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***PHOTONIC SERVICES FOR
NON-STANDARD APPLICATIONS
OVER ALL-OPTICAL NETWORKS***

Doctoral Thesis

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“An expert is a person who has made all the mistakes that can be made in a very narrow field.”

— Niels Bohr

I declare hereby that this presented thesis is, to the best of my knowledge, original and has not been submitted in whole or part for a degree in any university. I have written this doctoral thesis independently, under the supervision of my supervisor Prof. Ing. Stanislav Zvánovec, Ph.D. and supervisor-specialist Ing. Jan Radil Ph.D. I have cited all the literature sources used.

Prague 20.02.2017

Pavel Škoda

Abstract:

The thesis presents details about special applications provided by national research and education networks and highlights the need for the end-to-end optical channel through multiple optical network domains. This need is answered by introducing a new concept of Photonic Service that includes special applications into optical networks. The application of time transfer is selected for proof of concept application and a demonstration is carried out over international optical network links. Photonic services are very susceptible to wavelength contention in optical networks and require a suitable optical processing device to solve the issue. Optical processing methods utilising nonlinear effects in optical fibres were studied to design optical processing device able to resolve the wavelength contention – optical signal converter. The optical signal converter was optimised and the resolution of wavelength contention was demonstrated on time transfer scenario over an optical network of 2000 km. The methodology for implementation of Photonic Services in optical networks was proposed based on the results presented in this work.

Keywords:

Photonic Services, Optical Signal Processing, Four Wave Mixing, Wavelength contention, Time transfer, Alien waves, NRENS

Abstrakt:

Disertační práce popisuje detaily speciálních aplikací poskytovaných v národních sítích pro výzkum a vzdělání a zdůrazňuje potřebu optických kanálů mezi koncovými uživateli, které mohou procházet několika síťovými doménami. Jako odpověď na tuto potřebu je představen nový koncept fotonických služeb, který umožňuje přenos speciálních aplikací přes optické sítě. Koncept fotonických služeb byl předveden na aplikaci přenosu přesného času přes mezinárodní optickou síť. Fotonické služby jsou velmi náchylné na souběh optických kanálů a vyžadují zařízení schopné optického zpracování signálu pro řešení případného souběhu. Disertační práce představuje vhodnou metodu optického zpracování a navrhuje nové zařízení – optický signálový konvertor. Optický signálový konvertor byl optimalizován a jeho funkčnost byla ukázána na souběhu fotonické služby přenosu přesného času s datovým provozem přes optickou síť o délce 2000 km. Na základě výsledků práce byla připravena metodika pro návrh optických sítí umožňujících použití fotonických služeb pro speciální aplikace.

Klíčová slova:

Fotonické služby, Optické zpracování signálu, Čtyřvlonné směšování, Souběh vlnových délek, Přenos přesného času, Cizí vlny, Národní síť pro výzkum a vzdělání

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List of Abbreviations

APAN	Asia Pacific Advanced Networks
AW	Alien Wavelength
BEV	Bundesamt für Eich- und Vermessungswesen (Federal Office of Metrology and Surveying)
CW	Continuous Wave
DCU	Dispersion Compensating Unit
DP-QPSK	Dual Polarization Quadrature Phase Shift Keying
DWDM	Dense Wavelength Division Multiplex
E2E	End to End
EDFA	Erbium Doped Fibre Amplifier
FPGA	Field Programmable Gate Array
FWM	Four-Wave Mixing
GPS	Global Positioning System
HNLF	Highly NonLinear Fibre
IPE	Institute of Photonics and Electronics in Prague
MZI	Mach-Zehnder Interferometer
NREN	National Research and Education Network
OEO	Optical-Electrical-Optical
OMS	Operation and Management System
OOK	On-Off Keying modulation format
OSA	Optical Spectrum Amplifier
OSNR	Optical Signal to Noise Ratio
PM-16QAM	Polarization Multiplexed 16-Quadrature Amplitude Modulation
PoPs	Points of Presence
PPP	Precise Point Positioning method
PPS	Pulse Per Second
REC	Research and Education Community
ROADM	Reconfigurable Optical Add Drop Multiplexer
RZ-DPSK	Return-to-Zero Differential Phase Shift Keying
SKA	Square Kilometre Array
SOA	Semiconductor Optical Amplifier
SPM	Self-Phase Modulation

TDEV	Time DEVIation
TTA	Time Transfer Adapter
TWSTFT	Two Way Satellites Time and Frequency Transfer
UTC	Coordinated Universal Time
VLA	Very Large Array
WC	Wavelength Converter
XGM	Cross Gain Modulation
XPM	Cross Phase Modulation

1 Introduction

Optical networking has experienced a worldwide boom since the beginning of 1975 when the first generation of optical communication systems at a wavelength of 800 nm and rate of 45Mbps was commercially deployed. In the early 1980s, the second generation of optical systems was improved by InGaAsP semiconductor components operating at wavelengths around 1300 nm with rates reaching one Gbps. The third generation of optical systems came in at the end of the 1980s by utilising single-mode lasers at wavelengths around 1550 nm reaching 2.5 Gbps at an unrepeated distance of 100 km. Erbium-doped fibre amplifiers (EDFA) designed simultaneously in Southampton and Bell Labs [1] launched the fourth generation of optical systems when they were combined in the 1990s with wavelength division multiplexing [2]. In the new millennium, the introduction of dense wavelength division multiplex signalled the fifth generation of optical systems that increased fibre capacity to units of Tbps [3]. The sixth generation of optical systems started after 2010 when the first truly coherent 100Gbps signals appeared on the market with comprehensive digital signal processing [4]. Vendors of optical communication systems are now designing their systems to satisfy capacity requirements of telecommunication services providers transferring our everyday Internet applications. In contrast to this, never-ending rush for capacity, research and education networks are supporting the academic community by implementing new applications.

The academic community explores a number of very demanding applications not supported by telecommunication service providers [5]. Many of them require either extreme throughput or an all-optical connection between endpoints. This position increased the demands on the capabilities of research and education networks. Designing such networks with limited funding, and the fact that the market offers networks with optimal designs for telecommunication service providers appears to be a real challenge.

Therefore, the design of optical processing devices that support the implementation of special applications for the academic community is of great importance. Research and education networks utilise these optical processing devices to support research where there is no alternative device produced commercially.

Moreover, the design of optical networks for telecommunication service providers is widely known and targets maximum capacity of a covered area. In comparison, research and education networks

seek cost-effective designs that give them desired flexibility to support special applications. Design methodology for research and education networks is, thus, a very actual topic.

This dissertation thesis focuses on proposing a methodology of how to implement advanced scientific applications to optical backbone networks. We have verified the methodology by piloting an experiment of a single advanced scientific application of time transfer in a real network. A device for all-optical signal processing of optical signals has been designed to change the frequency of a temporal signal. The signal processing device was demonstrated as a solution for the traffic congestion of data traffic and temporal signal. Furthermore, the signal converter was used for the time transfer stabilisation.

The dissertation thesis is organized in the following parts. Chapter 2 discusses key concepts and technologies used in current optical research and education networks, and gives an overview of their diversity. It emphasises the need of network development at all its layers, from the physical fibre infrastructure to management and the operational system. The chapter also presents examples of advanced applications that are to be supported by these academic networks. The advanced applications put requirements not only on network capacity and data throughput but also on latency and delay jitter.

Chapter 3 focuses on linear and nonlinear effects in optical fibres and compares methods of optical signal processing. Nonlinear effects in dielectric media and, especially, wavelength conversion offer interesting features for optical signal processing. We conclude with a recommendation to select one of the nonlinear effects and realise a signal processing device.

Chapter 4 defines the main objectives of this work.

Chapter 5 introduces a new concept of photonic services and discusses it in contrast with current services. The biggest impact is expected with the adoption of flexible spectrum technologies.

Chapter 6 describes a pilot project of time transfer over research and education networks between Prague and Vienna. It offers insight into network design and advanced application performance.

Chapter 7 proposes an optical signal converter for a time transfer application to prove the main concept of photonics services. The signal converter parameters are afterwards identified and optimised.

Chapter 8 describes results from the intensive testing of the converter device in a long-haul optical testbed and discusses a subsequent demonstration of its functionality in a network traffic congestion scenario.

Chapter 9 discusses the delay stabilisation of the time transfer application. It demonstrates several advantages provided by the converter especially regarding delay stabilisation and summarises the main design rules.

Chapter 10 summarises a new methodology of designing optical research networks that will support advanced applications and services. It points out the key networking concepts that NRENs need to implement Photonic Services.

Finally, chapter 11 summarises the work and highlights achievements.

Throughout the thesis, I refer to CESNET achievements in the field of advanced network applications which I have been mostly directly and in some cases indirectly participating. CESNET is the non-profit organisation that has been associating network and telecommunication experts for more than 15 years forming Czech national research and education network. CESNET provides both operation services of the Large Infrastructure and research activities. The Large Infrastructure is the international optical backbone network composed of 5000 km of dark fibres connecting more than 120 locations of universities and research institutions with high capacity lines and supporting research in Czech Republic and abroad. Besides the state-of-the-art connectivity CESNET also provides research and development of new network components following up-to-date worldwide trends of optical networking. Applied research resulted in the development of new network devices that have been successfully deployed across the optical network CESNET2 and abroad as well. Devices are developed and sold under brand name Czech Light family, which forms a complete system enabling dark fibre lighting with hundreds of gigabits per second capacities with a strong emphasis on system cost-effectiveness and flexibility.

2 Current state of optical research networks

Optical networks began to replace backbone telecommunication networks since the first Erbium Doped Fibre Amplifier was introduced to the market. Optical amplification empowered frequency multiplex that supports the simultaneous transmission of more than 80 channels through one optical fibre [3]. With current channel capacities around 100 Gbit/s, the full C-band capacity of tens of Tbit/s may be easily reached for a single optical fibre [6]. This huge capacity is consumed by telecommunication operators and internet providers in order to deliver data, video and voice services to customers. There is a minority of research networks that serves primarily the Research and Education Community (REC) [7]. Since these research networks are made to interconnect the REC, rather than serve millions of users, they remain underutilised and do not benefit from standard

telecommunication technologies offered by big vendors. Research networks are distinguished by the fact that they require a different network design that is more focused on flexibility than transmission capacity.

More details about research networks and special applications are given later in this section.

2.1 Overview of networks for scientific community

Applications for communication in the academic community have changed dramatically during the last decade. New technologies for video conferencing have opened more intensive ways for international collaboration and helped the academic community around the globe to communicate on a daily basis. In addition, new and unique projects like very large array (VLA) [8] and square kilometre array (SKA) [9] are expanding to study fundamental questions of the universe and these will generate massive amounts of data that need to be transferred by so-called “elephant flows” [10] that can easily saturate capacity bottlenecks in the global network [11]. The expected SKA infrastructure would transfer more than a hundred Tbps internally and will require at least 100 Gbps links outside as shown in Table 1 and Figure 1.

SKA sub-arrays	Per site capacity [Gbps]	Local sites	Remote sites	Total capacity from sites [Tbps]	Capacity from preprocessing [Tbps]
SKA-low	10	866	45	9.110	6.5
SKA-survey	864	54	42	82.944	12
SKA-mid	90	218	36	22.860	8
Total				114.914	26.5

Table 1: Planned capacities in fully operational SKA [12]

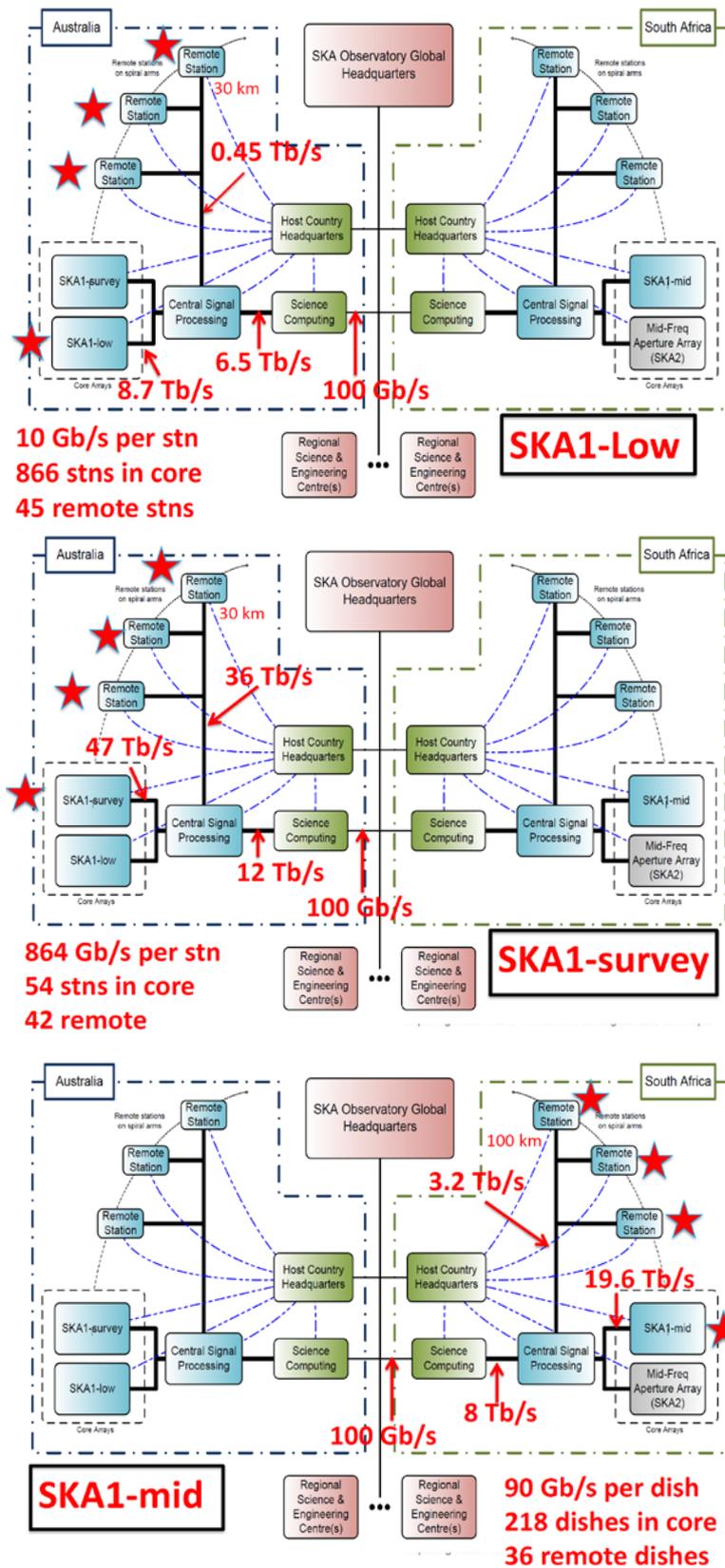


Figure 1: Optical infrastructure and planned capacities of three SKA sub-arrays [12]

Enhanced international collaboration also increases the requirements to move large amounts of data among academic partners [13]. The international collaboration is well displayed in co-citation map in Figure 2. The global answer for the ever-increasing demand of the academic community for quality network connections was an establishment of the National Research and Education Networks (NRENs) in almost every country [14]. These mostly state-funded organisations have the primary task to connect universities, research institutes and sometimes non-profit organisations by a state-of-art backbone network that delivers the required support to the academic community. Current backbone networks use light to carry information through optical fibres to its destination. Although it is possible to build a network based on leased circuits, NRENs have to understand the advantage of the flexibility and the capacity of a Dark Fibre (DF)-based infrastructure [15]. DFs are unlit optical fibres without any transmission technology on top of it. Nowadays DF can be also leased or swapped to someone who becomes operator or owner. Owner or operator may select an optical transmission technology that suits his needs to set up a transmission system over a dark fibre. Both flexibility and capacity **come** from the fact that an operator can use the most suitable transmission system to serve its users.

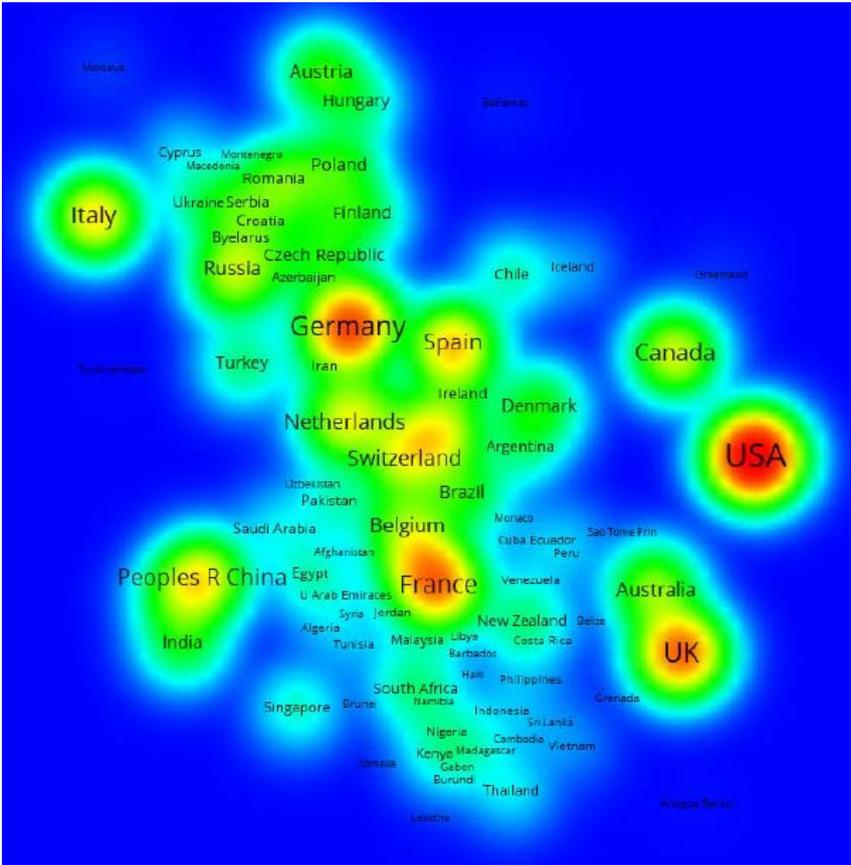


Figure 2: Global map based on the cosine-normalized network of coauthorship relations among 190 nations [13]

2.1.1 Physical Infrastructure

Most of the backbone networks form joint ring architectures that improve network resiliency. The ring structure allows, in the case of a cut fibre or a system failure at any point of the ring, to redirect the traffic through the other part of each ring. An example of joined ring architecture is shown in Figure 3. Network nodes or similarly points of presence (PoPs) interconnected together to form hexagonal rings that are joined at their sides and even if the very central network node failed, traffic would be rerouted over the edges of the other rings.

