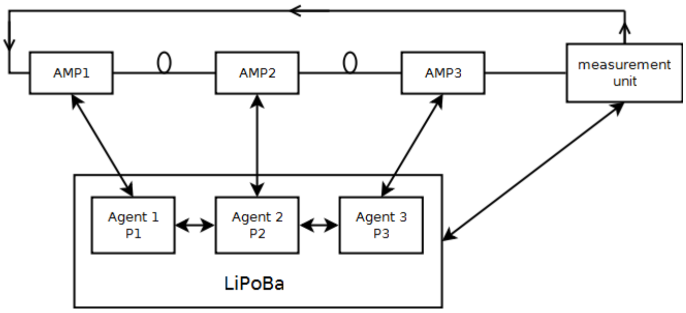

Figure 3.6: Multi-agent power balancing schematic

The LiPoBa (Light Power Balance) multi-agent system prototype consists of several types of agents, each of them with clearly defined goals. The LiPoBa agent platform schematic is shown in Figure 3.6. Some of the agents are control-assigned amplifiers along the fibre line, and one agent interacts with the application interface. The most important part of the whole multi-agent system is the agent type balancer. Its role is to communicate with all of the amplifier control agents, and sends them appropriate commands and requests for reports of the actual state. The quality of transmission is measured by a remotely controlled instrument.

The whole balancing process can be run both in manual and fully automatic mode. In both cases operators have access to a real-time monitoring dashboard for the amplifiers and link. They can also intervene manually into the power balancing process.

The prototype was tested on a small fibre testbed with two amplifiers and three spans of fibre. The first result brought a saving of around 20% of the amplifier's gain, with the whole link fully operational with BER 10^{-12} and better. This new feature is in the development phase, but after the lab tests described, the next step is to perform field tests.

3.2 Vendor independent monitoring

To ensure the reliability and availability of optical connections, it is necessary to monitor all elements of the optical path. CESNET uses two different types of software for monitoring optical elements. The first one (Cisco Transport Controller - CTC) is primarily designed for Cisco Systems device monitoring. The second one (CzechLight Monitor - CLMon) has been developed for the CzechLight family monitoring.

3.2.1 Cisco Transport Controller

The Cisco Transport Controller (CTC) is a GUI-based element management tool that can be used for the operations, administration, management, and provisioning (OAM&P)[1] of various Optical Network System (ONS) 15000 Multi-service Transport Platforms (MSTPs), such as the ONS 15327, ONS 15454, and ONS 15600.