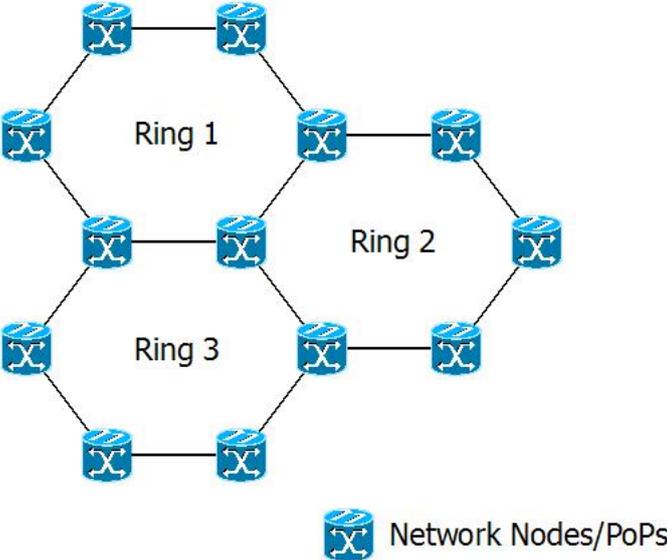


Figure 3: Joined Ring Architecture Model

Network failures and, in particular, fibre cuts are common problems in rural areas. Optical transmission network systems are designed to provide automatic protection of network services. As shown in Figure 4, a network operational system reroutes services over the cut orange link to the green link. Two complementary protective mechanisms are usually employed.

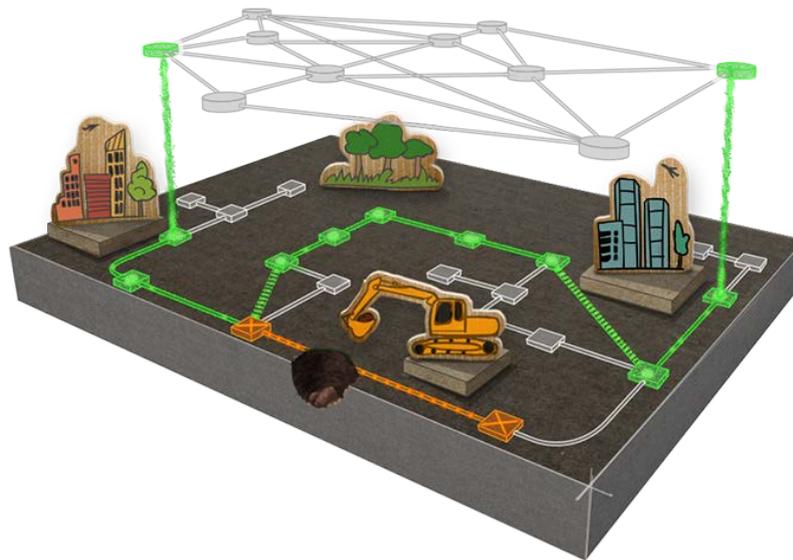


Figure 4: Automatic restoration of network service in case of failure, Orange link is the link with fibre cut, Green link is the new link used for protection (source: Sedona Systems)

The first is a network path protection that, in the case of failure, reroutes the optical channel at the physical layer of the network through the use of Reconfigurable Optical Add-Drop Multiplexers (ROADMs). The second is called network service restoration that, in the case of failure, reroutes the traffic at the IP layer utilising available network capacity.

The network is additionally protected by sensible planning and fibre path selection. It is important that optical links between network PoPs have a different physical path to eliminate a single point of failure in case of a cut fibre. Although aerial cables are cheaper to deploy, buried ones have more stable working conditions and usually achieve better parameters. For instance, chromatic dispersion and zero dispersion wavelength may change with temperature as much as $0.0025 \text{ ps/nm/}^\circ\text{C}$ and $0.025 \text{ nm/}^\circ\text{C}$, respectively [16]. Temperature dependence of PMD reaches 16% of the mean value [18]. Clearly buried optical cables turn out to be more stable as temperature variations in underground installations usually do not exceed 20°C [19], in contrast, aerial cable temperature may vary even over 70°C [20]. Obviously buried cables are usually preferred over aerial cables for a physical infrastructure of backbone telecommunication networks.

From a contractual point of view, the physical infrastructure is either built and owned or procured and leased. Since infrastructure construction is extremely expensive, most NREs lease pairs of optical fibres from network providers. Leased fibres are either under Irreversible Right of Use (IRU) terms, where, for an agreed period of time, the use of the resource is constant, or some kind of lease contract with expiration terms.

2.1.2 Transmission systems

On top of the physical infrastructure, usually formed from dark fibres, resides the optical transmission system. It “lights” the optical infrastructure and allows the utilisation of a great capacity of optical fibres. Information and data from end-users are aggregated in network nodes by routers and fed into the optical transmission system to carry it seamlessly to its destination. A transmission system for each network is created by a vendor who offers a network solution. But since there are many transmission system vendors, it is very likely that neighbouring networks will have different systems with similar capabilities. A map of NREN systems in Europe as of 2013 is shown in Figure 5. Optical transport network vendors are usually changing every five to ten years depending on NREN situation, but the diversity in systems remains.

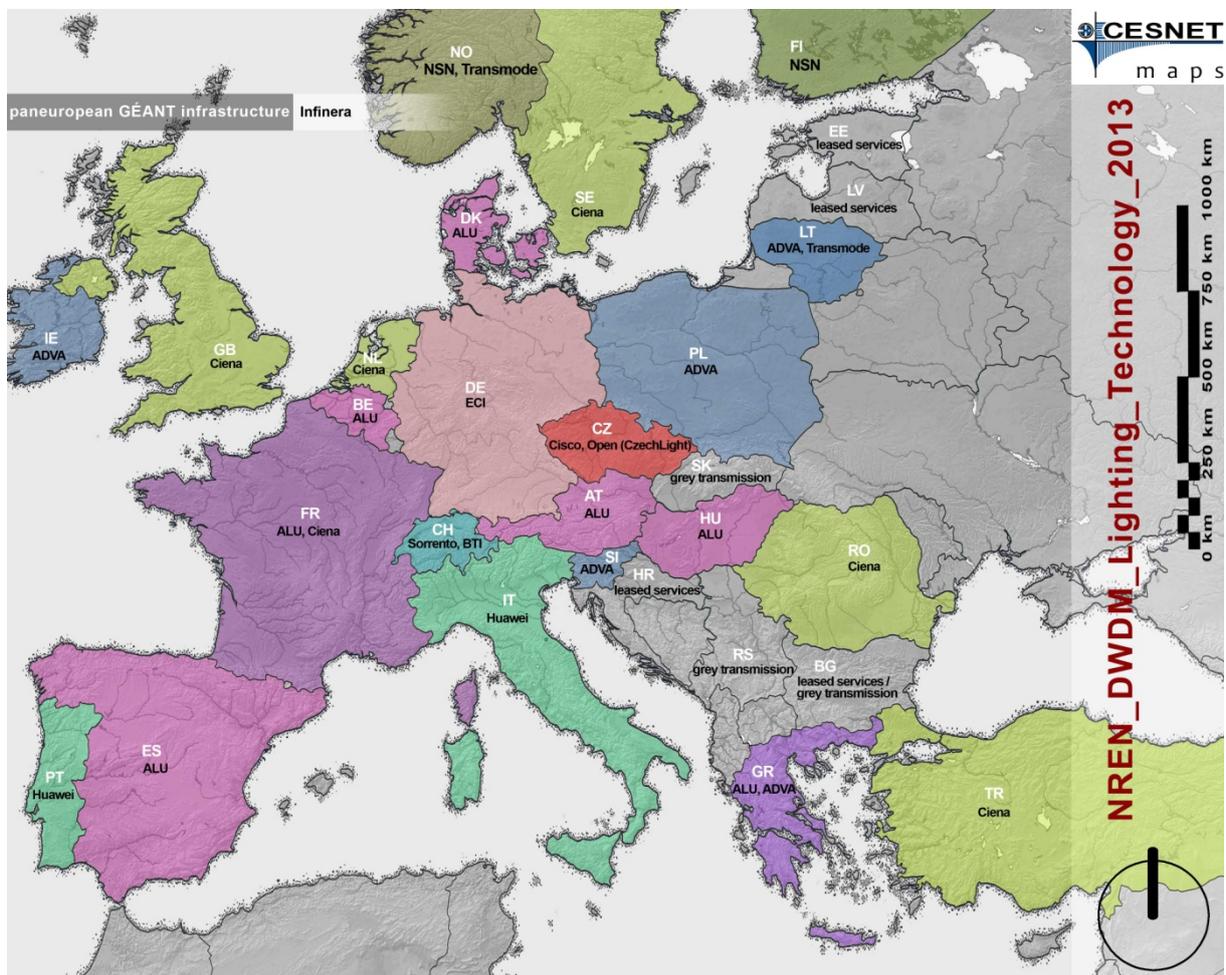


Figure 5: Optical transmission systems of European NRENs 2013 [21]

Nevertheless, many traits of these systems are similar in terms of network features and parameters. Some of them are discussed in the following sections.

2.1.2.1 Capacity

State-of-the-art networks use Dense Wavelength Division Multiplex (DWDM) and rates of standard amplitude modulations of 10 Gbps and new coherent modulations from 100 Gbps to 200 Gbps in one standard DWDM channel [25][26].

DWDM allows the simultaneous transmission of light on a number of optical channels that multiply the capacity of a single fibre pair. Optical backbone networks use, almost exclusively, the C-Band part of the available spectrum in an optical fibre. Optical bands for telecommunication are shown in Figure 6.

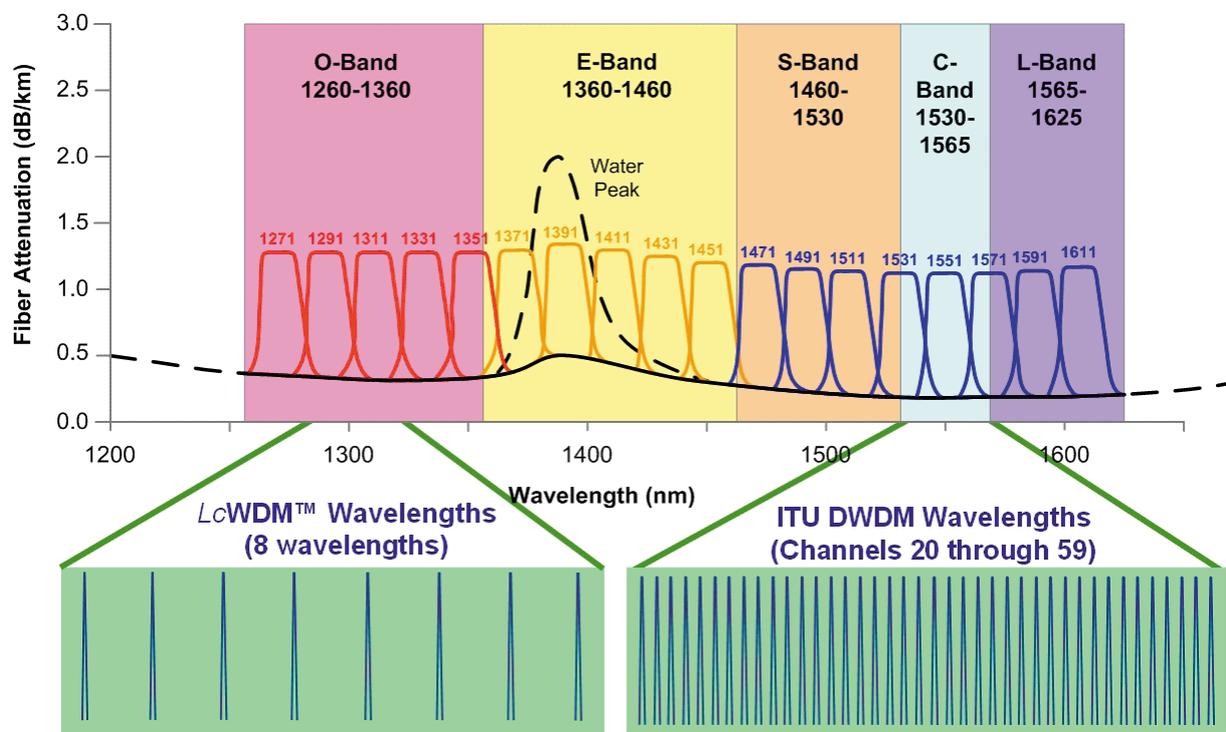


Figure 6: Optical bands used in telecommunication (Source: <http://a2net.eu>)

Figure 6 shows an attenuation profile across particular telecommunication bands that are shown in colour. A coarse WDM channel plan with respective central frequencies is shown at the top of the attenuation line. Backbone networks may use both C-band and L-band for transmission as both of bands are amplified by EDFA technology. Nevertheless, networks almost solely use the C-band because of well mature technology and reasonable costs. C-band may be divided into 80 DWDM channels with 0.4 nm (50 GHz) width. L-band would offer close to 150% of transmission capacity but at very high cost.

The C-band may thus carry as many as 80 standard optical channels with a bandwidth of 50 GHz. Such multiplexing increases the available capacity to 800 Gbps for 10 Gbps optical channels or even to 16 Tbps for 200 Gbps optical channels. The advancement from 10 Gbps to 200 Gbps has been achieved by the introduction of coherent modulation formats that better utilise IQ space than simple amplitude modulations. Constellation diagrams in IQ space are displayed in Figure 7.

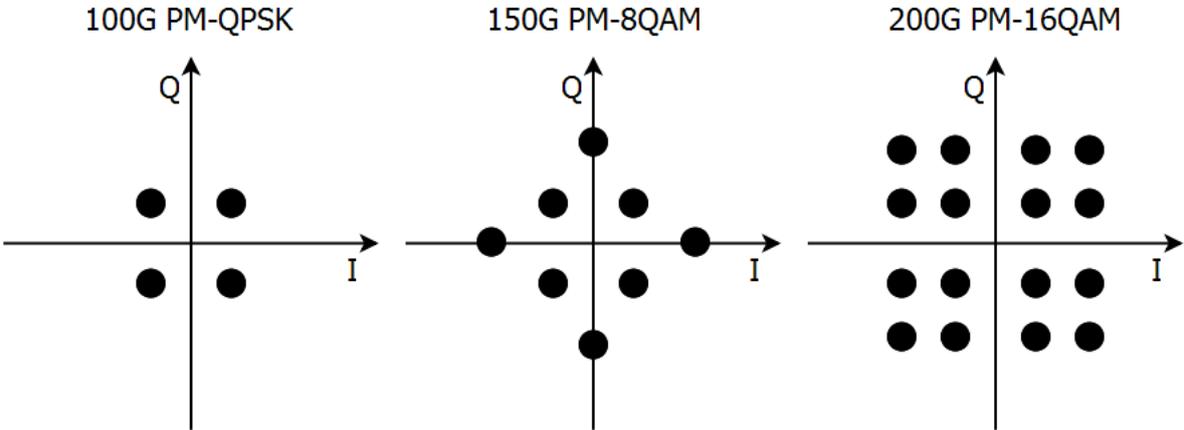


Figure 7: Constellation diagrams of typical coherent modulation formats in optical telecommunications.

Coherent optical modulations use polarisation multiplexing in two orthogonal states. The most promising solution for achieving a 400G service capacity is arranged on two carriers with 200 Gbps polarisation multiplexed 16-quadrature amplitude modulation (PM-16QAM). The symbol rate of these systems is running at 32 Gbaud.

Carriers for all mentioned modulations fit standard 50 GHz optical channel space and the advancements on channel rate are at the expense of optical reach. This type of trade-off has to be taken into account when designing long-haul networks.

2.1.2.2 Network Flexibility

A number of flexible network devices and system functions have been developed to increase network flexibility and simplify operations. Remote control and some intelligence have been introduced to almost all network elements. For instance, network ingress and egress ports support power equalisation and signal monitoring [23]. Some amplifiers are already equipped with mini Optical Time-Domain Reflectometers (OTDRs) [24] for immediate link evaluation in case of a signal drop. But, most significantly, important nodes host light switching devices called Reconfigurable Optical Add-Drop Multiplexers which allow certain optical channels to bypass a node when they target a different destination. Such functionality has a great impact on system consumption because

some traffic does not need to be processed in each node along the route. The key building stone of ROADMs is a Wavelength Selective Switch that switches optical channels to the right direction. The complexity of ROADM increases with a number of degrees and ROADM features. An example of four degrees ROADM is shown in Figure 8.

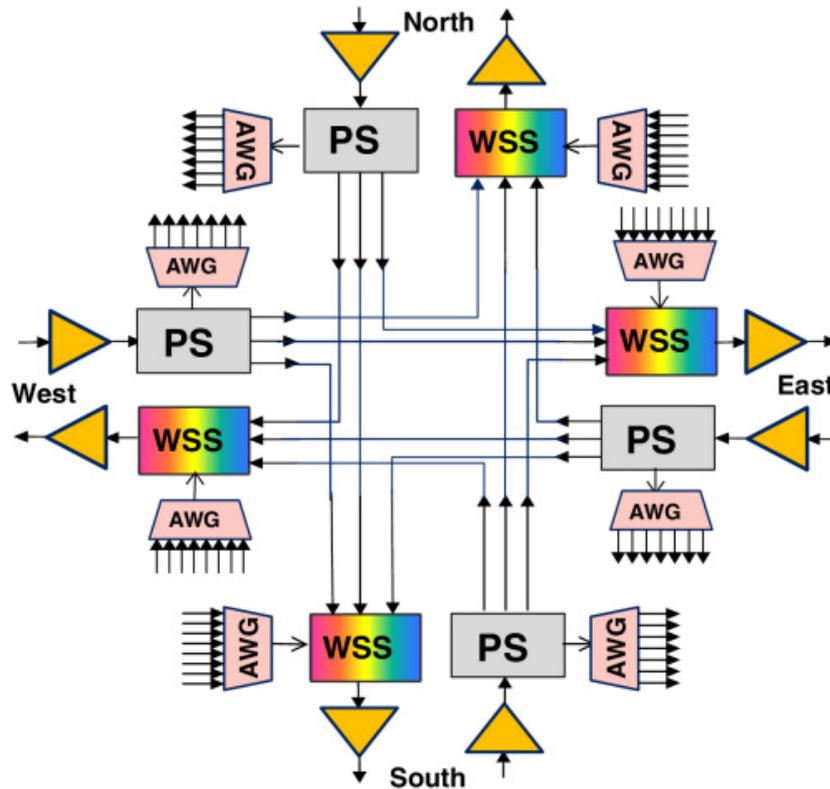


Figure 8: Classical four-degree ROADM architecture [27]

Each direction is equipped with a Protection Switch (PS), Wavelength Selective Switch (WSS) and Arrayed Waveguide Grating (AWG) demultiplexer. Modern ROADMs have three important networking features – Colourless, Directionless and Contentionless. Colourless is a feature of local add/drop ports to accept a wavelength tunable transponder with any wavelength. Directionless is a feature of local add/drop ports to route any wavelength in any direction. Contentionless is the latest feature that allows ROADM to add and drop the same wavelength to and from multiple directions.