[1] http://en.wikipedia.org/wiki/OAMP

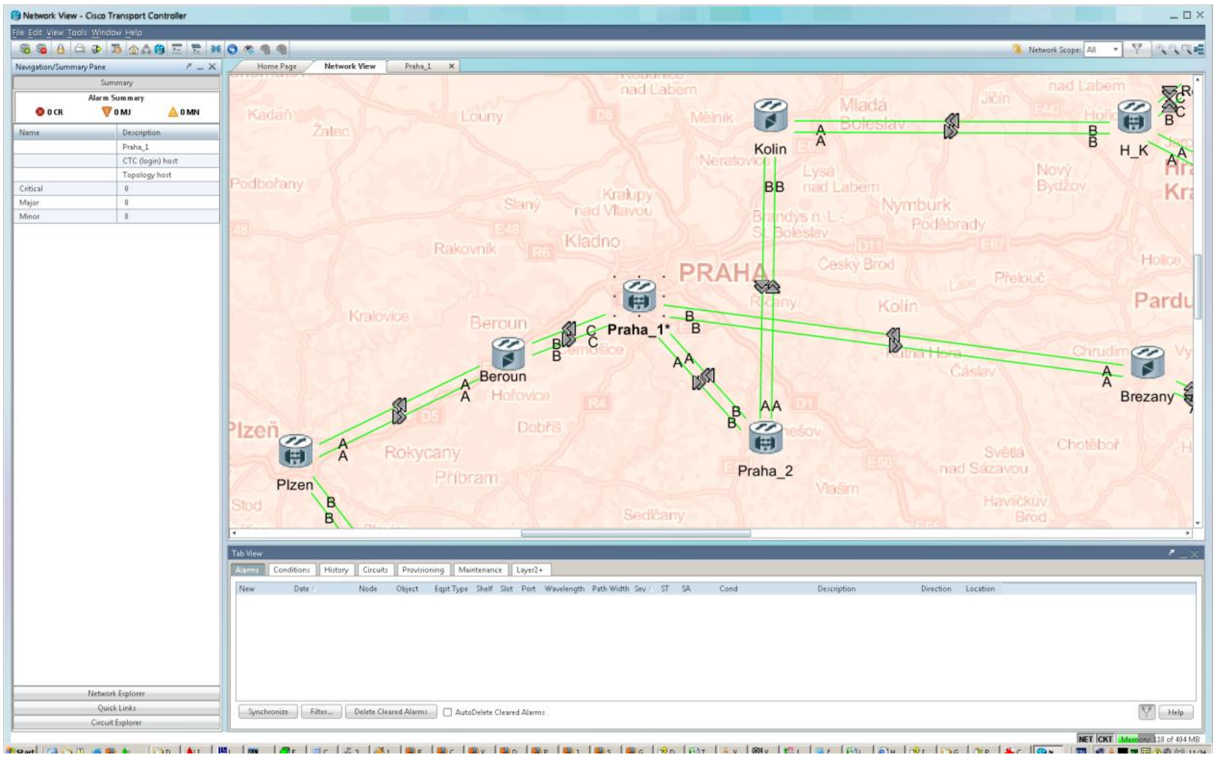

Figure 3.7: Cisco Transport Controller screenshot

The CTC is typically used as a GUI-based craft tool during the deployment and implementation of an ONS-based network. The CTC is a Java application that accepts graphical user input and converts the commands to Transaction Language 1 (TL1)[2] commands accepted by the ONS Network Elements (NE).

3.2.2 CzechLight Monitor

The CzechLight Monitor (CLMon) is a GPL-based monitoring tool that can be used for the monitoring of CzechLight devices. CLMon uses an SNMP protocol for remote read-only access to devices. A new version currently under test also includes support for monitoring Cisco Systems equipment. The aim is a centralized supervision of all optical elements by a single software product because CTC cannot be modified by the customer (including by CESNET). CLMon can use both in-band and out-of-band management to access devices remotely.

2 http://en.wikipedia.org/wiki/TL1

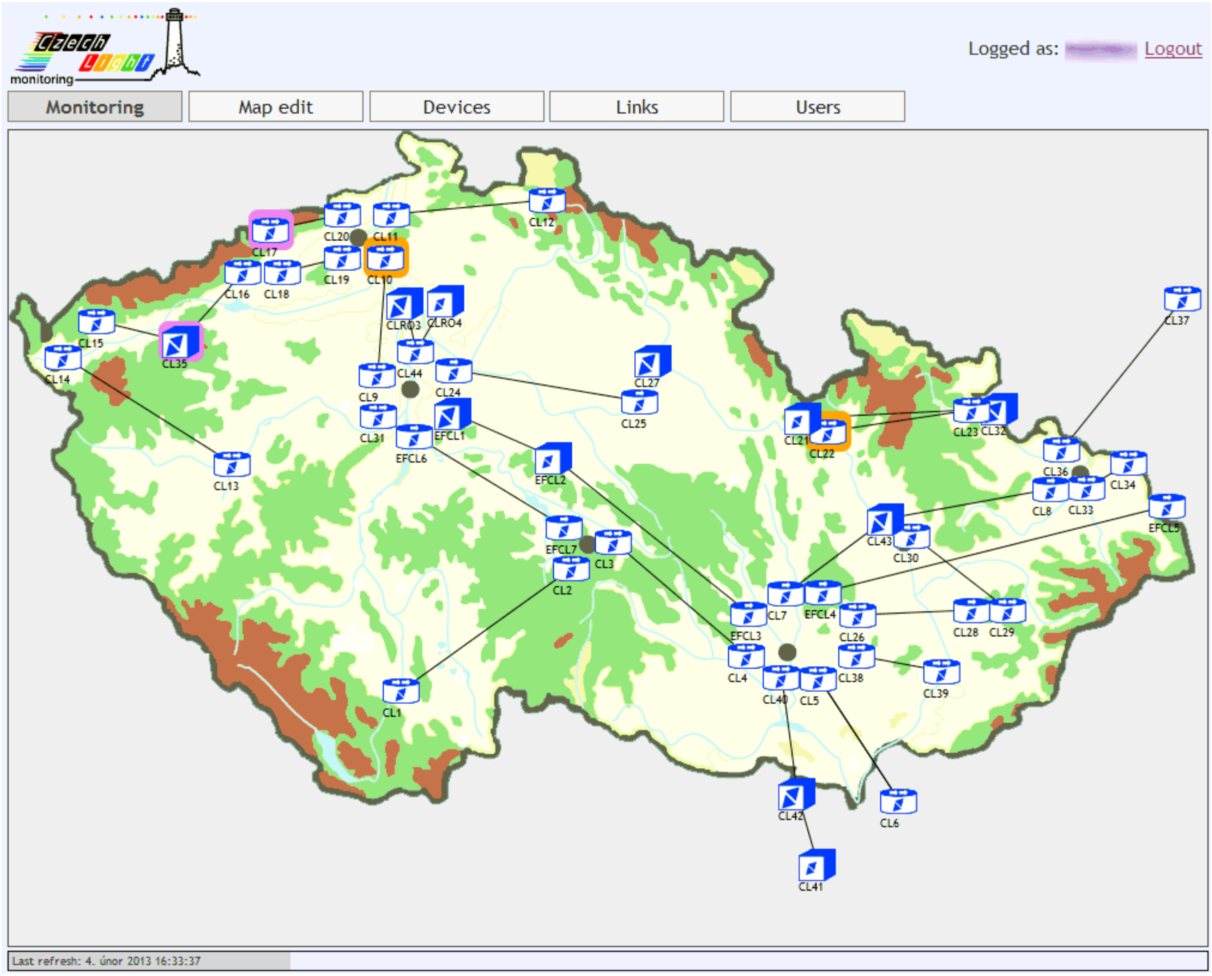

Figure 3.8: CzechLight Monitor screenshot

3.2.3 OAM&P

OAMP (traditionally OAM&P), stands for Operations, Administration, Maintenance, and Provisioning. The addition of 'T' in recent years stands for Troubleshooting, and reflects its use in the environment of network operations. Generally, the term is used to describe the collection of disciplines, as well as whatever specific software package(s) or functionality a given company uses to track these problems.

Even though the term and the concept originated in the wired telephony world, the discipline (if not the term) has expanded to other spheres in which the same sorts of work are done, including cable television and many aspects of Internet services and network operation. 'Ethernet OAM' is another recent concept which borrows this terminology.

The following section is an example of OAMP, using the IPE – BEV optical path as a practical example. EDFA modules are used to monitor the light spectrum. In the event of loss of signal an alarm is raised, for processing by the management software. Access to the facility is also controlled by the management software: an authorized user can change power levels, but there are also power limits defined by the administrator. OAMP defines many such activities and operations such that a description of all these activities results in a very comprehensive document. The following three tables give a brief example of part of the OAMP.

Table 3 describes the light path segments and responsibilities of all involved partners.

Light path segments	**Responsibility**			
Project partner	**IPE**	**CESNET**	**ACOnet**	**BEV**
IPE; CESNET PoP Prague		x		
CESNET PoP Prague; Brno University		x		
Brno University; Niederabsdorf		x		
Niederabsdorf; Vienna University		x		
Vienna University; BEV				x

Table 3: The light path segments and responsibilities of all involved partners

Table 4 describes the tasks and responsibilities for all partners involved. Monitoring points are shown in Figure 3.8.

Tasks	**Responsibility**			
Project partner	**IPE**	**CESNET**	**ACOnet**	**BEV**
Monitoring point 1		x		
Monitoring point 2		x		
Monitoring point 3		x		
Monitoring point 4		x		
Monitoring point 5		x		
Monitoring point 6			x	X
Monitoring point 7		x		
Monitoring point 8		x		
Monitoring point 9		x		
Monitoring point 10		x		
Monitoring point 11		x		
Monitoring point 12	x			
Documentation for onsite support		x		
Ticket system information exchange		x	x	

Table 4: Tasks and responsibilities for all partners involved

It is important to define the monitoring ports early in the design stage of the optical paths. By analysing the data from each measuring point, the operator can quickly detect the type and approximate cause of the problem. Table 5 describes some problems and their possible causes.

MP	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Most probable cause**
	LOS												IPE TX failure
	LOS											**LOS**	IPE-CESNET fibre-pair cut
		LOS											Amplifier failure on PRG-BRNO
											LOS		Amplifier failure on PRG-BRNO
		LOS									**LOS**		PRG-BRNO fibre-pair cut
			LOS										BRNO ONS device failure
			LOS							**LOS**			BRNO fibre-pair cut
				LOS									Amplifier failure in BRNO's CLA
										LOS			Amplifier failure in BRNO's CLA
				LOS					**LOS**				Brno-Niederabsdorf fibre-pair cut
					LOS								Amplifier failure in Niederabsdorf
									LOS				Amplifier failure in Niederabsdorf
					LOS			**LOS**					Niederabsdorf-Vienna fibre-pair cut
						LOS							Amplifier failure in Vienna
								LOS					Amplifier failure in Vienna
						LOS	**LOS**						Vienna-BEV fibre-pair cut
							LOS						BEV TX failure

Table 5: Problems and their possible causes

3.3 Computer-Aided Design and Planning

This section briefly compares the manual design process of an optical transmission system with a procedure employing proper CAD tools.

3.3.1 Manual Network Design

Designing an optical transmission system is far from being a trivial task. The devices have to be operated within their respective design envelopes, otherwise connectivity loss (in case of the signal being too weak) or even property damage (in the case of power being set too high) could occur. The design of each segment is constrained by external criteria (e.g. the locations of the available service facilities and the length of the fibre spans), by economic factors (e.g. availability of N fibres, cost of equipment, cost of groundwork) as well as by transmission system user requirements, the available devices and their technical parameters.

Within these constraints, the engineers work towards designing a line that is affordable, yet operates with a reasonable performance margin to account for the time-based deterioration of the equipment. A typical task is to place the in-line EDFA amplifiers so that the signal level never drowns in noise, while ensuring that the light intensity never exceeds the limits of the receivers' photo receptors. Without the proper tooling, the engineers typically employ *ad hoc* methods like custom, hand-crafted spreadsheets, which carefully take into account the lengths of fibre spans, the actual quality measurements and the performance characteristics from datasheets. In the end, the correct setup is always the responsibility of the specialist. Subsequent modifications to the properties of the light path (perhaps a change of the supplier for the leased fibre pair, or an emergency in-field repair after an unfortunate accident by third-party construction workers) require manual verification whether the desired properties are still maintained. Propagating the observed changes into all places where they are used relies on strict discipline of the human operators; failure to update a single point can lead to an inaccurate diagnosis. Clearly, a process which puts a burden of repetitive, tedious tasks to be performed by hand is a prime candidate for computer assistance.