Additionally, a flexible spectrum feature has been introduced as a reaction to bandwidth variable transceivers and super-channels. Elastic spectrum allocation with a granularity of 6.25 GHz may bring up to 30% of capacity improvement when combined with suitable signalling protocols [33]. The idea of super-channels is already supported by flexible spectrum for purpose of super-carriers with densely spaced subcarriers that employ orthogonal frequency division multiplexing (OFDM), see in Figure 9. In OFDM, neighbouring subcarriers are orthogonally modulated to minimise their crosstalk

[28]. The super-channel concept was first introduced by Bell Laboratories by S. Chandrasekhar and X. Liu back in 2009 [29]. The super-channel occupied a continuous spectrum of 300 GHz with a capacity of 1.2 Tbps. The system was working with the outstanding spectral efficiency of 3.7 b/s/Hz over a distance of 7200 km with Raman amplification. Since that time the idea of grouping several co-propagating signals that belong to a single service into a super-channel was tested in applied research. Nyquist-WDM Terabit super-channels of closely spaced sub-carriers with various phase modulations were analysed up to capacities of 27 Tbps [30] and improvement in Q-factor performance was suggested by employing multi-channel equalisation [31]. The flexible spectrum technology has been introduced by transmission system vendors recently [32].

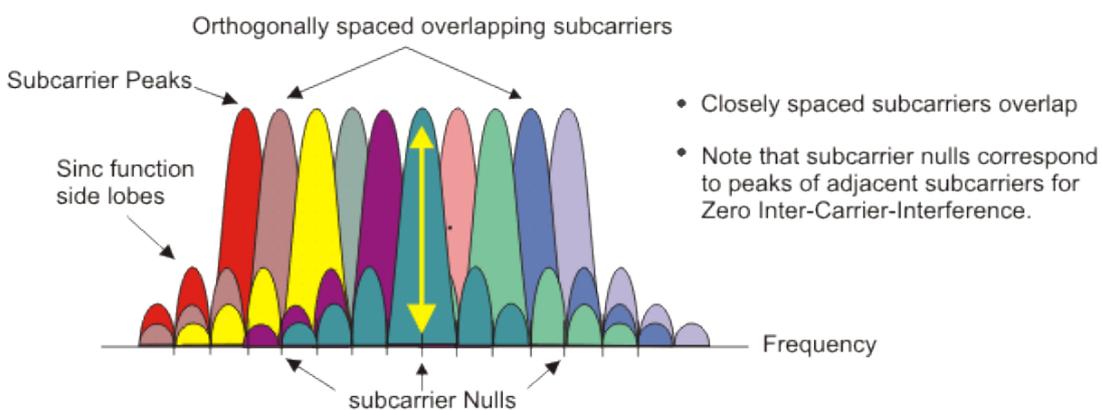


Figure 9: OFDM signal frequency spectra (source: keysight.com)

The step from a static DWDM channel plan has also been followed by network devices to allow flexible spectrum functionality at network nodes. Such nodes can accept a number of different services with various data rates and spectral occupation as shown in Figure 10. The spectral occupancy depends on a specific transmission technology. We measured several optical signals with extra high resolution of 0.04 pm, as can be seen in Figure 11. The signals are representing groups of signals that may be sharing spectrum in NREN networks. The first spectrum from left shows OOK modulation of 10 Gbps, second shows the first generation of phase modulated signals of 40 Gbps DPSK, third displays ultra-stable CW laser used for frequency transfer and last spectrum represent the first generation of coherent 100 Gbps of dual polarisation quadrature phase shift keying (DP-QPSK) without extensive spectral shaping. The modulation format spectra also vary from vendor to vendor.

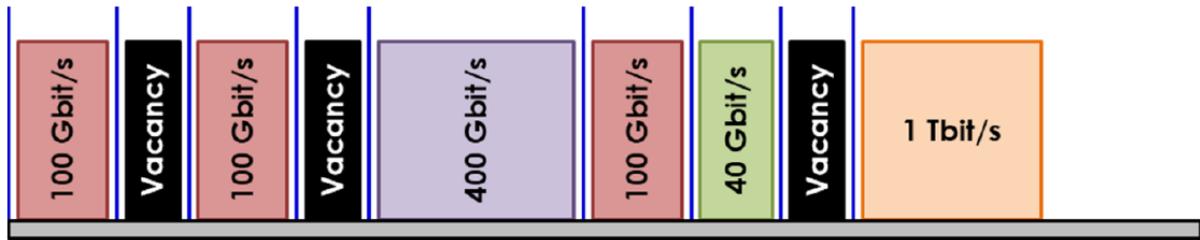


Figure 10: Flexible spectrum with super-channels (source: Fujitsu, 2015)

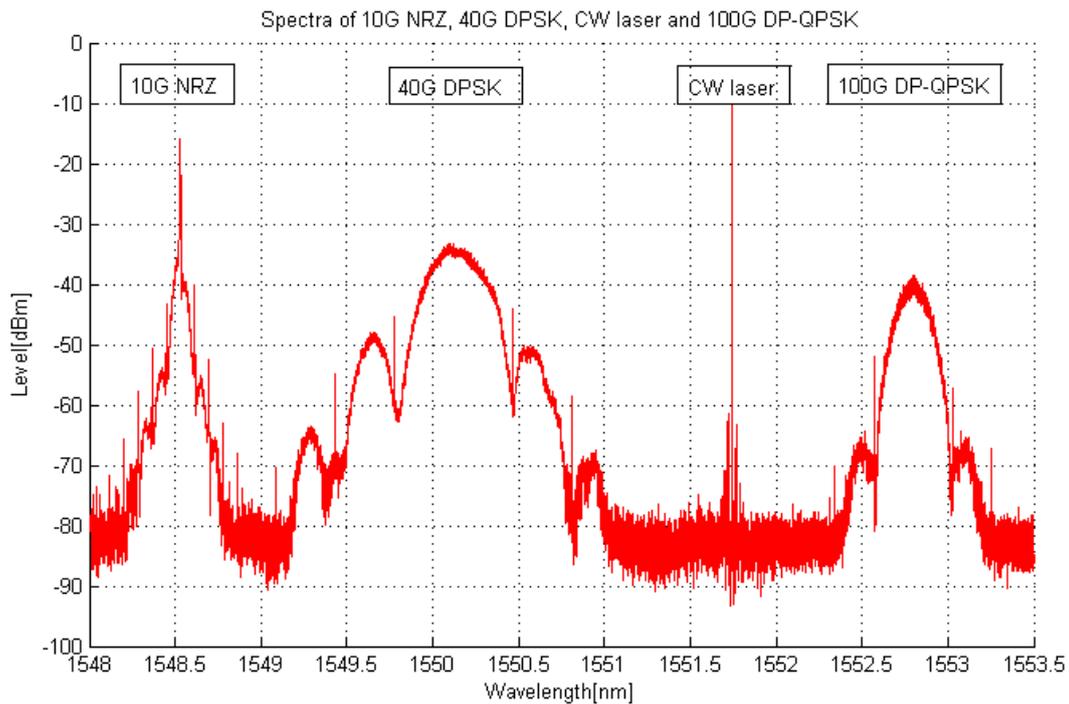


Figure 11: Measured optical spectra for different modulation schemes (from left 10 Gbps OOK NRZ, 40 Gbps DPSK, CW and 100 Gbps DP-QPSK)

2.1.3 Operation and Management System

The brain of an optical network is a centralised Operation and Management System (OMS) which is responsible for operations of all active network devices, the DWDM channel plan, fault reporting and maintenance [34].

NRENs provide, besides the connection to Internet, end-to-end (E2E) services with dedicated bandwidth to directly support academic end users. Such E2E services have a form of Virtual LAN connections, guaranteed capacity or even optical lambda channel. The true value of NRENs is in creating a connection to end users in other countries. Such a connection may be complicated

because NRENs have different transmission systems with their own OMS that do not communicate with each other. The gate between networks is usually a transponder. The first half of this device receives all information coming from one network and hands it over to the other part as an electrical bit stream. The other half of the transponder transmits a bit stream in the form of light to a second network. The transponder thus becomes a demarcation point between two networks and is used every time two networks from different vendors have to be joined. Table 2 provides information about transmission system vendors of European NRENs. The more extended version can be then found in the annexe A1. The actual size and complexity of each network reflect the needs and budget of particular NRENs. The fact that each NREN is building its network independently and with different aspects is reflected in the diversity of networks transmission systems throughout Europe [35][36].

NREN name	Country	DWDM Lighting technology
ACONET	Austria	Alcatel-Lucent
ARNES	Slovenia	Adva
CESNET	Czech Republic	Cisco, Open(CzechLight)
DFN	Germany	ECI
FCCN	Portugal	Huawei
FUNET-CSS	Finland	NSN, Ciena-Nortel
GARR	Italy	Huawei
GRNET	Greek	Alcatel-Lucent, ADVA
JANET	Great Britain	Ciena-Nortel
LITNET	Lithuania	Adva, Transmode
NIIF	Hungary	Alcatel-Lucent
PIONER	Poland	ADVA
REDIRIS	Spain	Alcatel-Lucent
RENATER	France	Alcatel-Lucent, Ciena
RoEduNet	Rumania	Ciena-Nortel
SANET	Slovakia	Infinera
SURFNET	Netherlands	Ciena-Nortel
SWITCH	Switzerland	Sorrento, BTI

Table 2: Transmission system vendors of selected European NRENs

Figure 5 shows the true multivendor environment of European NREN backbone systems. It shows that NRENS have deployed different transmission systems that may not be interconnected by their optical layers. It is easy to see that multinational E2E service may pass through several different transmission systems (network domains) to reach its destination. Some examples of advanced applications that are designed to cross several network domains are described in following sections.

2.2 Interactive human communication

Interactive human communication is supported by ITU-T recommendations G.107 [37], G.108 [38] and G.109 [39] that define the latency limit of up to 150 ms for any high-quality communication. Nevertheless, even speech quality is a relatively complex matter. When echo and loss are not present latency can be higher and users do not experience any discomfort even with latencies of up to 300 ms. It is worth mentioning that a latency of 200 ms is a widely accepted empiric value also supported by ITU-T recommendation G.114 [40]. Interactive human communication over networks considers voice and video services and online classes. Voice and video services also span from one way streaming to real-time video conversation. Classes and lessons range from online streamed webinars to interactive classes. Their sensitivity to latency is gathered in Table 3.

	Low sensitivity to latency	Medium sensitivity to latency	High sensitivity to latency
Voice and video Services	Simple voice and video streaming	<i>Voice and video messaging</i>	Real-time video and voice conversation
Classes and lessons	Class streaming	<i>Responsive classes, webinars</i>	Interactive classes

Table 3: Sensitivity of communication to latency

The most demanding examples of the Photonic Service application in this area are remote fine arts lessons (such as piano or violin lessons), where a teacher should be able to guide students according to visual and aural experiences delivered over the network. Fine arts lessons have been successfully tested in Brazil across the Atlantic Ocean (between Brazil and Spain) [41]. The piano master class was given by Prof. Jose Feghali in Brazil to piano student Eloi Marin in Spain. Performances were exchanged with HD video and audio system over 1 Gbps dedicated network capacity.

Musical concerts with musicians separated by hundreds of kilometres pose another challenge for high-quality audiovisual communication. A musician band performed a concert for two audiences and at two stages separated by a distance of 150 km [42]. One musician played trombone at a stage in Irvine and other two bass and piano players at a stage in San Diego. Performances were streamed by UltraGrid technology developed at CESNET at both stages for the full experience of both audiences. The transmission of UltraGrid streams fit in two gigabit lines delivering latency only around 1 ms related to signal processing. Latency and jitter are of great concern since one should distinguish negligible latency from that to which an end user can adapt [39]. The negligible latency value is given by sound propagation into the air and is related to the size of the orchestra. For example, negligible latency is about 5 ms for a chamber orchestra and 40 ms for a symphonic orchestra. Users should be able to adapt to latencies of up to 100 ms. The EU FP7 project entitled “Achieving LOw-LATency in Wireless Communications” (LoLa)[43] focused on low latency audio-visual applications over networks. New adaptations of PHY and MAC layers to achieve a lower latency of wireless communication were developed. A solution package for 5G systems was based on specific traffic scheduling and coordinated multi-point transmission and reception.

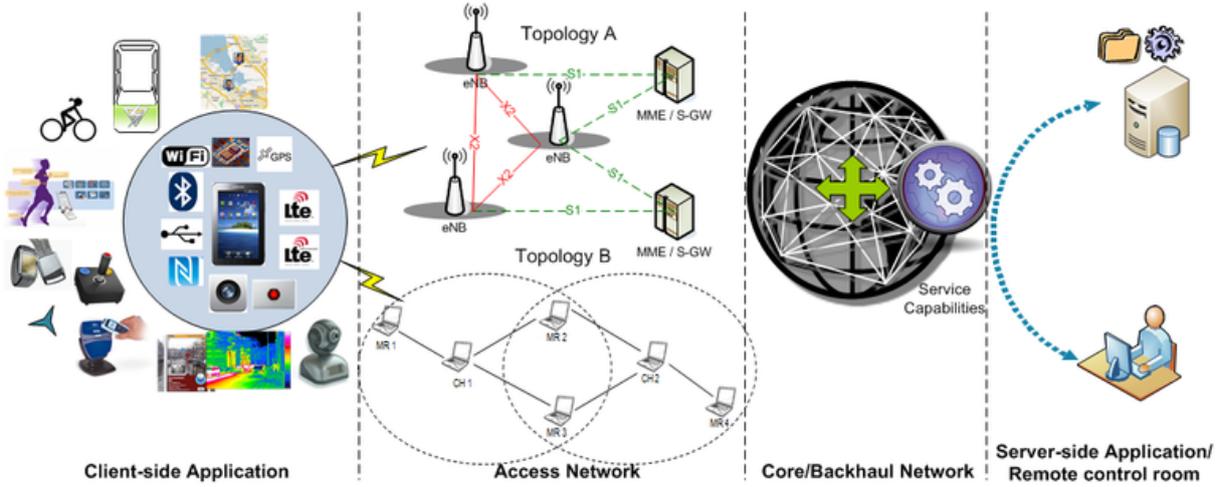


Figure 12: LoLa project topology for high-performance applications (source: ict-lola.eu)

Overall audio quality is also strongly dependent on the video codec used. Two techniques are generally applied to improve packet loss robustness and sensitivity to variation in the delay of received packets. The first - packet loss concealment technique [44] - masks the effects of packet loss from its simplest form, entailing the repetition of the last frame received, to the development of the most sophisticated algorithms with applied Hidden Markov Models. The second technique - an adaptive mode of playout delay buffer – then dynamically adjusts its value to the amount of latency

jitter present where this value is calculated as the duration of one frame multiplied by an integer number [45][47].

2.3 High definition video and Cave-to-Cave

A high-resolution video transmission of two 4K streams was realised over 10 000 km to San Diego CineGrid 2011 event [46]. The technology demonstration put San Diego audience in interactive control of walk-through 3D Langweil model of Prague. Figure 13 shows the Cave technology experienced by the audience at the CineGrid event in San Diego. The visualisation was provided by C2C software and controlled by the audience in San Diego.



Figure 13: Cave 3D experience of digitalized Langweil model of Prague (source: www.praha.eu)

Cave-to-cave and HD video have recently enabled doctors and students of medicine to watch on-line real-time high-resolution video of major surgeries and to enjoy the precise work of the most accomplished and experienced surgeons in the world. These high bandwidth applications usually require a dedicated Lambda to provide users with the full experience. A practical demonstration of 3D HD video transfer was accomplished by a CESNET team using a dedicated 10 Gbps link over a distance of 150 km from Ústí nad Labem Masaryk hospital to Charles University in Prague [48]. Figure 14 shows a robot-assisted operation on the left part of the figure and real-time transferred 3D HD video stream projection on the right part of the figure. The data stream reached transfer speeds of approximately 2.5 Gbps with a signal delay along the transmission stream of less than 1 ms, enabling truly real-time and interactive communication [48].



Figure 14: (left) Da-Vinci Surgical Robot in a remote hospital, (right) Real-time Transferred 3D HD video stream projection [48]

The same data from robotic surgery were transferred to Asia Pacific advanced Network (APAN) meeting in Hong Kong across international connections [49]. During technical tests, a big end-to-end latency difference between communication directions was observed. Troubleshooting revealed that information from Czech Republic travelled across Asia international links while responses from Hong Kong took the longer route over Pacific Ocean, United States and Atlantic Ocean.

2.4 Remote instrument control

New equipment and facilities are sometimes built in places extremely suitable in terms of measurement requirements but which are, unfortunately, not easily accessed by research staff. As an alternative to relocating experts to assist directly on the site, remote control of such instruments can save time and expenses. For a few examples, we can refer to a unique 2-m aperture observatory in India, which was built in the barren desert of Ladakh, see Figure 15, over 4500 metres above sea level [50]. The extreme high altitude causes serious health problems to astronomers carrying out observations. The observatory is remotely controlled in real time over a satellite link from CREST campus in Hasakote, Bangalore.