3.3.2 Available Tools and Vendor Neutrality

We acknowledge that we are not the first organization to realize this opportunity for providing computer assistance with the optical network planning. Equipment vendors are keen on offering a value-added, integrated service which includes the initial planning and design of transmission paths. Naturally, such designs are strongly biased towards single-vendor solutions. Some commercial suppliers offer their own CAD tools in an attempt to provide an added value to their prospective customers. However, to the best of our knowledge, each of these systems is limited to working with a subset of the devices available on the market.

We cannot blame the manufacturers of the networking equipment for their attempts at strengthening their market share by not allowing their customers to easily switch to the competitor's devices. However, such a vendor lock-in does not help the network operators, the infrastructure owners and service providers. On the contrary, an NREN which has invested into documenting their infrastructure using a proprietary software offering cannot effectively change their equipment supplier without spending significant resources on migrating to a new tool. Such a situation might even lead to a need to maintain multiple instances of the planning tools, each covering only a subset of the stakeholder's network, especially in the case of multi-vendor transmission systems. A possible migration may also involve stepping back to a tedious, manual process if the CAD tools do not share an interoperable data interchange format.

3.3.3 Open Network Planning

Some NRENs have been long-term proponents of open technologies, investing in research to enable them to work with different manufacturers to drive down costs and to maintain independence from the transmission systems technology development roadmap of any single vendor. CESNET are investigating an open, vendor-neutral tool to assist in all aspects of running their own optical network, from the initial design phase, to change tracking and on-going monitoring. They are also seeking to collaborate with industry partners and NRENs towards the development of a comprehensive CAD solution to help providers run their infrastructure at lower expense and higher reliability: such collaboration was acknowledged in the FP6 project Phosphorus [49].

4 Global Collaboration

Many research, academic and scientific networks around the world are interested in photonic networking. Some of them perform their own experiments on dark fibre testbeds and some of them have been successful with implementing PS in their production networks. CESNET have approached some researchers and scientists and received useful responses. Some countries outside of Europe interested in PS experiments and potential deployment include Australia, Brazil, Chile, Japan, and the USA. There are interesting projects like NLHCP, EVALSO or ALMA and Brazilian REN, RPN, and Chilean REN, REUNA, together with RedCLARA which interconnects the national advanced academic networks from Latin America; these all have a positive attitude to new trends in networking including Photonic Services. The Australian network AARNet is currently considering the deployment of accurate frequency transfer, which is one of the most demanding photonic applications. This project can be compared to the REFIMEVE project in France, which is run on the RENATER production network. Of course many European NRENs are interested too, especially countries collaborating on the metrology NEAT-FT project, which is mentioned in section 2.5.

Vendor support and enthusiasm for deploying PS is another interesting topic because not all vendors share our vision or attach importance to new applications like accurate time or ultra-stable frequency transfers.

Results of our global collaboration activities are summarized in this section. The first one provides a comprehensive list of our global results presented on international conferences and workshops. The second one provides supporting documentations of optical transmission equipment which can be used to deploy Photonic Services.

4.1 Discussions with vendors about Photonic Services

Vendors of backbone optical systems are naturally focused on requests from ISPs and telecommunication companies as the big market players. Nevertheless we approached them with a request for network solutions supporting Photonic Services and new applications. We invited several vendors to present their solutions and options on the following topics.

Photonic Service - an end-to-end (E2E) communication channel without Optical-Electric-Optical (OEO) regeneration

- Supported modulation formats and maximal data rates
- Optical reach without OEO regeneration
- Increase of optical reach by special amplification or optical regeneration
- Availability of contention-less and flexigrid ROADM
- Plans for wavelength conversions inside network to decrease blocking probability (e.g. some spare transponders in each node)

Planning and monitoring – formation of Multi-vendor E2E communication channels on-demand and their monitoring by Network Management Software (NMS)

- Network Planning Software (NPS) interoperability with other vendors, new device definition
- E2E channel single domain continuous along path monitoring – presence and parameters
- E2E channel multi-vendor or multi-domain monitoring – communication among NMS
- NMS support for flexigrid channels and super channels
- NMS support for alien wavelengths, ITU black links and traversing lambdas

Hardware interoperability – formation of optical links with equipment of multiple vendors

- Requests for interoperability on physical layer from end-users
- Tests of links with equipment from multiple vendors (lab or field tests)
- Requests for interoperability: e.g. preferred protocols or description language

Real-time applications – applications that put constraints at on-time delivery of information

- Demos or pilot projects real time applications over optical networks
- Special equipment for real time and low-latency applications including high frequency trading

A number of vendors accepted the invitation and presented their view on the topics mentioned. Their presentation and more information can be found at [50]. Many vendors would be able to deliver Photonic Services in their own networks, but their major issue is the multi-domain and multi-vendor scenario of Photonic Services. We can say that big vendors are interested in requests from the NREN community, but the NREN market is too small to be have much weight. This situation could be changed by a successful demonstration of PS applications having the potential for a wider deployment in industry or the public sector – see examples in Section 1.6. There are also opportunities for smaller companies and research spin-offs to fill this economic space.

4.2 Searching for worldwide partners and feedback

The results of CESNET's Photonic Services experiments and deployment have been published in numerous conferences with a global audience, receiving much positive feedback from many research networks and institutions. In addition, there are a number of European NRENs actively deploying PSs, and other worldwide partners have serious plans in this area for the near future.

Photonic Services and related topics have been presented at the following global events; online references are given where available.

1. R. Vohnout, L Altmannová, S. Šíma and P. Škoda : Infrastructure Overview with focus on Experimental Facility, TRIDENTCOM 2012, Thessaloniki, 11.-13.6.2012, Greece

2. J. Vojtěch, V. Smotlacha, S. Šíma, P. Škoda: : Photonic Services and their Applications, TRIDENTCOM 2012, Thesaloniki, 11-13.6.2012, Greece,

http://czechlight.cesnet.cz/documents/publications/transmission-systems/2012/Tridentcom2012_poster_PS.pdf

3. J. Vojtěch, P. Škoda, V. Smotlacha: Photonic Services and their Applications, ICTON2012, Coventry, 2-5.7.2012, UK, http://czechlight.cesnet.cz/documents/publications/transmission-systems/2012/Tridentcom2012_poster_PS.pdf

4. J. Vojtěch, V. Smotlacha, P. Škoda, A. Kuna, M. Hůla, S. Šíma: Photonic Services, their enablers and applications, SPIE Optics+Photonics 2012, San Diego, CA, 12-16.8.2012, USA, http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=1386834

5. P. Skoda et al: Photonic Services Enables Real-time Applications over Long Distances, ICP2012, Penang, 1-3.10.2012, Malaysia, http://czechlight.cesnet.cz/documents/publications/transmission-systems/2012/PS_IPC2012_01_print.pdf

6. K. Slavíček, CEF Approach in CESNET Backbone Network, v International Conference on Advanced Computer Science Applications and Technologies, Kuala Lumpur , 26. 11. 2012, Malaysia

7. J. Vojtěch, V. Smotlacha, P. Škoda, A. Kuna, M. Hůla, J. Radil, S. Šíma: Photonic Services for real time applications, Photonics Global, PGC2012, 13-16.12.2012, Singapore

8. J. Vojtěch, L. Altmannová, M. Hůla, J. Radil, V. Smotlacha, S. Šíma, P. Škoda: Photonic Services, Towards Terabit per Second Optical Networking Workshop, CPqD Campinas, SP, 10.05.2012, Brazil, http://czechlight.cesnet.cz/documents/publications/network-architecture/2012/PhotonicServices_Vojtech_CPqD_Campinas1.pdf

9. V. Smotlacha, J. Vojtěch, P. Škoda: Photonic Services and their Applications, COIN 2012, Yokohama, 29-31.5.2012, Japan, http://czechlight.cesnet.cz/documents/publications/transmission-systems/2012/poster_COIN_v4.pdf

10. J. Radil et al, Photonic Services and the Global R&E Networking Community, GN3 NA4 meeting, Jerusalem, 3-4. 9.2012, Israel

11. L. Altmannová, M. Hůla, R. Velc: CESNET connects R&E premises for photonic services, 7th CEF networks workshop: Praha, 12.-14.9., 2012, Czech Republic, http://www.ces.net/events/2012/cef/p/CESNET%20connects%20R&D%20premises%20for%20photonic%20services.pdf

12. S. Šíma: New requirements for R&E networks, 7th CEF networks workshop: Praha, 12.9.2012, Czech Republic, http://www.ces.net/events/2012/cef/p/New%20requirements%20for%20R&E%20networks.pdf

13. J. Vojtech, J. Radil, P. Skoda: E2E photonic services and fibre sharing for R&E Community, 7th CEF networks workshop: Praha, 12-14.9.2012, Czech Republic, http://www.ces.net/events/2012/cef/p/E2E%20photonic%20services%20and%20fibre%20sharing%20for%20R&E%20Community.pdf

14. P. Skoda, J. Vojtech, Optical Transmission Cost Reduction via Fibres Sharing, NORDUnet 2012, Oslo, 18-20.9.2012, Norway, http://czechlight.cesnet.cz/documents/publications/transmission-systems/2012/NORDUnet2012_Skoda_03.pdf

15. J. Vojtěch, L. Altmannová, M. Hůla, J. Radil, S. Šíma, P. Škoda: Koncepce CzechLight, plány nasazení ROADM v síti Cesnet, WDM summit 2012, Praha, 18.4.2012, Czech Republic, http://czechlight.cesnet.cz/documents/publications/transmission-systems/2012/Vojtech-WDMSummit2012v02.pdf

16. J. Radil, J. Vojtěch, P. Škoda, S. Šíma: JRA1 T2, Photonic Services What has been done, Joint JRA1 T1 & T2 workshop, Kobenhavn, 20-21.11.2012, Denmark

17. E. Camisard, P. Skoda: Time and Frequency transfer over optical networks, TIP, Honolulu, HI, 13-18.1.2013, USA, http://events.internet2.edu/2013/tip/agenda.cfm?go=session&id=10002693&event=1261