Also the highly specialised robot-assisted da Vinci surgical system with 3D HD view inside patient's body, which has been established in some of the most famous hospitals in the world [51]. The minimally invasive surgery combines a large variety of tiny surgical tools with the magnifying camera at rotatable joints allowing the surgeon to perform the operation under any angle and minimal space. A Strasburg hospital carried out a tele-surgery as far back as 2001 [52] when the robotic tele-surgery connected a surgeon from New York to a patient in Strasburg. The connection setup is in Figure 16, the round distance was approximately 14 000 km with round trip time of 200ms. The

connection was realised by an optical link with a dedicated capacity of 10 Mbps. It is worth mentioning that there were also experts ready on site to take over the manual control of the robot in case of network failure.



Figure 15: Himalayan Chandra Telescope (source: astroproject.in)

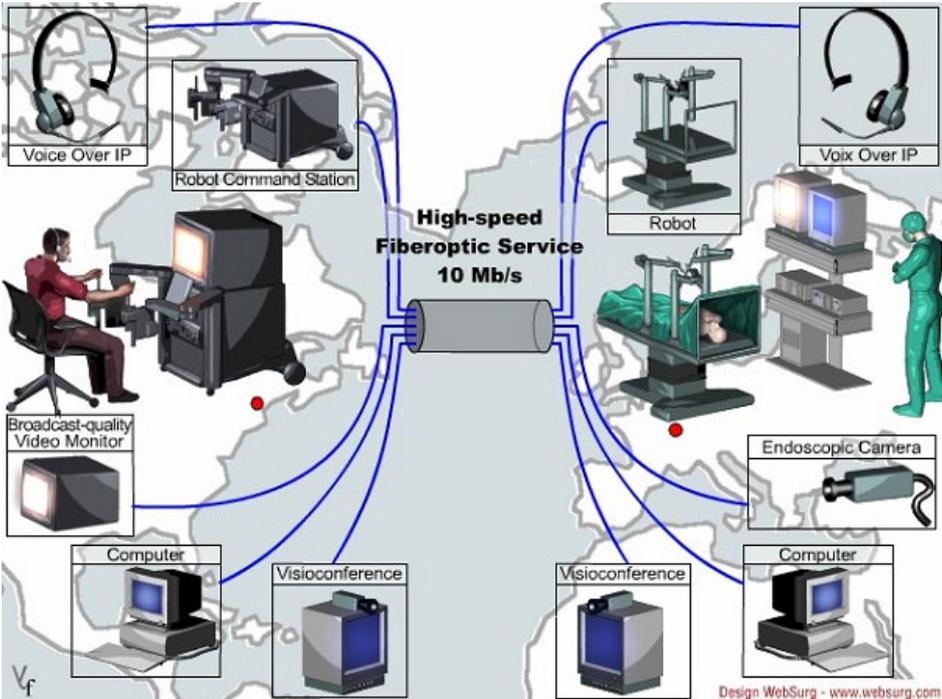


Figure 16: New York to Strasburg Tele-surgery setup [53]

The Aichi world exhibition of robotics and tele-surgery, see Figure 17, was held in August 2005 in Japan following this new trend. Most recently, a joint team consisting of our laboratory at CESNET and the Masaryk Hospital in Ústí nad Labem has demonstrated its experience with the transmission

of robotic surgeries from the Czech Republic to KEK—High Energy Accelerator Research Organization—IT centre in Tsukuba, Japan [54]. Although some applications may have low requirements on bandwidth and network latency, any interruption to the connection is unacceptable because it can directly endanger human life. This raises questions about connection stability and resiliency and it may be difficult to comply with these requirements using standard over-provisioned networks.



Figure 17: Tele-surgery at Expo 2005 Aichi in Japan (source: ai.stanford.edu)

2.5 Comparison of atomic clocks

Each country depends on its local approximation of UTC (Coordinated Universal Time) that is estimated from a set of time standards in the form of free running atomic clocks. These atomic clocks are usually Cesium clocks that are stationed in controlled environments of specialised laboratories. Each laboratory has to compare its own atomic clock with others to determine the actual time offset between the local atomic clock and the national approximation UTC. The time standard corrected by offset from UTC is distributed throughout the country to organisations relying on precise timing.

The preferred method of comparison of dislocated atomic clocks is radio signal over stationary satellites. Such a method requires complex communication instruments and suffers from atmosphere disturbances and satellite orbit drag [56]. Solar wind and consequently magnetic storms have an alarming impact on satellite orbits. Figure 18 shows a number of satellites off their orbit after the magnetic storm on 13.-14. March 1989. Advances in optical networking have opened a new method for comparison which utilises precisely timed light pulses that travel over an optical network to achieve resolution in the order of tens of nanoseconds [57].

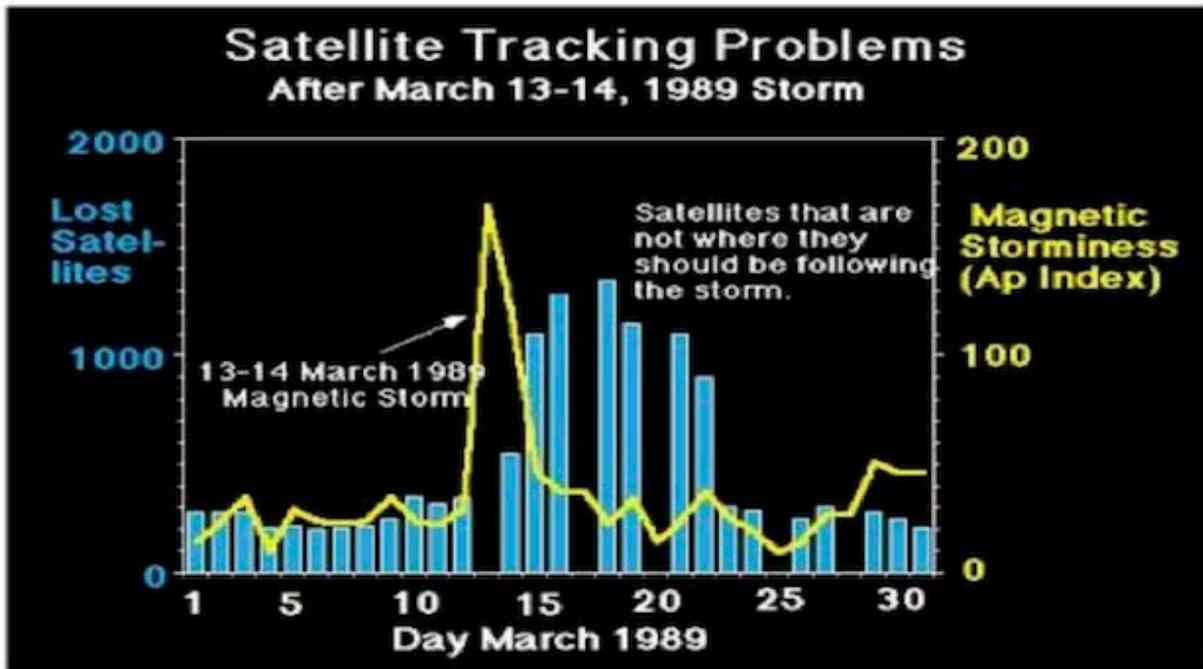


Figure 18: Number of satellites lost in connection with the March 13-14, 1989 storm (source: UCAR)

Traditional radio methods include TWSTFT (Two-Way Satellites Time and Frequency Transfer) utilising geostationary satellites for time and frequency transfer, or, a less accurate indirect method through a global navigation system, typically GPS (Global Positioning System) [75]. Recent advances in the photonic industry have also enabled optical transmission. Besides the utilisation of telecommunication protocols, e.g. SDH (Synchronous Digital Hierarchy), various methods based on photonic fibres have been reported, for example, the transmission of solitons, pulses from femtosecond lasers, a carrier modulated by RF or the direct transfer of stable carrier frequency [76]. Although the deployment of a dedicated infrastructure over long distances is very challenging in terms of economics, NRENs can offer free lambda channels for time transfer in their DWDM systems once their systems are capable of Photonic Services (specifically, once their networks become transparent to optical signals). These lambda channels can provide an alternative infrastructure for precise time transfer running in parallel with standard IP traffic.

2.6 Ultra-stable frequency transfer

The transfer of an ultra-stable frequency between two distant points is required by experts working in the fields of time and frequency metrology, astrophysics, particle accelerators and fundamental physics [58]. One straightforward and beneficial approach is to utilise NRENs that already connect

many research institutes and universities [59]. The successful transfer of ultra-stable frequency has been already demonstrated over a network with live traffic [60]. This application requires dedicated equipment in network nodes, but it is possible to run it alongside standard long-haul equipment. Any Optical-to-Electrical-to-Optical (OEO) conversion would violate this service since it requires special continuous-wave narrow-linewidth single mode lasers. The use of a mode-locked laser has been demonstrated over a 158 km link where both time and frequency were transferred together [61]. The sole frequency has been transferred over 1840 km by using very narrow single frequency lasers and highly specialised Brillouin amplification [62]. The achieved fractional frequency stability expressed as the modified Allan deviation was in the order of 10^{-19} for 100 s averaging. Similar fractional stability was achieved for a frequency comb but only at a much shorter distance of several km [63]. Although the performance of fibre stabilisation systems outweighs satellite stabilisation systems, availability and affordability of fibre infrastructure play a key role in final solution decision making. Therefore, it is of utmost important to learn how to share a spectrum of the current backbone network among standard digital data transfer and transfer of frequency signals.

2.7 Analysis of challenging and non-standard network applications

Taking known and future applications for Photonic Services that have been discussed above, three important parameters that can be derived from the needs of specific applications and their direct impact on the Photonic Services can be identified.

PHOTONIC SERVICE	LATENCY JITTER LIMIT	E2E LATENCY	PENALTY
Interactive human collaboration	10-50 ms (adaptive playout delay buffer)	100-200 ms	Mild (user disappointment)
High definition video and Cave-to-cave	20 ms (buffer dependent)	150 ms	Mild (user disappointment)
Remote instrument control	20 ms	100 ms	depends on the application (severe in the case of tele-surgery)
Comparison of atomic clocks	50 ps (fluctuation over 10 min) and 1 ns (fluctuation over days)	Should be minimised to signal propagation delay	Mild (experiment failure)
Ultra-stable frequency transfer	NA	Should be minimised to signal propagation delay	Mild (experiment failure)

Table 4: Recommended Values for Photonic Services Related to Tested Applications

The sensitivity of an application to electronic processing is described by the first parameter, “latency jitter limit”, representing the longest time between any two consecutive application data segments. This parameter places requirements on network devices and limits or excludes any OEO from the photonic-path of the Photonic Service. Real-time applications usually pose this kind of hard constraint on service timing. Applications may also be sensitive to the total time needed for information to reach its destination. Therefore, the parameter “E2E latency” is very important for synchronised performances. For example, interactive human communication may be affected when - exceeding this limit. The last parameter “penalty” represents the impact on users when limits of two previous parameters are exceeded. It ranges from mild to severe according to the reversibility and severity of its impact on the user. This parameter clearly distinguishes the critical performance of each specific application. Table 4 summarises the parameters for the applications mentioned above, based on our experiences of the implementation of Photonic Services.

2.8 Conclusion

National research and education networks are usually based on commercially available systems designed for telecommunication operators. But they have to evolve at all network layers to keep up with the demand of the academic community and to support novel applications. There are many high technology applications requested from the academic community, but some international end-to-end applications pose a real challenge to optical networking and, in particular, network interoperability. Such advanced applications of time and frequency transfer require not only network availability but also constant end-to-end latency. These requirements can be met either by extremely specialised hardware or a reserved optical channel without OEO regeneration. These applications are then highly susceptible to traffic congestion and wavelength contention at network nodes. An optical processing device that would change a wavelength of an optical signal in the optical domain would be a convenient solution.

3 Optical techniques for signal regeneration

Every signal propagating through optical fibres experiences distortion through its interaction with optical fibre materials. At some point, a propagation signal reaches a place where it needs to be regenerated to be successfully received at its destination. A common way to regenerate a signal is OEO conversion. A signal is detected by an appropriate detector, regenerated, usually by 3R (amplitude, shape and timing) in the electrical domain, and retransmitted back into the optical domain. Demands on electronics performing the regeneration scales with optical transmission rate turn out to be very challenging for the high-rate state-of-the-art signals because electronics do not scale in rates as well as optics. Therefore, networks are designed to amplify optical signals along their path with EDFAs to prolong signal reach and avoid OEO.

Signal regeneration in the optical domain promises to overcome the bottleneck in electronic processing. Although there have been several optical regeneration techniques introduced, none of them has been successful in commercial application. Paragraph 3.1 discusses the utilisation of nonlinear effects in optical fibres for signal processing.

3.1 Nonlinear phenomena for all-optical processing

Signals in an optical fibre are influenced by many effects such as attenuation, chromatic dispersion, polarisation mode dispersion (PMD), self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM) [65]. Attenuation and chromatic dispersion have a linear character and may be easily removed by digital signal processing at the receiver side. Stochastic effects such as PMD are negligible for modulations with a repetition rate up to about 10 GHz. The higher rate modulations of hundreds of Gbps employ also digital signal processing to overcome stochastic PMD effects. Finally, the nonlinear effects SPM, XPM and FWM are mitigated by keeping peak powers of optical signals under 20dBm. A full summary can be found in Table 5.

Effects on signal	Character	Mitigation
Attenuation	Linear	Amplification
Chromatic dispersion	Linear	Dispersion compensation
Polarization mode dispersion	Stochastic	Fibre design
Self-phase modulation	Non-linear	Low powers
Cross-phase modulation	Non-linear	Low powers
Four-wave mixing	Non-linear	Low powers

Table 5: List of selected effects that influence signal quality in optical communications

The last three nonlinear effects have the potential for optical signal processing and will be discussed in detail in the following paragraphs.

3.2 Study and measurements of nonlinear effects

Although optical communication struggles to mitigate non-linear effects, new technologies often exploit nonlinear phenomena to unlock special features. The nonlinear phenomena originate from the interaction between light and matter in the optical waveguide. The transmission media for optical backbone networks are optical fibres thanks to their extremely low attenuation of light carrying information. The optical fibre is also a dielectric medium that behaves nonlinearly in the presence of high optical powers. The electrical field of propagating light induces polarisation of light P given by [64],

$$\vec{P}(E) = \varepsilon_0(\chi_1\vec{E} + \chi_2\vec{E}^2 + \chi_3\vec{E}^3 + \dots) \quad (1)$$

where ε_0 is permittivity of vacuum, E is a vector of the intensity of electrical field and χ_n is the n-th order of susceptibility [64]. The dielectric media behaves linearly for small intensities where only the first term from equation (1) is accounted. When the intensity is increased gradually, the second, the third and higher terms are considered. The second term is negligible for center-symmetric structures as optical fibres are, so the most important nonlinearity in optical fibres is the third term of (1). Higher terms are negligible for powers acceptable for optical fibres and therefore are excluded from this analysis.

In the case of spectral width of an optical signal that is much smaller than its carrier frequency, the vector of the intensity of electrical field can be expressed as [65]

$$\vec{E}(t) = \bar{E}(t)\exp[j2\pi\nu t] \quad (2)$$

where ν is the carrier frequency and the complex envelope is defined as [65]

$$\bar{E}(t) = \vec{x}\bar{E}_x(t) + \vec{y}\bar{E}_y(t) \quad (3)$$

where \vec{x} and \vec{y} are orthogonal unit vectors with respective terms of the electric field envelope [65]. These terms can be expressed in [65]

$$\bar{E}_{x,y}(t) = E_{x,y}(t)\exp[j\phi_{x,y}(t)] \quad (4)$$

with ϕ representing the phase of the electric field and $E(t)$ its amplitude of respective terms [65]. The total phase of a signal after distance L in a dielectric medium is described by its refractive index in [64]

$$\phi = n(I)\frac{2\pi}{\lambda}L \quad (5)$$

where the intensity of the optical signal is equal to the square of the envelope of the intensity of electrical field $I(t) = |\bar{E}(t)|^2$ [64]. The dependence of the refractive index on optical intensity is called Kerr's optical effect and can be written as [64]

$$n(I) = n + n_2I \quad (6)$$

where n is the refractive index of dielectric media for a given signal frequency and n_2 is the nonlinear part of the refractive index [64]. It is related to the third order of electrical susceptibility of an optical fibre [65]

$$n_2 = \frac{3}{8n}\chi_3 \quad (7)$$

By combining equations (5)(6)(7) we see that an optical signal with high intensity modulates its own phase

$$\phi = \frac{2\pi}{\lambda}L(n + n_2I) \quad (8)$$

This effect is called self-phase modulation (SPM) and refers to the influence of the second term in the equation (8). It is, therefore, possible to create, for example, Kerr-lens [64], a medium that focuses high-intensity signals while leaving low intensities intact.

Moreover, an intense optical signal changes the refractive index of dielectric media that, in return, changes its own phase in the same way as the phase of any other present optical signal. Such an effect is called Cross-Phase Modulation (XPM) [65] and for two signals with intensities I_1 and I_2 this results in a refractive index for the first signal [65]

$$n(I_1, I_2) = n + n_2(I_1 + 2I_2) \quad (9)$$

and, consequently, the phase of the first signal will be [65]

$$\phi_1(I_1, I_2) = \frac{2\pi}{\lambda} L(n + n_2 I_1 + 2n_2 I_2) \quad (10)$$

Constant 2 in the last term of equations (9) and (10) is valid for co-polarized signals, while it becomes 2/3 for orthogonal polarisations. If both signals are intensive enough, they will influence each other's phase. A similar effect of the mutual influence of two co-propagating signals also appears in gain media of Semiconductor Optical Amplifiers (SOA). Two signals in gain media of SOA share the gain potential of SOA and, therefore, one signal without the other is amplified by the gain of SOA, although in the presence of a second signal, the gain is shared. This Cross-Gain Modulation (XGM) results in a rather complex imprinting pattern of one signal upon the other and vice versa. Fortunately, XGM only happens in gain media with a short upper-state lifetime and not, for example, with EDFAs.