18. J. Vojtěch, V. Smotlacha, P. Škoda: Transmission of Timing Sensitive Information Using Photonic Services, ICMII International conference on mechatronics and industrial informatics, Guangzhou, 13.-14.3.2013, China

19. P. Škoda, J. Vojtěch, V. Smotlacha: Transmission of Precise Time Using Photonic Service, KEMCS 2013, Phuket, 3.-4.3., 2013, Thailand

Contributions have been accepted for following event:

1. J. Vojtěch, P. Škoda, M. Hůla, S. Šíma: Further fibre capacity increase for accommodation of new services, TNC 2013, Maastricht, 3.-6.6., 2013, Netherlands

The feasibility studies that we have conducted for lighting of spare dark fibre lines for testing purposes take into account three optical network device vendors. An OpenDWDM for the design of flexible photonic networks has been developed in CESNET. The family of optical network devices is called CzechLight. A description of each device is referenced to the datasheet of the individual manufacturer. This documentation is necessary for full understanding of the Open approach to fibre lighting described in section 3.1.1 (such a method is known as Specification by Example). Any devices with equivalent functions can be used instead of CzechLight devices.

The CzechLight amplifier (CLA) [51]. The first CzechLight device, the CLA is based on a commercially available module of an Erbium-doped fibre amplifier that is embedded together with a mini-PC for remote management and with control electronics. The package is placed in a standard 1U or 2U rack-mount chassis. The CLA device can be used in the route as a booster, in-line and preamp. The interface presents a large display with buttons for manual configuration, together with CLA web applications for remote access.

The CzechLight tunable chromatic dispersion compensator [52] (CLC). This device offers tuneable dispersion compensation, an essential feature for modern optical networks. The CLC device contains two modules of tunable dispersion compensators, a mini-PC and control electronics. A fully redundant power supply unit is provide for greater reliability. The tunability of the dispersion compensator allows CLC operators to react to dynamic changes of the transmission, such as fibre link switching or changes in a link hardware. The flexibility of the CLC is enhanced by remote access to the device through a web interface.

The distribution of optical channels in the nodes of an optical network is usually static and defined by the hardware configuration. Any modification thereafter requires an on-site service action by technical support staff. These disadvantages and expenses can be minimized with **the CzechLight Reconfigurable Add-Drop Multiplexer** [53] (CL-ROADM). This device allows the operator to configure the signal distribution in an optical network node remotely from their office. The CL_ROADM contains the ROADM module, a mini-PC, and control electronics. Communication with the device is via a web application.

A crucial part of a modern optical network is the optical switch. **The CzechLight Switch** and **the CzechLight Multicast switch** [54] (CLS & CLM) are devices that route optical signals from each input to one of the outputs. The switch can be used as a smart patch panel with the added benefit of vastly increased durability in terms of switching cycles, thanks to its non-mechanical switching matrix. The CLS device contains the switching matrix, a mini-PC and the support and control electronics.

An Optical multiplexer is one of the key components for modern DWDM transmission systems. **The CzechLight Variable Multiplexer** [55], (CL-VMUX) combines the individual optical channels into the DWDM signal and – on the opposite end of the line segment – separates the combined signal into individual light paths. An important advantage of the CL-VMUX is the option of level equalization of the multiplexed optical channels, a feature which is essential for the optical amplification in optical amplifiers further down the fibre path. The remote control of the CL-VMUX allows authorized users to monitor and control the power in optical channels and to react to any performance variation within the transmission system. The device contains the VMUX module, a mini-PC and the support and control electronics.

Conclusions

The new concepts and ideas introduced in this document can provide architecture or layouts for NRENs and the GÉANT community. These communities can test, verify, design and then deploy and implement a new class of services which are called Photonic Services.

Several scientific experiments have emerged over the last few years that have raised the demands on the European fibre infrastructure (for example, the European FP7 project JRP-s11 ‘Accurate time/frequency comparison and dissemination through optical telecommunication networks’). Nevertheless, a continent-wide fibre infrastructure is unaffordable and a sharing of fibre footprint by deploying Photonic Services is needed. Some applications, for example ultra-stable frequency transfer, require active stabilization of fibre dilation caused by temperature change, which is achievable via bidirectional transmission within a single fibre. Applications of Photonic Services in research and production are being developed as well (for example remote control of instruments or processes).

PS provisioning is another important topic and innovative transmission services in NRENs are mentioned, with practical examples of accurate time transfer between CESNET – ACOnet and ultra-stable frequency transfer in RENATER. Other candidates for PS deployment in the Czech Republic are mentioned and the important role of dark fibre testbeds is mentioned.

Results of CESNET's joint work have been published and recognized worldwide, with many of colleagues interested in the intriguing new possibilities which are facilitated by Photonic Services. Countries such as Australia, Brazil, Chile, the USA or Japan have already shown an appreciation of the potential of Photonic Services.