Optical signals can also interact through dielectric media if their parameters are properly aligned. One such case is called Four-wave Mixing (FWM). Two signals at frequencies ω_1 and ω_2 interact in media and create two other signals at ω_3 and ω_4 . This interaction must comply with the following conditions [64]

$$\omega_1 + \omega_2 = \omega_3 + \omega_4 \quad (11)$$

$$k_1 + k_2 = k_3 + k_4 \quad (12)$$

where $\omega_{1..4}$ are frequencies of mixing signals and $k_{1..4}$ are respective wavenumbers [65]. Equation (11) determines the frequencies of newly created signals while equation (12) addresses the fact that mixed signals have to be reasonably close in frequency. FWM can be also explained by particle optics, where two photons at frequencies ω_1 and ω_2 are annihilated and two other photons at frequencies ω_3 and ω_4 are created. If we multiply equations (11) and (12) by the reduced Planck constant \hbar , we get energy and momentum conservation laws for the FWM process. A model spectrum of FWM is shown in the left part of Figure 19.

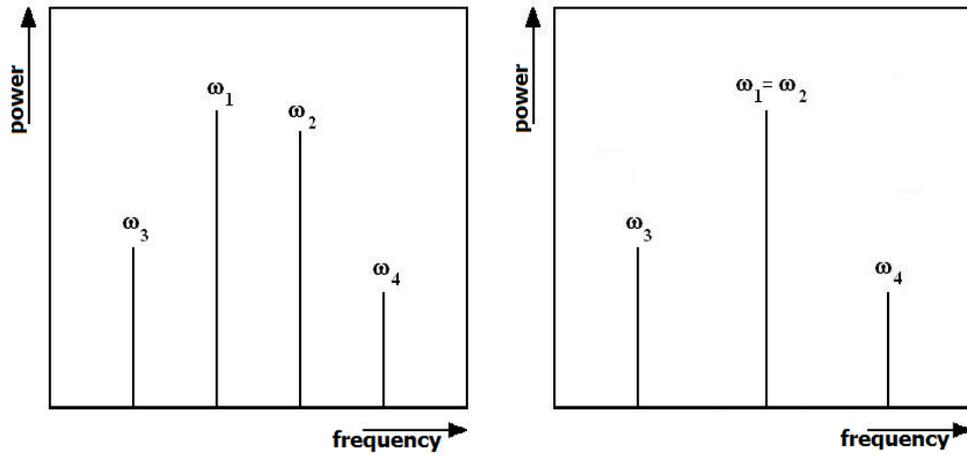


Figure 19: Model spectrum of full Four-wave Mixing phenomena (left) and its degenerate version (right)

An application of FWM is parametric amplification. This process is also sometimes called degenerate FWM as only three signals interact together. Model spectrum can be seen in the right part of Figure 19. Again, an explanation by particle optics is quite straightforward. Two photons from a signal at frequency ω_1 interact in a dielectric medium, annihilate and create one photon each for signals at frequencies ω_3 and ω_4 . It is, nevertheless, necessary that at least a weak signal at frequency ω_3 or ω_4 is present in the medium. Photons created at frequency ω_3 are coherent with photons of the weak signal and therefore amplify it.

The FWM effect can also be used for wavelength conversion (WC). Such a process replicates a signal at frequency ω_2 to frequency ω_3 and creates an idler signal at frequency ω_4 that is also carrying the information of the original signal. Specific details about optical signal processing devices will be discussed in the following chapters.

3.3 Optical signal processing

Signal processing devices modify parameters of the input signal and perform logical functions. Optical signal processing devices do the same just in the optical domain without converting the optical signal into its electric representation. Such processing usually involves the interaction of two or more light signals together through a nonlinear optical media. In following subchapters we are introducing three processing concepts - nonlinear optical loop mirror (NOLM) that performs a switching function, optical parametric amplifier (OPA) that selectively amplifies a signal of choice and wavelength converter that replicates a signal at a new wavelength.

3.3.1 Nonlinear optical loop mirrors

A nonlinear optical loop mirror is a device reflecting all input signals back from where they came until the input signal is powerful enough to switch the NOLM and let the input signal pass to the output. NOLM has the structure of optical fibre Sagnac interferometer as shown in Figure 20. The functionality is based on splitting input signals equally in their respective clock-wise and counter clock-wise parts in an optical coupler and their interference at the optical coupler after propagation through a fibre loop. For small powers and use of standard optical fibres, the NOLM reflects input signals acting as perfect mirror [66]. When input signals power rise to a certain level the NOLM will no longer function as a mirror and let all signals pass. The transmissivity of NOLM is found to be [67]

$$T = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_{in}L]\} \quad (13)$$

where ρ is a fraction of input power in one direction (related to splitting ratio of fibre coupler), γ is a nonlinear parameter of fibre in the loop of length L and P_{in} is input power. Clearly for 100 m of highly nonlinear fibre loop with γ of $10 \text{ W}^{-1}/\text{km}$ the input power should be above 31 W for NOLM to switch and light to be passed on [66]. Further improvements may be achieved by inserting EDFA and HNLF into fibre loop. Then required input power may be below 1 mW for 4.5 m of Nd-doped fibre in 306 m long loop [68]. Similar performance may be achieved by inserting asymmetrically placed semiconductor optical amplifier into 17 m long loop [69]. Recently this concept has been used in the 2R regeneration of 50% duty-cycle return-to-zero differential phase shift keying (RZ-DPSK) [70]. Signal enhancement of 1.5 dB by removing some accumulated amplified spontaneous emission was demonstrated by improving eye-diagram of RZ-DPSK signal.

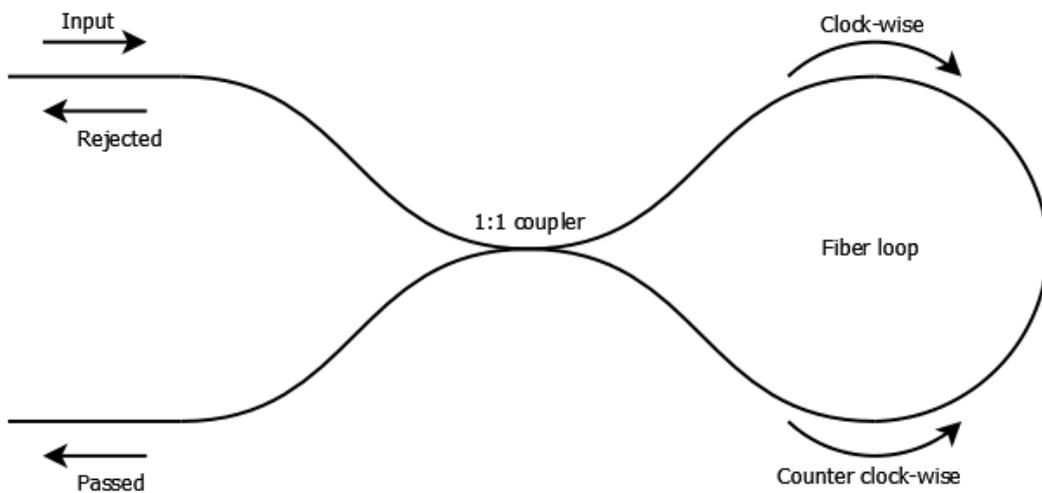


Figure 20: Nonlinear optical mirror loop

3.3.2 Optical parametric amplifiers

Optical parametric amplifiers are devices selectively amplifying input signals by transferring power from the optical pump to desired signals. OPAs are essentially based on degenerate FWM effect where four photons interact with optical media as displayed in Figure 19. Two photons belong to a pump signal, one to input signal and one to idler signal that is created during the process. All interacting photons have to satisfy the phase matching condition [66]

$$\omega_{idler} = 2\omega_{pump} - \omega_{signal} \quad (14)$$

where ω stands for respective photon's frequency. The gain of optical parametric amplifier may be expressed as [66]

$$G \approx \frac{1}{4} \exp(2\gamma P_{in}L) \quad (15)$$

where P_{in} is power of pump and signal together. The equation (15) insists that the gain rises exponentially with pump power, but a number of assumptions have been taken into account. Firstly, gain saturation and pump depletion effects have been neglected for simplicity of calculation. Secondly, the performance of the amplifier is very sensitive to parameters of nonlinear media and expects pump frequency to be very close to the zero-dispersion wavelength of nonlinear media. Unfortunately, gain profile of a single pump optical parametric amplifier is quite narrow which limits amplifier applications [66].

This problem is overcome in dual pump setup which extends flat gain region to tens of nanometres. In 2003 the parametric amplification of 40 dB was realised in 1 km of highly nonlinear fibre over a bandwidth of 34 nm [71]. More recently extremely low noise gain of 10 dB was realised over 170 nm of four telecommunication bands S-, C-, L- and U-band [72]. Although parametric amplification offers interesting features it is still limited to amplification just low number of optical channels that limits its deployment in nowadays transmission systems with WDM.

3.3.3 Wavelength converters

Wavelength converter is a device transferring information from an input signal to a signal at a new wavelength. Converters are usually based on optical fibres or semiconductor optical amplifiers. Further, they may combine nonlinear effects mentioned in section 3.2 with interferometry setups. For instance, NOLM may become a wavelength converter by inserting input signal to fibre loop rather

than sending it to original NOLM input as can be seen in Figure 21. The phase of input CW signal is modulated by XPM in nonlinear media of fibre loop by the data signal. Such phase modulation of CW signal will result in misbalancing NOLM and translate inscribed phase modulation into amplitude modulation of CW signal at the output of NOLM. A wavelength conversion of the signal in NOLM was realised over a range of 26 nm with pulses of 500 fs in just 50 m of highly nonlinear fibre [73].

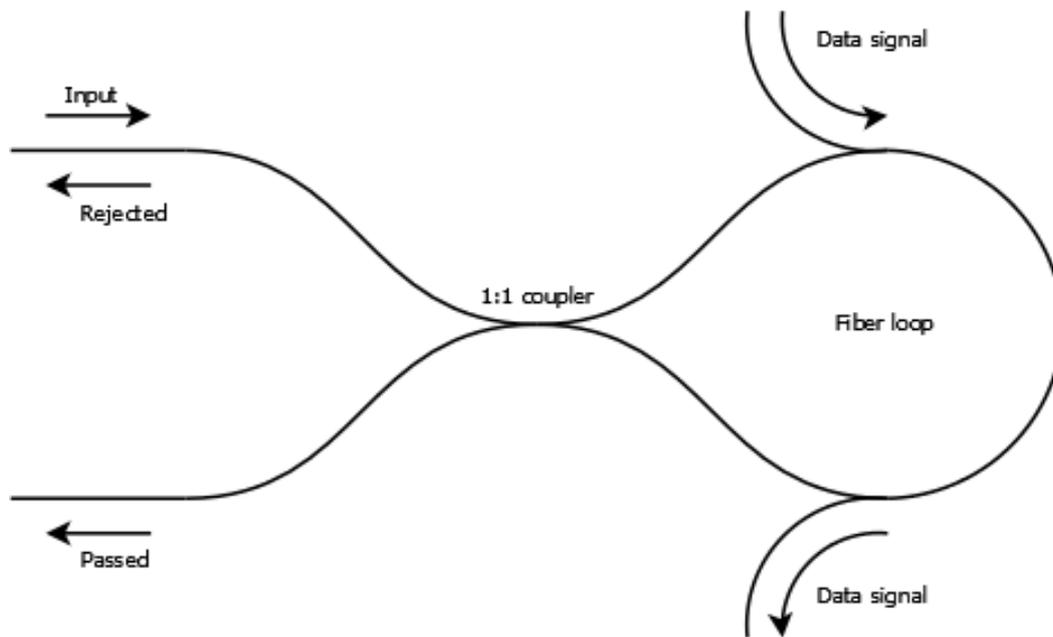


Figure 21: Wavelength converter schematic in NOLM

Another option takes advantage of spectral broadening a CW probe signal due to imprinted phase modulation through XPM. This method requires sharp filtering of probe signal spectrum as shown in Figure 22. CW probe signal and pump signal with amplitude modulated data are interacting in highly nonlinear fibre (HNLF) that results in XPM of CW probe signal. The phase modulation of CW signal is inherently connected to its spectrum broadening. The application of sharp tunable band-pass filter (TBPF) will suppress CW probe and pump signals and pass just part of broadened spectrum of probe signal, see right part of Figure 22. This principle was able to convert 10 Gbps signal across 15 nm in highly nonlinear fibre with holey core utilising its normal dispersion region [74].

More wavelength converters employing semiconductor optical amplifiers or FWM effect are described in following chapters together with our own measurements.

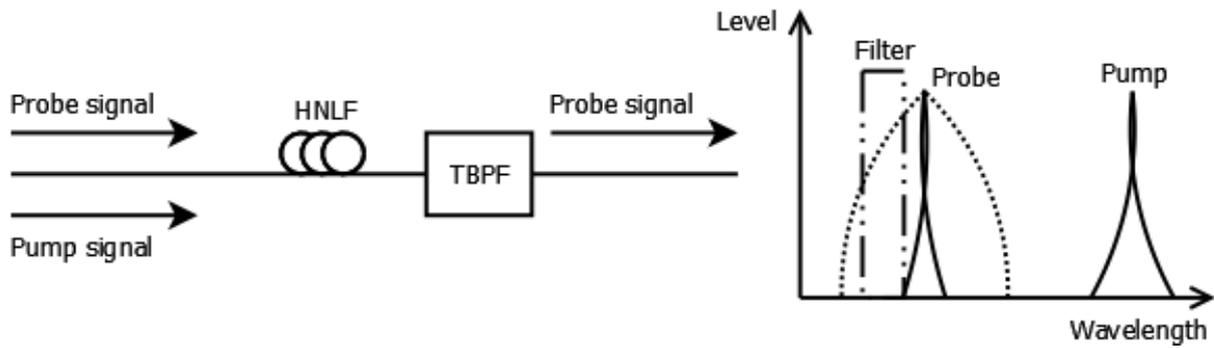


Figure 22: (left) setup of XPM wavelength converter setup, (right) schematic of spectral filtering of XPM broadened spectra of Probe signal

3.4 Wavelength contention in optical networks

An advanced application connecting two distant end users is likely to cross several network domains. Each network domain usually has a different channel plan for their traffic and the frequency band assigned to the advanced application may already be allocated to some other service. Such a status is called frequency band contention or wavelength contention. In order to resolve the contention the local traffic may be reengineered, which often requires the direct involvement of the Network Operation Centre and sometimes the manual deployment of new network equipment. A convenient option is a wavelength conversion that shifts the signal to a suitable wavelength in a free frequency band. Solutions for the wavelength conversion are discussed in following paragraphs.

3.4.1 OEO conversion as a general approach

Standard wavelength conversion method to solve wavelength contention is OEO regeneration. Network nodes may have spare transceivers that perform wavelength conversion through OEO regeneration if necessary. This increases the cost of the network to include standby transceivers or requires a considerable engineering effort for static networks to install spare transceivers in right nodes. This approach is feasible for low rate signals, but higher rate interfaces of 100Gbps and more are both very expensive and power hungry. Purely optical regeneration at these rates and complex modulations is still subject to intensive research. Some results were achieved in Southampton Optoelectronic Research Centre for differential phase shift keying signals where phase noise was improved by about 10 dB [82]. Improvement on the signal pattern is seen in Figure 23. Demodulated eye diagrams after balanced detection and differential constellation diagrams (showing bit-to-bit

phase changes) are measured at 10 Gbps. Diagrams are measured at input and output of regenerator respectively.

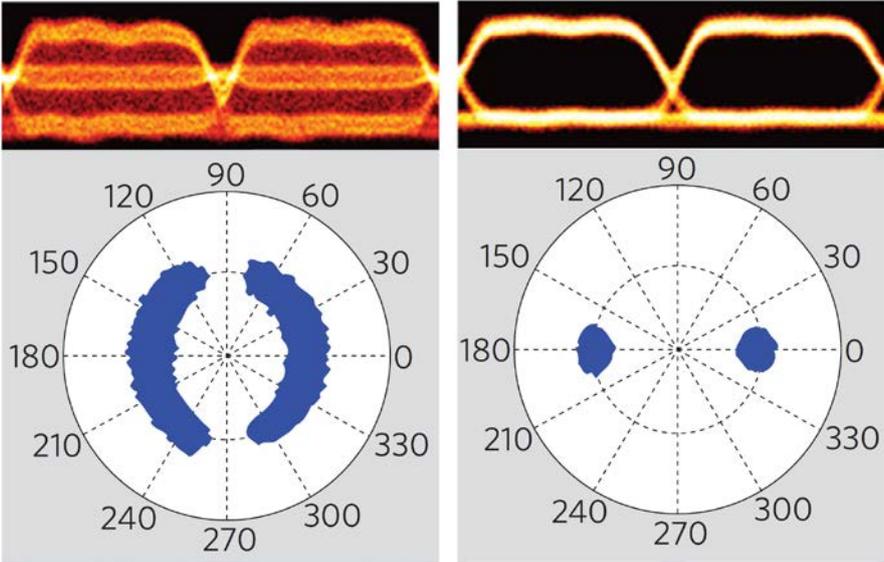


Figure 23: Demodulated eye diagrams after balanced detection and differential constellation diagrams (showing bit-to-bit phase changes) are measured at 10 Gbps. Diagrams are measured at input and output of regenerator respectively.

3.4.2 Wavelength converter with SOAs

As stated above, nonlinear effects require a suitable medium for them to take place. One option is the use of Semiconductor Optical Amplifiers (SOA) that, in addition to nonlinear interaction, also provides optical gain. Such wavelength converters combine SOAs with a Mach-Zehnder Interferometer (MZI). The idea of wavelength conversion is based on XPM and may be well understood from Figure 24.

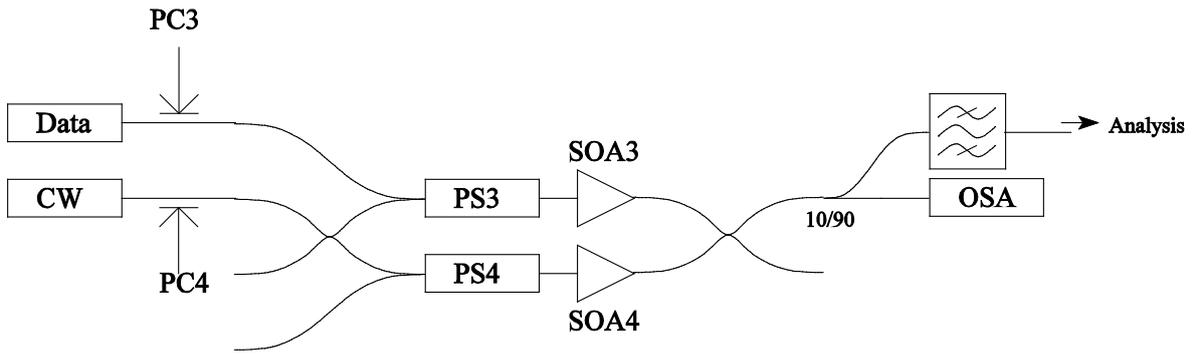


Figure 24: Wavelength conversion scheme with SOAs and Mach-Zehnder interferometer

At the beginning, we introduce only the CW signal to the MZI structure and balance it in a way that it destructively interferes at the analysing port (the one heading to an optical spectrum analyser (OSA) and interferes constructively at the other port with the blind end. The balanced MZI structure may now be outweighed by introducing the data signal to an upper arm of MZI. The data signal is present in SOA3 together with a CW signal and changes the CW's phase through XPM in a nonlinear medium of SOA according to the data pattern. The phase change induced by the data signal to the CW signal then results in the constructive interference of the CW signal at the analysing port. Therefore, the CW signal appears at the output port for analysis only when the data signal is present copying the data pattern. The performance of the mentioned WC during the conversion of the signal over 4 channels can be seen in Figure 25.

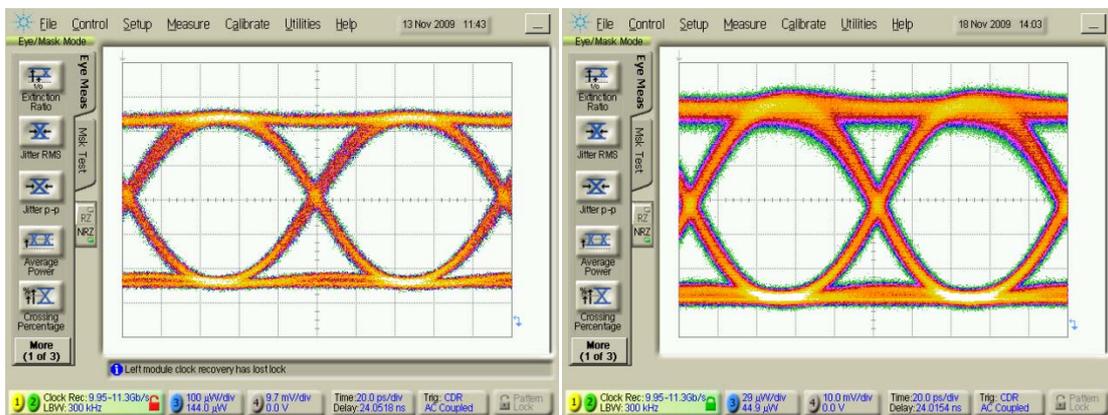


Figure 25: (left) Eye diagram of the Data signal at 1551.72nm, (right) eye diagram of the converted signal at 1548.51nm

Figure 25 shows an eye diagram of the original data of the data signal with a clear pattern on the left. The image on the right displays an eye diagram of converted data to the new wavelength of the CW signal. Although the presented converted signal quality is comprehensive and this type of WC is a promising candidate, it still faces some challenges. First of all, the data signal has to be amplitude modulated. Although the amplitude modulation is the most wide-spread modulation in current backbone networks, the trend tends to favour state-of-art coherent modulations that offer better parameters for long-haul networks. Secondly, the dynamic range of the input signal is limited to just several dB and the signal to noise ratio is not usually better than 25 dB [95]. Further, there is complex dynamics of SOA gain especially for high symbol rates above 40 Gbps and polarisation dependency of SOA behaviour as we found in [96].

3.4.3 Wavelength converter with FWM

Another nonlinear phenomenon offering wavelength conversion is FWM which incorporates the important advantage of transparency to a data signal for meeting stricter signal alignment. The transparency of a data signal means that FWM will convert both amplitude and phase modulated signals regardless of their bit rate or modulation scheme. The stricter signals alignment represents the need to fulfil both conditions (11)(12). A simple scheme to measure conversion efficiency for available components has been set up according to Figure 26.

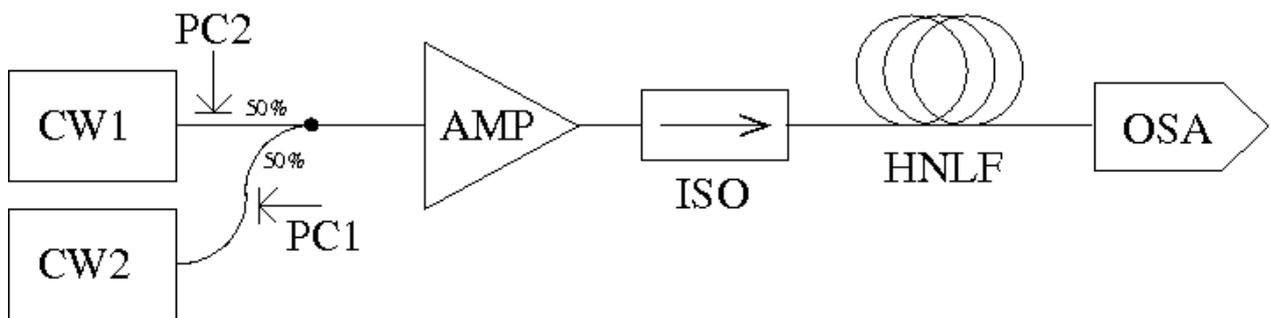


Figure 26: Setup for the measurement of conversion efficiency

Two laser sources CW1 and CW2 produce two continual signals at 1568.5 nm and 1579.2 nm. Two polarisation controllers PC1 and PC2 are used to align the polarisation of signals before they are coupled to an optical amplifier. Amplified signals pass an optical isolator and propagate through

500m of Highly Nonlinear Fibre. The two signals interact through a nonlinear medium to give rise to new signals. A measured optical spectrum is shown in Figure 27.

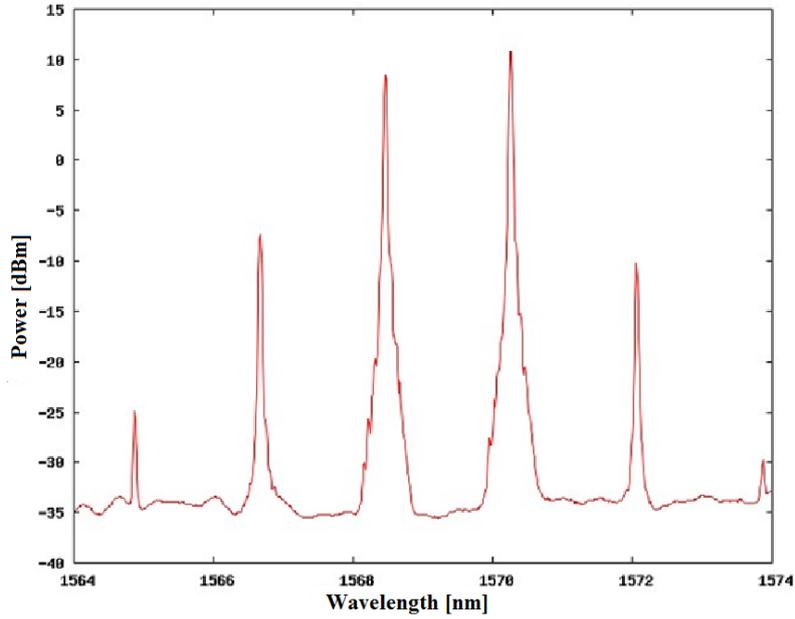


Figure 27: Spectrum of FWM interaction in a nonlinear medium

The figure shows that nonlinear interaction gave rise to four new signals that could be used for wavelength conversion. The efficiency of FWM is dependent on the power of interacting signals and their distance in wavelength. Figure 28 displays conversion efficiency for four wavelength distances of the two interacting signals. The signal was fixed at wavelength 1568.36 nm and pump wavelength was varied +1, +3, -1 and -3 channels (0.8 nm) at 100 GHz grid. All four settings have similar efficiency for each level of amplifier output power. The efficiency rises steeply until it reaches about 15 dBm of the optical amplifier output power for our setup. Then the slope relaxes as Brillouin scattering become important. The value of conversion efficiency for -1 channel detuning and 15 dBm of amplification power output is a measurement error not connected to any physical process. Generally, conversion efficiency is a function of fibre length L , nonlinear coefficient γ and input optical power P_{in} [66]

$$\eta = \left(\frac{\gamma P_{in}}{g} \right)^2 \sinh^2(gL) \quad (16)$$

where g is parametric gain equal to [66]

$$g = \sqrt{(\gamma P_{in})^2 - \frac{\kappa^2}{4}} \quad (17)$$

where κ is total phase mismatch defined as [66]

$$\kappa = \beta(\omega_s) + \beta(\omega_i) - 2\beta(\omega_p) + 2\gamma P_{in} \quad (18)$$

where β is propagation constant related to signals at frequencies ω_s , ω_i , ω_p that are referring to three signals of degenerate FWM ω_3 , ω_4 , $\omega_1 = \omega_2$ from Figure 19. Experimentally, conversion efficiency may be estimated from optical powers of signal before nonlinear media $P_s(0)$ and optical power of converted idler $P_i(L)$ after nonlinear media of length L [66]

$$\eta = \frac{P_i(L)}{P_s(0)} \quad (19)$$

We used this formula for our measurement of conversion efficiency.

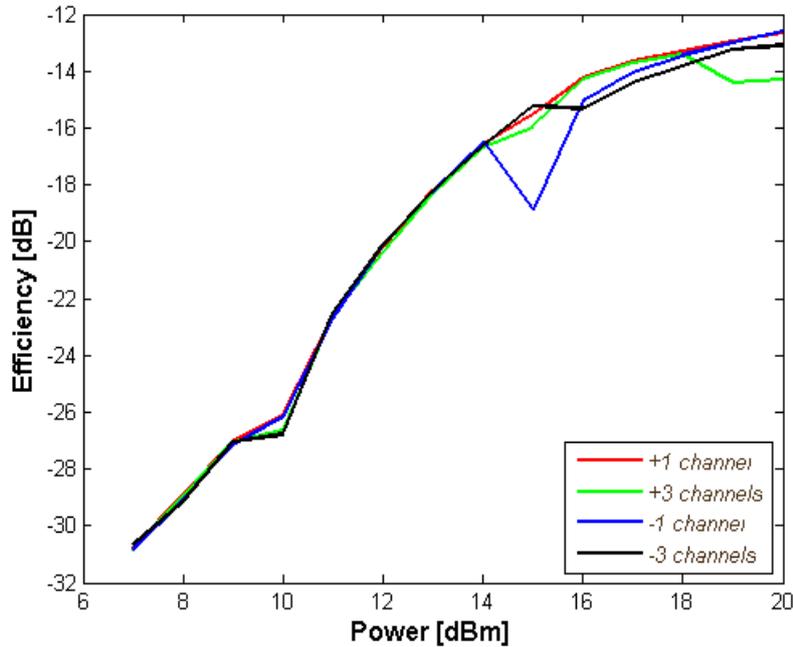


Figure 28: Conversion efficiency of FWM for several distances of two interacting signals

3.5 Conclusion

A variety of effects influences optical signal during its propagation through optical fibres. Some of them have nonlinear character and may be utilised for optical signal processing. XPM and FWM have been evaluated in terms of their flexibility and performance. Although XPM takes advantage of gain from SOA structures to have excellent conversion efficiency, it is limited to amplitude modulated signals. FWM, on the other hand, has negative conversion efficiency, but is not limited by modulation format and, therefore, is promising for a wider range of applications.

The proposed optical signal converter to validate the concept of Photonics services will take the best advantage of flexibility and wide applicability. We, thus, have chosen FWM effect for an optical signal converter although the time transfer application uses amplitude modulated signals. Therefore, our proposed optical signal converter will be based on the FWM effect.

4 Thesis objectives

The main objective of the dissertation thesis is to propose and demonstrate a novel generalised **methodology of Photonic Services** for advanced network applications. More specifically, **the thesis proposes an embedding of advanced applications to optical DWDM backbone networks of NRENs and their processing to prevent a wavelength contention with standard traffic and to adjust transmission parameters.**

To validate the proposed methodology, several following assumptions have been taken:

- A single advanced application will be selected for demonstration
- A single processing device will be designed and evaluated
- A single nonlinear effect will be used as processing device

From a wide range of advanced applications for optical networks, the time transfer for the atomic clock comparison was selected to satisfy requests from backbone network users who are looking for an alternative to GPS units.

The time transfer applications require an optical E2E channel that may cross multiple optical domains but may not fit the DWDM channel plan of all involved domains. Therefore, a wavelength converting device has to be designed and evaluated. A careful wavelength tuning may also compensate for E2E propagation delay between signal directions.

The processing device will benefit from the transparency of the FWM nonlinear effect to signal modulations. FWM wavelength conversion is suitable for a wide range of modulation formats including phase and amplitude modulations.

Therefore, the thesis will consider a demonstration of time transfer and the design of a wavelength conversion device based on the FWM nonlinear effect.

Further, the methodology of implementation of Photonic Services into NRENs considers the following aspects:

- Dark fibre infrastructure
- Open systems
- Nothing In Line
- Single Fibre Transmission
- Flexible photonic layer

5 Proposal of Photonic Services for optical research networks

Chapter 2 described advanced network applications that require multi-domain E2E services to overcome international distances. Sub-chapter 2.1.3 and annexe A1 specifically showed that Europe is a true multi-domain environment with several different network technologies. Chapter 5 proposes our new solution for E2E services over optical backbone networks generalising an approach to optical channels and is compatible with the technology of Super-channels in the near-future.

5.1 Proposed definition of Photonic Services

A general E2E service between two or more points in the optical connection-oriented network can be described by its path and the network resources utilised. The path is a physical route along which light travels from one endpoint to the other, or to multiple other endpoints. The network resource used can be described as an allocated part of network bandwidth that is reserved all along the photonic-path for the service user. It is particularly important that a service must not be affected by the network as it transfers information over it, to ensure that the information carried between endpoints is only dependent on the application itself. This type of network is considered transparent from a service perspective. Let us consider that a network managed by a single Operation and Management System (OMS) is a network domain. This type of network domain is usually designed by a single vendor unless the Open Dense Wavelength Division Multiplex (OpenDWDM) approach is used [86].

We are introducing **Photonic Service** as a service provided over an optical network where information is carried over a transparent network from one end-user to another exclusively in optical form. Each Photonic Service can be defined by its photonic-path and frequency band. The frequency band can involve either a single optical channel (50 GHz or 100 GHz according to the ITU grids) or a variable frequency band, depending on the service details. In other words, different services may require different bandwidths while sharing the same optical fibre line. Moreover, no two services can occupy the same frequency band, or its part, implying that OMS is essential to control Photonic Service throughout the network. The photonic-path is a physical path throughout a transparent optical network that will light take to reach its destination. The rest of the Photonic Service parameters such as bit rate, modulation format or line coding are application related and, therefore,

irrelevant from a network point of view, as long as the optical network is transparent to the transferred information.

5.2 E2E applications as Alien Wavelengths

Photonic Service can be easily related to Alien Wavelength (AW) because AWs could be regarded as a special case of Photonic Services. AW is a networking concept used in optical communications to carry data between two endpoints over multi-domain networks without OEO conversion. Traditionally, optical signals are converted to their electric representations at each border of a network domain. This made networks logically separated with transponders used as “bridges” between networks. An optical signal that evades transponders at network borders to enter the network is called “alien” since it does not originate in the network. AWs can be understood as first attempts to interconnect optical layers of backbone networks. An end-to-end service over AW was realised over a the multi-domain network of CESNET [87]. This concept has potential to save cost, increase reliability, provisioning speed and transparency of services [88]. AWs are defined to fit in one optical channel that may limit transmission modulation of carried data. ITU standardised a specific type of AWs as ITU Black Links, but ITU specification is limited only to some bit rates and protocols [89]. In general, AWs are not bound just to one domain, but traversing multiple domains that always brings interoperability issues. CESNET offers a Lambda service that allows the user to have a dedicated optical channel through CESNET’s multi-domain network under CESNET administration [90]. Another example of an optical network service is represented by the GÉANT Lambda service [91], where a 10 or 100 Gbps capacity is being reserved over a pan-European network within a single domain. Figure 29 shows GEANT pan-European topology map as of October 2015. A comparison of these advanced optical network services is given in Table 6.

Robotic surgeries and especially Tele-surgery applications (e.g. [48][52]) require low network latency and, therefore, the shortest Photonic-path available. Time transfer applications [57] pose limits on the jitter of network latency, the time deviation from average network latency. The jitter in network latency might also be described by lags introduced by buffering during Optical-to-Electrical-to-Optical conversion in over-provisioned networks. Although the penalty for not meeting the jitter limits or service failure is mild in the majority of applications, in the case of some specific applications any failure in these limits may interrupt the entire experiment or even endanger human life. Examples of demanding applications, along with their parameters and relevant references, were discussed in Chapter 2.