References

[1] L. Altmannova, T. Breach, M. Campanella, M. Carboni, M. Enrico, L. Fischer, R. Pekal, J. Radil, R. Sabatino, M. Scarpa, S. Sima, T. Szewczyk, R. Tuminauskas, C. Tziouvaras, J. Vojtech: Final GÉANT Architecture, DANTE, 2011, http://www.geant.net/Media_Centre/Media_Library/Media%20Library/GN3-10-279_DS1.1.1,2%20Final%20GEANT%20Architecture_v1.pdf

[2] R. Evans, D. Salmon: CEF 2012 Janet Update: Janet6 & Aurora, http://www.ces.net/events/2012/cef/p/Janet6%20and%20Janet%20Aurora.pdf

[3] K. Predehl et al: A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th Decimal Place. Science 336, 441, 2012

[4] http://www.ptb.de/emrp/neatft_home.html

[5] Project REFIMEVE+: REseau FIbré MEtrologique à Vocation Européenne+, http://www.univ-orleans.fr/osuc/pdf/REFIMEVE+_203077.pdf

[6] http://www-lpl.univ-paris13.fr/UK/billet_complet.awp?blog=science_news&id=72&lang=us

[7] http://www.idil-fibres-optiques.com/

[8] http://first-tf.com/perch/resources/bipm-april-2012-dimarcq-1.pdf

[9] https://tnc2012.terena.org/core/presentation/43

[10] http://www.porta-optica.org/publications/POS-D3.2_Economical_analysis.pdf

[11] E. Tipsuwannakul et al, Mitigation of Fiber Bragg Grating-Induced Group-Delay Ripple in 112 Gbit/s DP-QPSK Coherent Systems, OFC 2012.

[12] Benoit Maheux-Lacroix, TeraXion, High Level Dispersion Compensator for Ultra Long-Haul Coherent Detection Links, 2012, http://www.teraxion.com/images/stories/pdf/White_paper_HLDC_v5.pdf

[13] J.L. Augé, Can we use Flexible Transponders to Reduce Margins?, OFC 2013.

[14] http://www.ict-fireworks.eu/fileadmin/events/EU-Japan_08/Presentations/09-06-08/5B-Photonic_Networks/15-TETSUYA_MIYAZAKI_-_Photonic_Networks.pdf

[15] http://www.eso.org/public/announcements/ann12082/

[16] http://internationalnetworking.iu.edu/sites/internationalnetworking.iu.edu/files/michael-stanton-latin_america.v2.ppt

[17] http://www.nestor.noa.gr/

[18] http://www.gtc.iac.es/

[19] http://tnc2010.terena.org/files/Robles-TNC10_vpdf.pdf

[20] https://events.nordu.net/display/ndn2012web/Planning+a+submarine+cable+in+the+Arctic+-+the+NYAAL+cable

[21] Knowledge without Borders, GÉANT 2020 as the European Communications Commons, Luxembourg: Publications Office of the European Union, 2011, ISBN 978-92-79-21036-5, http://cordis.europa.eu/fp7/ict/e-infrastructure/docs/geg-report.pdf

[22] ESFRI: research infrastructures for Europe, Brussels, 10 October 2012, http://europa.eu/rapid/press-release_MEMO-12-772_en.htm?locale=en

[23] Conclusions on 'A reinforced European research area partnership for excellence and growth', COUNCIL OF THE EUROPEAN UNION, Council meeting, Brussels, 11 December 2012, (in point 13) http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/intm/134168.pdf

[24] Horizon 2020, http://ec.europa.eu/research/horizon2020/index_en.cfm?pg=h2020

[25] L.Altmannová, S.Šíma: Development of the CESNET2 Optical Network, Terena Networking Conference 2002, Limerick, https://www.terena.org/events/archive/tnc2002/Papers/p3c2-sima/sima1.html

[26] S.Šíma, Proceedings of Customer Empowered Fibre Networks workshop, Praha, May 2004, http://www.ces.net/events/20040525/

[27] L. Altmannová, M. Hůla, R. Velc: CESNET connects R&E premises for photonic services, 7th CEF networks workshop: Praha 2012, http://www.ces.net/events/2012/cef/p/CESNET%20connects%20R&D%20premises%20for%20photonic%20services.pdf

[28] http://wiki.ict-fire.eu/index.php/FIRE_event_Poznan

[29] S. Šíma: Testbed for real-time applications and reproducibility of experiments, EU FIRE Event Poznan, October 2011, http://wiki.ict-fire.eu/images/8/84/6_CESNET_-_Testbed_for_real-time_applications.pdf

[30] http://www.ces.net/events/2012/cef/p/RENATER-5%20update%20on%20topology%20and%20advanced%20projects.pdf

[31] http://www.apc.univ-paris7.fr/LISA-France/2011-2012_files/santarelli.pdf

[32] http://www.ces.net/events/2012/cef/p/Global%20facilities%20for%20research%20networking%20using%20alien%20wavelengths.pdf

[33] S.Šíma: New requirements for R&E networks, 7th CEF networks workshop: Praha 2012, http://www.ces.net/events/2012/cef/p/New%20requirements%20for%20R&E%20networks.pdf

[34] S. Šíma: Proceedings of 7th Customer Empowered Fibre Networks workshop, Praha, September 2012, http://www.ces.net/events/2012/cef/