Service name	Bandwidth	Data representation	Comments
Photonic Service	Variable	Application specific	Variable bandwidth will be available with FlexiGrid-like technologies. Data representation will only be limited by network transparency and the distance between endpoints.
Alien Wavelength	50/100 GHz	OOK, coherent modulations	E2E data transport over multi-domain networks without OEO
CESNET Lambda Service	50/100 GHz	OOK, coherent modulations	E2E data transport over multiple domains under CESNET administration
GÉANT Lambda Service	25/50 GHz	OOK, coherent modulations	E2E data transport over the single domain pan-European Géant network with OEO

Table 6: Comparison Of Advanced Optical Network Services

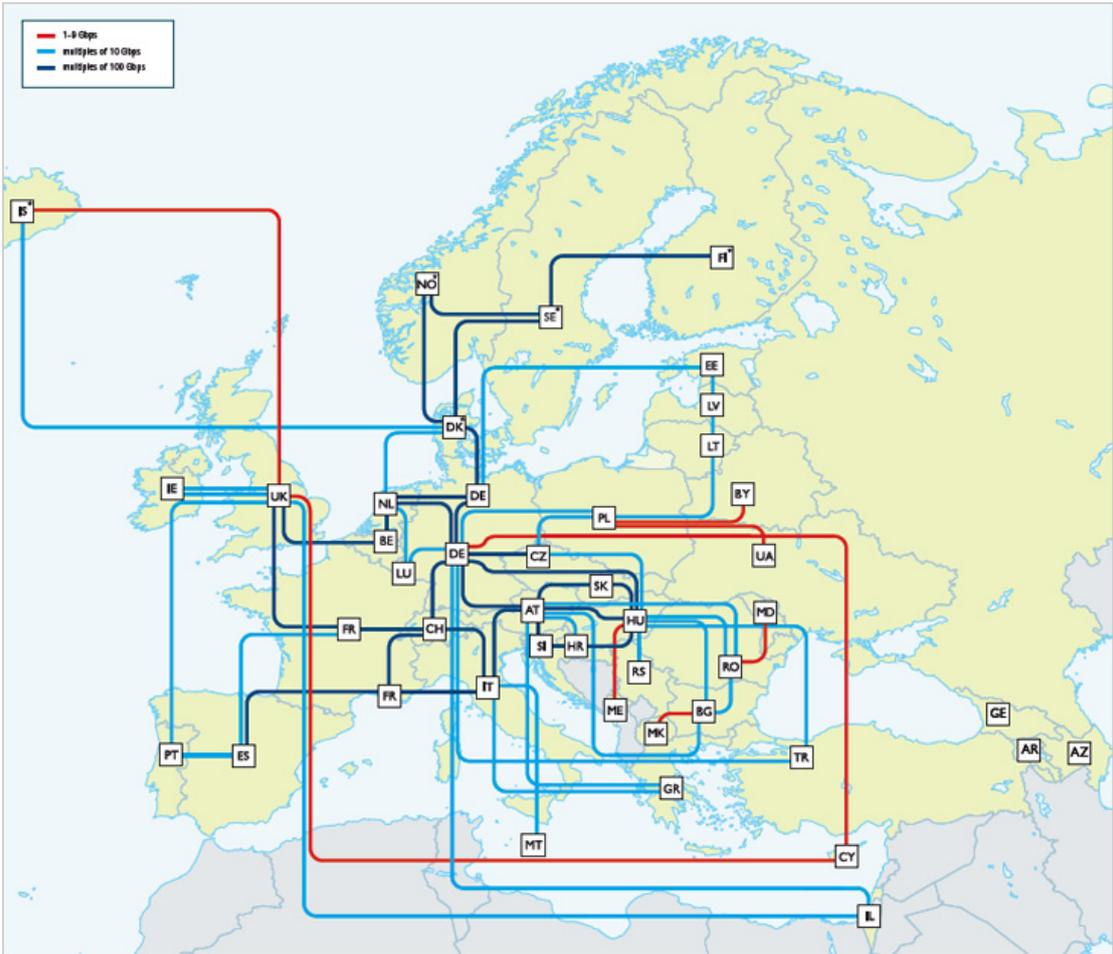


Figure 29: GEANT pan-European topology map

5.3 Conclusion

Advanced academic applications require an end-to-end optical channel between users. Connecting two users in the same network is an easy networking exercise, but connecting internationally in multi-domain environment represents a considerable challenge. ITU black links and Alien Wavelength are limited by modulation schemes and fixed ITU DWDM grid networks. We introduced the generalised concept of photonic services that opens more options for academic applications and complies with new network concepts of flexible network grid. We used this concept in a pilot time transfer experiment in an international multi-domain network environment described in the following chapter.

6 Demonstration of Time transfer in Czech NREN

Optical backbone networks are primarily used for so-called “digital services” that carry large amounts of data over huge distances. New applications although require a different approach that should perhaps be called “non-digital services”. Implementation of these new applications in a network requires all optical end to end channels introduced by Photonic services described in chapter 5. The chapter 6 demonstrates and discusses a pilot demonstration of the challenging application of time transfer that initiated the focus of this thesis. Temporal signal transfers precise temporal information as a pattern of amplitude modulation. The pattern transmission is triggered by commercially accessible atomic clocks. CESNET developed a special adapter device that utilises standard communication transceivers to generate temporal signals that can be sent across standard optical backbone networks. The next subchapters describe the pilot project of time transfer and the measurement of the stability of the transceivers within Photonics Services.

6.1 Time transfer pilot

A time transfer system has been demonstrated in CESNET within the Czech-Austrian experimental project [57]. This system implements a two-way transfer method that relies on a symmetrical transport delay in both directions. In such a system two adapters are connected by a bidirectional optical link. These adapters are based on a Field Programmable Gate Array (FPGA) Virtex-5 chip and use SFP (Small Form-factor Pluggable) transceivers for electro-optical conversion. Figure 30 shows a working sample of a time transfer adapter (TTA).



Figure 30: Working sample of a two-way time transfer adapter

The goal of the first part of the network experiment was to measure the delay in a long optical loop to predict the stability of propagation delay, mainly the influence of daily temperature variations. A

Photonic Service was established within the OpenDWDM system of the CESNET2 network as a bidirectional channel. A Pulse per Second (PPS) signal from a rubidium clock was transmitted in both directions over a 744 km all-optical loop and both propagation delays were then compared.

Figure 31 displays the stability of the time transfer in terms of Time Deviation, denoted as TDEV $\sigma_x(\tau)$. For average intervals up to 200 s, the white phase noise given by an empiric equation prevails

$$\sigma_x(\tau) \approx \frac{100\text{ps}}{\sqrt{\tau}} \quad (20)$$

here τ is the averaging time. It is assumed that this noise originates in the modulation/demodulation of the carrier signal and the output circuits of the adapters. The lowest value of the noise of about 8.1 ps for an averaging time interval of 500 s has been observed. Details of this experiment are described in [77].

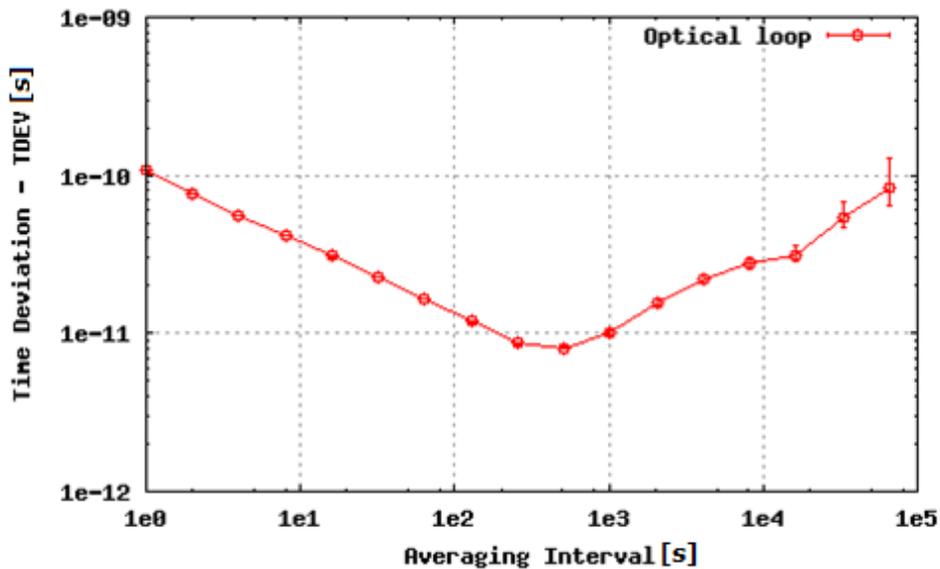


Figure 31: Time stability, lambda loop of 744 km

We successfully demonstrated time transfer between atomic clocks in Prague and Vienna [57]. The all-optical path was created through the operational DWDM network and an OpenDWDM link operating in a so-called “hut-skipping” or Nothing-In-Line (NIL) regime over 220 km. The overall setup is shown in Figure 32. The time comparison of time scales as a Photonic Service between Czech and Austrian national time and frequency laboratories in Prague and Vienna has been in long-term operation since 2011. The photonic path between the Institute of Photonics and Electronics (IPE) in

Prague and the Bundesamt für Eich- und Vermessungswesen (BEV) in Vienna has a total length of 550 km and consists of several segments. The longest part, connecting Points of Presence (PoPs) in Prague and Brno, utilises a dedicated DWDM channel in the CESNET2 production network. The link between Brno and Vienna University uses the same DWDM channel in the cross-border fibre link connecting CESNET and AConet. Both national laboratories covered the last mile to the NRENs point of presence using rented dark fibre lines. The path is amplified by seven EDFAs and uses an optical channel of 1551.72 nm (i.e., C-band, ITU channel #32) in both directions. A description of particular segments is summarised in Table 7.

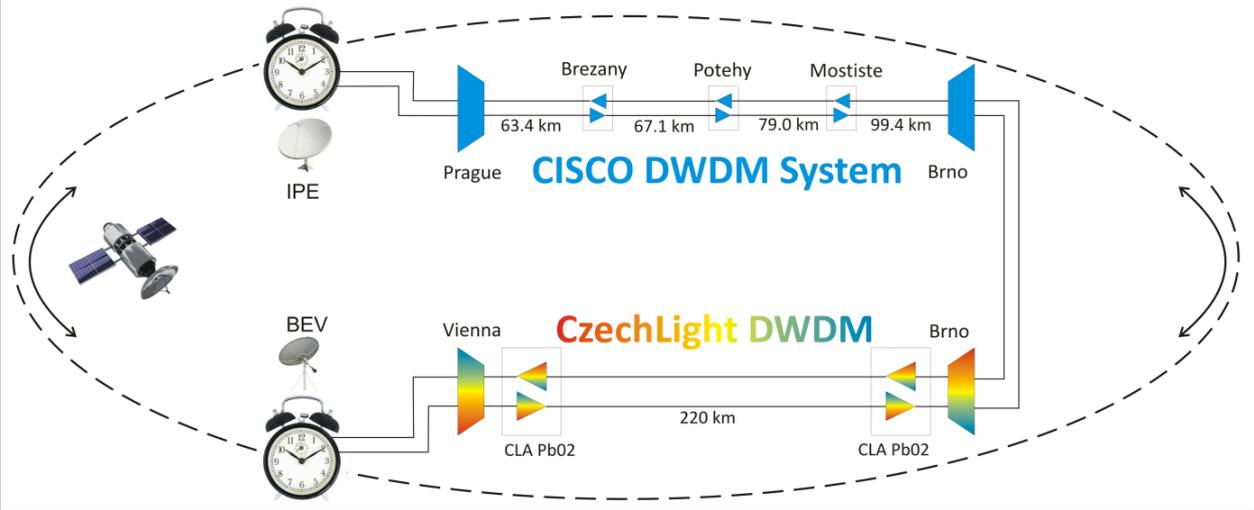


Figure 32: IPE - BEV all-optical path

Segment	Length [km]	Attenuation [dB]	Technology
IPE – CESNET PoP	16	7.0	dark fibre
CESNET PoP – Brno University	309	78.6	Cisco ONS (DWDM channel)
Brno University – Vienna University	220	50.0	CzechLight (DWDM channel)
Vienna University – BEV	5	1.5	dark fibre

Table 7: Photonic path segments

This optical method has been compared with the Common View GPS standard method [75] and later with the more accurate Precise Point Positioning (PPP) method [78]. A very good correlation between optical time transfer and GPS based methods was observed. The difference between optical time transfer and PPP method is up to 200 ps with observed daily periodicity. Measurement data of the time stability are shown in Figure 33. The red line represents optical measurement data, the green line stands for Common View GPS method, and the blue line shows the stability computed

according to the PPP method. The E2E delay of an optical fibre line varies with temperature and other environmental changes. Temperature alone changes group propagation time by about 35 ps per Kelvin and kilometre [75]. Fortunately, environmental parameters are varying gradually and do not influence the stability measurement. The temporal evolution of the E2E delay of the IPE-BEV optical line can be seen in Figure 34. More details can be in [79][80][81]. It is important to note that the Photonic Service of time transfer is now running over the same fibres as IP traffic, on an adjacent channel, and with no measurable impact. A sample of IP traffic flow in CESNET backbone is in Figure 35 [83][84].

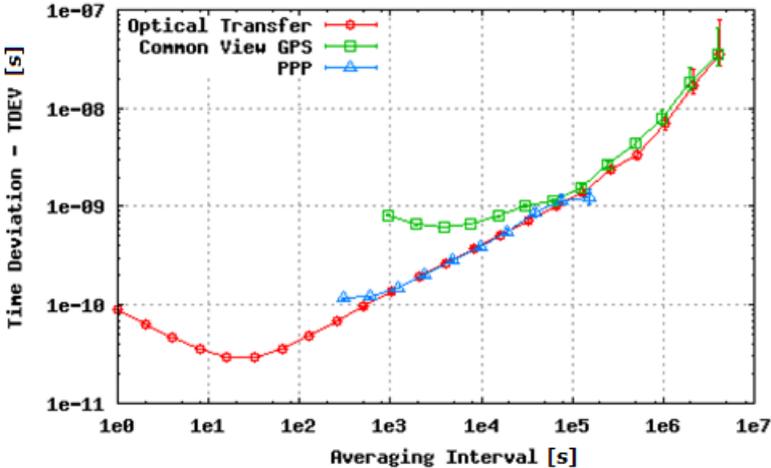


Figure 33: Time stability measured by an optical link (red), GPS (green) and PPP method (blue)

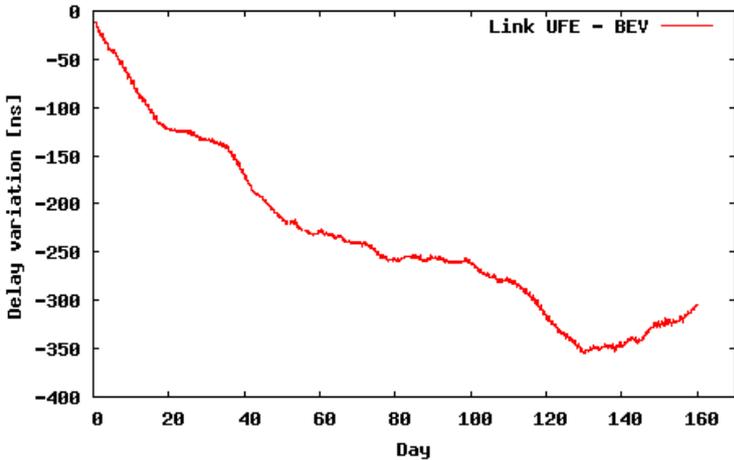


Figure 34: Temporal evolution of the E2E delay of the IPE-BEV fibre link.

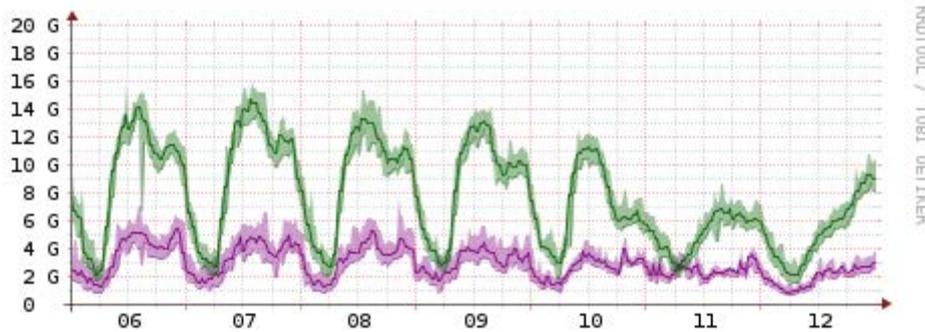


Figure 35: CESNET Backbone utilisation for Praha-Brno link for 1 week in February 2017, (green) direction Praha->Brno, (violet) direction Brno->Praha

6.2 Transceivers stability

One uncertainty concerning precise time transfer delay measurements is the stability of the central frequency of transceivers. Every small fluctuation in temporal signal frequency translates through the dispersion parameters of the fibre link into a light propagation delay. It is, therefore, important to understand the stability of optical transceivers which is strongly influenced by their design and the technology used. Suitable stabilisation technology often comes from spatial requirements given by the transceiver's form factor. For example, DWDM transceivers utilise distributed optical filter inside the laser cavity (distributed feedback laser) to stabilise the output lasing frequency [85]. High rates of 10 Gbps and more are realised with the integrated absorption-modulator section. Here we focus on DWDM telecommunication devices that are deployed in many backbone and metropolitan optical data networks. Small Form-factor Pluggable transceivers (SFPs), defined in specification INF-8074i of the SFF committee, became an important standard for traditional optical data networks.

SFP transceivers come in various types according to optical reach, bitrate and multiplex. Since end users of a precise time distribution over a backbone network are separated by tens or hundreds of kilometres, we targeted transceivers with higher chromatic dispersion tolerance.

We performed six continuous days of tests of transceiver stability while transferring time stamps. We selected six commonly used in CESNET DWDM backbone network. Two fixed wavelength SFP modules for 80 km reach, two fixed wavelength SFP+ modules for 10 Gbps rate and two tunable SFP+ modules for 10 Gbps rate. Each transceiver was tested while inserted inside the Time-Transfer Adapter (TTA), as shown in Figure 30, in a controlled environment of the optical laboratory. The stability of the transceiver central wavelength was monitored every six seconds by an Optical Spectrum Analyzer (OSA) with 0.004 nm minimum sampling resolution. Stability measurements are gathered in separate plots as can be seen in Figure 36.