[35] http://www.ces.net/doc/press/2010/pr100401.html

[36] http://www.ces.net/services/photonic.html

[37] http://www.ces.net/doc/press/2013/pr130208.html

[38] http://www.ces.net/doc/press/2013/pr130320.html

[39] http://www.geant.net/Media_Centre/Media_Library/Media%20Library/GN3-12-063_DJ-1-2-2_State-of-the-Art-Photonic-Switching-Technologies-Study-and-Testing.pdf

[40] H.Schnatz: Comparison of clocks using optical fiberlinks: recent results and future projects. 7th CEF networks workshop, Praha September 2012, http://www.ces.net/events/2012/cef/p/Comparison%20of%20clocks%20using%20optical%20fiber%20links%20in%20recent%20results%20and%20future%20projects.pdf

[41] http://www.ces.net/events/2010/cef/p/sima.ppt

[42] R. Nuijts: Global facilities for Research Networking Using alien waves, http://www.ces.net/events/2012/cef/p/Global%20facilities%20for%20research%20networking%20using%20alien%20wavelengths.pdf

[43] V.Smotlacha, A.Kuna, W.Mache: "Optical Link Time Transfer between IPE and BEV", in Proceedings of Precise Time and Time Interval Meeting (PTTI) 2011, Long Beach, CA, USA, November 2011

[44] V.Smotlacha, A.Kuna: "Two-way Time and Frequency Transfer between IPE and BEV", in Proceedings of EFTF-2012, Gothenburg, Sweden, April 2012

[45] M. Rost, D. Piester, W. Yang, T. Feldman, T. Wübbena, A. Bauch,Time transfer through optical fibers over a distance of 73 km with an uncertainty below 100 ps, 2012.

[46] N. Fontaine, R. Ryf, J. Bland-Hawthorn, and S. Leon-Saval, Geometric requirements for photonic lanterns in space division multiplexing, Opt. Express 20, 27123-27132 2012.

[47] S. J. B. Yoo: Optical packet and burst switching technologies for the future photonic internet, J. Lightwave Technol., 24, pp. 4468-4492, 2006.

[48] Fernandez-Ruiz, M., "Design of ultrafast all-optical signal processing devices based on fiber Bragg gratings in transmission", Journal of Lightwave Technology, 2012, http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6487367

[49] http://www.ist-phosphorus.eu/

[50] CEF Networks 2012, http://www.ces.net/events/2012/cef/

[51] CLA - CzechLight Amplifier, http://czechlight.cesnet.cz/documents/download/30-EN-CSNT-CLA_v1.3.pdf

[52] CLC – CzechLight tunable chromatic dispersion Compensator, http://czechlight.cesnet.cz/documents/download/41-EN-CSNT-CLC_v1.3.pdf

[53] CL-ROADM - CzechLight Reconfigurable Add-Drop Multiplexer, http://czechlight.cesnet.cz/documents/download/42-EN-CSNT-CL-ROADM_v1.3.pdf

[54] CLS & CLM - CzechLight Switch & CzechLight Multicast Switch, http://czechlight.cesnet.cz/documents/download/43-EN-CSNT-CLS_v1.3.pdf

[55] CL-VMUX - CzechLight Variable Multiplexer, http://czechlight.cesnet.cz/documents/download/44-EN-CSNT-CL-VMUX_v1.3.pdf

[56] M. Karásek, J. Radil, J. Vojtěch: Optical amplifiers in CzechLight & CESNET2 http://www.ces.net/events/20050516/

Glossary

BER	Bit Error Rate
BERT	Bit Error Rate Tester
BGP	Border Gateway Protocol
CAD	Computer Aided Design
CBF	Cross Border Fibres
CD	Chromatic Dispersion
CEF	Customer Empowered Fibre
CLI	Command Line Interface
CTC	Cisco Transport Controller
dB	Decibel
DCF	Dispersion Compensating Fibre

DCM	Dispersion Compensating Module
DF	Dark fibre
DP-QSK	Dual-polarization Quadrature Phase Shift Keying
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
DWDM	Dense Wavelength Division Multiplexing
E2E	End-to-End
ECOC	European Conference on Optical Communication
EDFA	Erbium Doped Fibre Amplifier
EFTA	European Free Trade Association
FBG	Fibre Bragg Grating
Gbps	gigabits per second
GPS	Global Positioning System
HLDC	High Level Dispersion Compensator
ICT	Information and Communications Technology
ITU	International Telecommunication Union
LiPoBa	Light Power Balance
MAS	Multiagent system
MPLS	Multi Protocol Label Switching
MSTP	Multiple Spanning Tree Protocol
NE	Network Element
NIL	Nothing in line
NREN	National Research and Education Network
OA	Optical Amplifier
OAM&P	Operations Administration Maintenance Provisioning
OEO	Optical-Electrical-Optical
OFC	Optical Fiber Conference
OOK	On-Off Keying
PPS	Pulse per second
PS	Photonic Service
R&D	Research & Development
R&E	Research & Education
REN	Research and Education Network
RX	Receive
TX	Transmit
UTC	Coordinated Universal Time
WDM	Wavelength Division Multiplexing