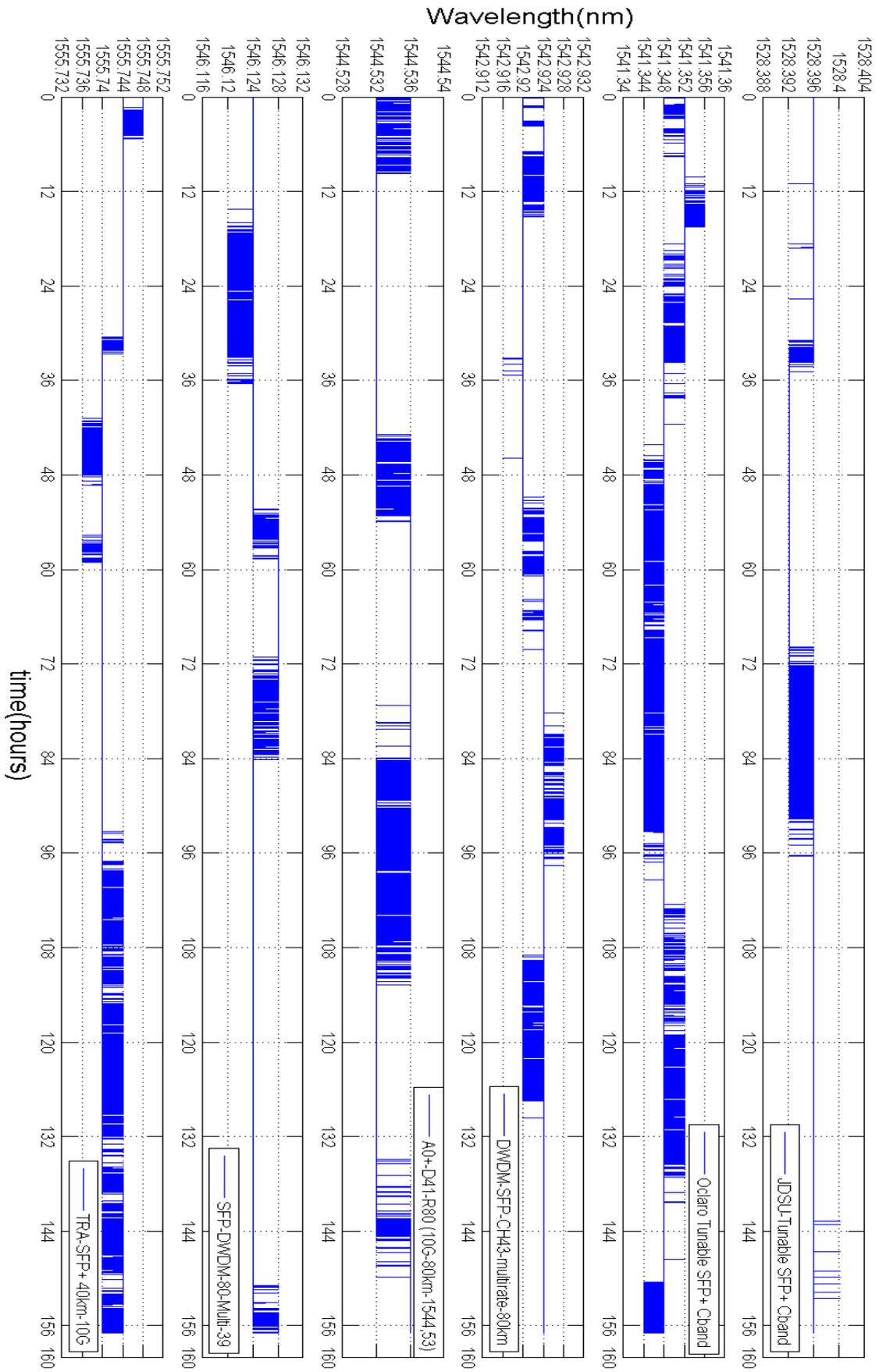


Figure 36. Central wavelength stability measured over 6 days for 6 types of optical SFP transceivers.

Figure 36 shows the temporal evolution of the central wavelength of six transceivers. The measured values are close to the fundamental limit of our OSA, therefore, discrete jumps are seen rather than the continuous evolution of the central wavelength. This fact implies a maximum error equal to OSA minimum sampling resolution. Results are summarised in Table 8 and show a variation of central wavelengths over a maximum of 12 pm without any correlation to day and night periods. In addition, room temperature changes of 10 degrees Celsius had no impact on stability because of the stable working environment inside the TTA enclosure.

Transceiver	Stability	Wavelength	Description
A0+-D41-R80(10G-80km-1544,53)	4 pm	1544.532 nm	10G for 80km
SFP-DWDM-80-multi-39	8 pm	1546.124 nm	Multirate for 80km
“A” Tunable SFP+ Cband	8 pm	1528.396 nm	C-band tunable
“B” Tunable SFP+ Cband	12 pm	1541.348 nm	C-band tunable
DWDM-SFP-CH43-multirate-80km	12 pm	1542.924 nm	Multirate for 80km
TRA-SFP+ 40km-10G	12 pm	1555.740 nm	10G for 40km

Table 8: Stability performance of SFPs subjected to testing

Therefore, we may expect a worst case scenario of a 16 pm central wavelength shift per link endpoint. Such central wavelength change induces a difference in propagation delay that is dependent on link parameters. Since chromatic dispersion of standard optical fibre SMF-28 is close to 17 ps/nm/km around 1550 nm, we expect a maximum of 54.4 ps per 100 km of optical fibre link. Although the additional delay accounted to the stability of transceiver central wavelength is negligible for short links, we recommend using quality SFPs for longer links with time transfer service.

6.3 Conclusion

The pilot project of time transfer has proved to work out well over the established photonic service between Prague and Vienna. We demonstrated time transfer over a multi-domain network where the Photonic Service had been created to host time transfer application. The outcome of the atomic clock comparison over an optical network outperformed standard GPS equipment by a factor of two and shortened the time needed for optimal averaging ten times. We also evaluated the temporal evolution of the end-to-end delay due to environmental temperature change. We performed long-

term testing of optical transceivers for the time transfer application to understand the fluctuation of their central wavelength which contributes to changes in end-to-end delay. The delay stabilisation method for the application is described more in detail in chapter 9. The time transfer application cannot be regenerated throughout the network aside from reamplification and dispersion compensation. It is, therefore, prone to wavelength contention with other network services. The proposed wavelength converter device was to be designed to support the time transfer application in the mitigation of the contention issue and to stabilise the end-to-end delay.

7 Proposal of specific network component - Optical Signal Converter

New applications for optical networks, which need to reach their destination without leaving the optical domain, are required by the research community. A network component for future flexible networks that will solve wavelength blocking inside the network is therefore required. A wavelength blocking issue occurs when there is no single free wavelength channel all along the service path and this means that the travelling signal has to change its wavelength at some point in the network. Commercially the change of wavelength in networks is realised by OEO conversion which involves the detection of an optical signal in an electrical domain and the retransmission of it at a wavelength which is unacceptable for the mentioned application. The change of signal wavelength directly in the optical domain may be done using nonlinear phenomena. A device performing the change of the signal wavelength is called an optical signal converter (OSC). The next chapter will discuss a scheme of the OSC that will be used for the evaluation of new methodologies in NRENs.

7.1 Optical signal converter for time transfer signal

Wavelength conversion is a continuous process in an optical domain that is transparent to the original signal and requires the mixing of two signals in the nonlinear media. We designed the Signal converter in such a way that it has two incoming signals, the details of which are displayed in Figure 37. The signal that will be converted is called the seed and the signal providing the mixing within the nonlinear media is called the pump. Both the seed and the pump are aligned in polarisation by polarisation controllers (PC1, PC2) and coupled together to be amplified to an optimal power level. Amplified signals will mix in nonlinear media of highly nonlinear fibre (HNLF) and the first order of Stokes and anti-Stokes signals will rise according to equations (21) and (22) respectively.

$$\lambda_{Stokes} = 2\lambda_{pump} - \lambda_{seed} \quad (21)$$

$$\lambda_{Anti-Stokes} = 2\lambda_{seed} - \lambda_{pump} \quad (22)$$

where λ_{pump} , λ_{seed} , $\lambda_{Anti-Stokes}$, λ_{Stokes} stand for pump and seed signals and the first order of new signals of anti-Stokes and Stokes that are products of nonlinear interaction. The Stokes or anti-Stokes signals appear at our desired output signal wavelength with the correct wavelength of the pump and seed. The desired new signal is spectrally filtered and amplified to a suitable power level. Other mixing signals are dropped and attenuated.

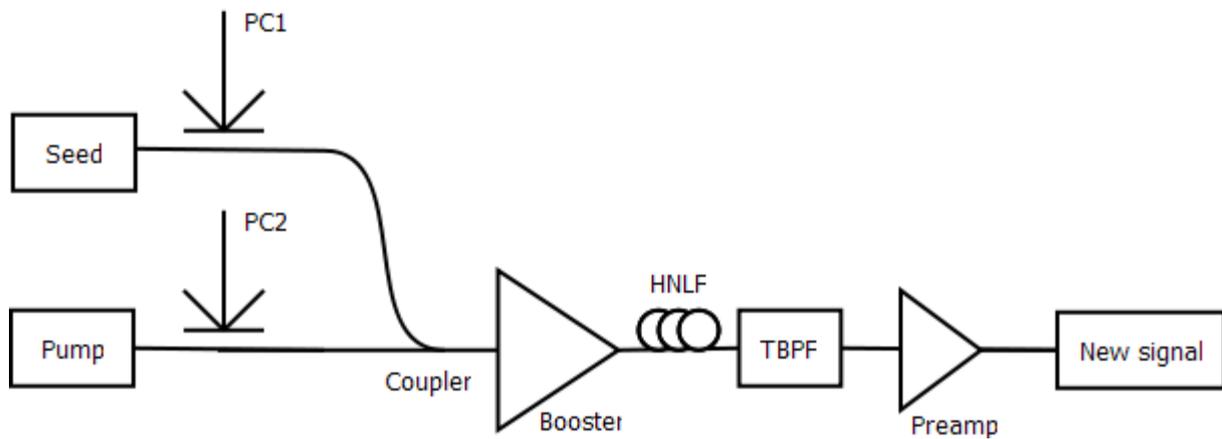


Figure 37: Signal converter using the FWM process

Our optical signal converter has three key functional blocks that define the final performance of the device. The first one, the nonlinear media is a place where light nonlinearly interacts with the material of the media. The selection of right media has a direct impact on the conversion efficiency of the converter. We define conversion efficiency according to equation (19) as the difference between new product peak power after HNL and original signal peak power before HNL where both values are expressed in dBm. Negative conversion efficiency means that the new signal is less powerful than the original signal and may need additional amplification. The second one, the polarisation control of signals in the FWM method is very important because FWM is effective only for co-polarized signals. The options of polarisation alignment are discussed in next chapters. The third one, the pump signal power levels influence the amount of nonlinear interaction. An optimal performance of the converter is achieved by a pump signal with optimal power levels. Evaluation of a range of pump power levels helps to find an optimal working range.

The Signal converter blocks will be optimised in the following subchapters.

7.2 Nonlinear media optimisation

The efficiency of the FWM process is highly dependent on the parameters of nonlinear media. Nonlinear fibres are a reasonable option for fibre based setups and devices and they feature three of the most important parameters. Nonlinear coefficient γ evaluates how effective the nonlinear effects are for Watt of optical power and kilometre of HNL. The nonlinear fibre length of HNL shows how long the media is for nonlinear interaction. Zero dispersion wavelength and dispersion slope describe the dispersion parameters of nonlinear media. The best conversion efficiency is close

to a zero dispersion wavelength where interacting signals tend to travel together. This parameter is critical for pulse pumped FWM processes. We tested four different HNLFs with lengths of 49m, 151m, 354m and 750m with parameters described in Table 9. Each HNLF has a different zero dispersion wavelength because this parameter evolves along the fibre according to microscopic fibre structure differences. During the final HNLF measurement, the zero dispersion wavelength parameter is the average number for the specific fibre. Each fibre, thus, has different Dispersion at for example 1560nm. Although different HNLFs have a different Dispersion slope for wavelengths in the region around 1560 nm, all fibres have a similar dispersion value. The long 750 m HNLF has a dispersion of 0.252 ps/nm/km and the other HNLFs have dispersion around 0.2 ps/nm/km. This means that the dispersion impact on FWM performance will be at a similar level.

Nonlinearity of a media is often described by the nonlinear coefficient gamma. We had fibres of the same type and, therefore, similar gamma. The total nonlinearity of a medium is the product of Gama and fibre length. The longest HNLF has the highest nonlinearity and will be used in our setups.

HNLF length [m]	Zero Disp. Wavelength [nm]	Dispersion slope [ps/nm²/km]	Loss [dB]	Gamma [1/W/km]
49	1551.88	0.02	0.53	10.5
151	1550.31	0.02	0.7	10.6
354	1552.23	0.02	0.77	10.6
750	1518	0.006	0.57	10.7

Table 9: Tested HNLF fibres

7.3 Conversion efficiency optimisation

Conversion efficiency is the key parameter for signal conversions because it is directly translated to the optical signal to noise ratio (OSNR) penalty, thus degrading the total reach of such communication. The conversion efficiency depends both on the nonlinear medium where the conversion takes place and the satisfaction of phase conditions that drop with frequency distance of interacting signals in the conversion as has been shown in equations (16)(17)(18). Figure 38 shows the conversion efficiency of FWM in 750 m of HNLF, where the time signal was at 1564.68nm and the pump was tuned from 1564.27 nm to 1556.55 nm by increments of 50 GHz. The conversion is more efficient for anti-Stokes products and keeps similar level for up to seven channels detuning for both Stokes and anti-Stokes products. For this range of fourteen DWDM channels, we expect a balanced conversion performance.

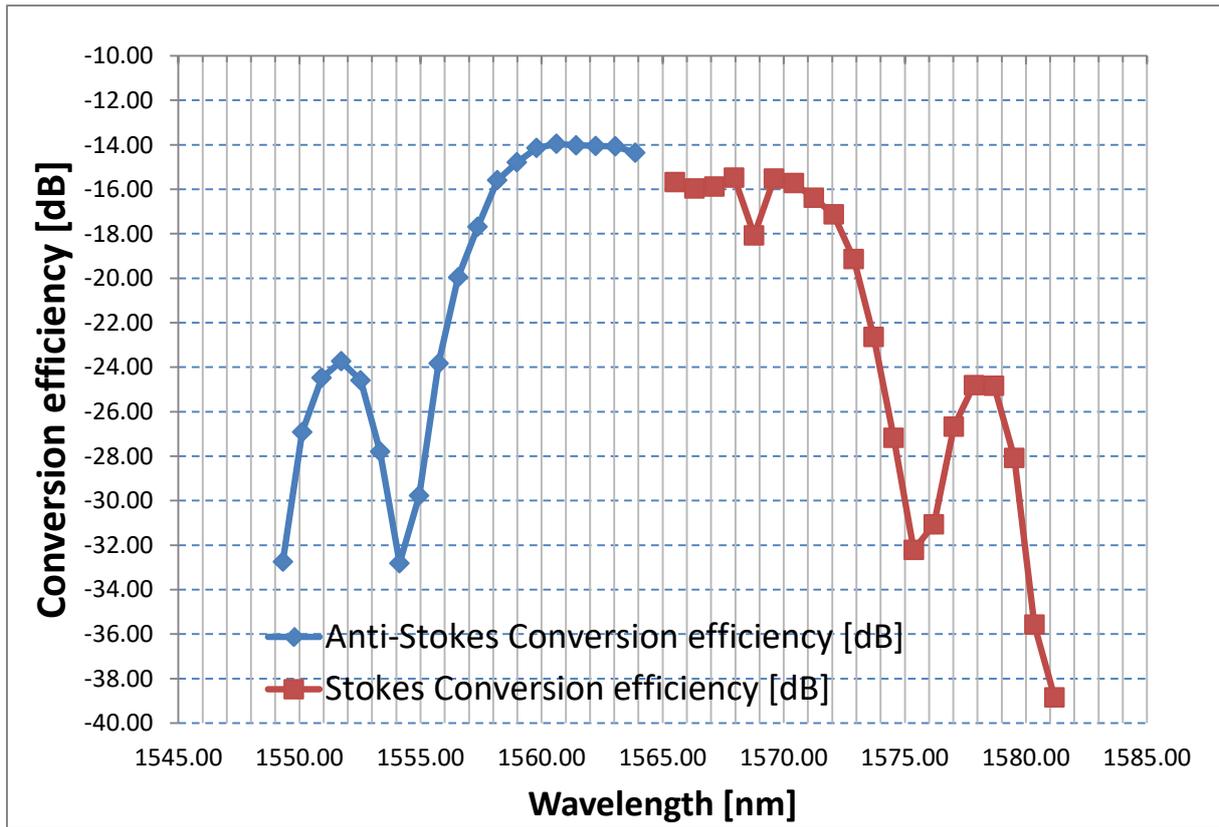


Figure 38: Measured conversion efficiency for case of the 750 m HNLF

7.4 Polarization alignment

Signals interacting through FWM in nonlinear media should have identical polarisation. The FWM efficiency drops rapidly when signal polarisation becomes misaligned and this is why polarisation controlling devices are used. In a temperature unstable environment, an automatic alignment method needs to be implemented or a polarisation insensitive setup needs to be used. One option of a polarization insensitive setup is displayed in Figure 39 which shows how the pump laser light propagates through the optical circulator (CIRC) to the optical polarization beam splitter (PBS) where the light is aligned with polarization axes in such a way that each half of the pump power is equally divided to their respective PBS outputs. Both pump halves are then counter-propagating through the HNLF fibre and interacting with any polarisation of seed signal. This setup was tested but suffered from a conversion efficiency drop due to the fact that FWM occurs in both polarisation planes separately and, therefore, needs double pump power level to match the efficiency of a standard setup.

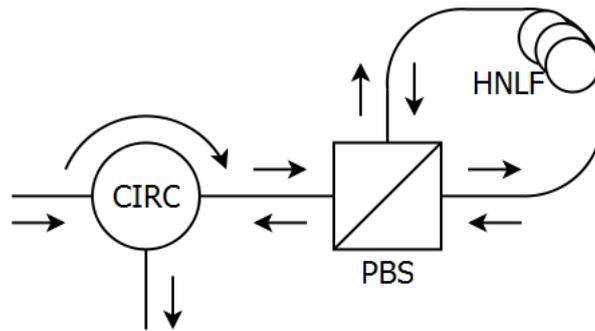


Figure 39: Polarisation independent conversion setup

7.5 Pump power optimisation

Nonlinear effects of FWM grow with the total amount of power in nonlinear media. We have tested four HNLFs with parameters according to Table 9. For each nonlinear medium, a wavelength conversion has been performed over 1.6 nm at 3 different wavelengths to evaluate wavelength dependent performance. At each wavelength, we varied pump power between 15 and 23 dBm and measured conversion peak power. Conversion efficiency was then calculated as the difference between the original and converted signal peak powers. Conversion efficiency is a negative value for our setup. To avoid any confusion we will change the sign and call value Conversion penalty. The Conversion penalties for our HNLF fibres and evaluated power range are shown in Table 10.

Data from Table 10 are displayed in Figure 40, which clearly shows that the conversion penalty highly depends on the length of HNLF and that it improves with HNLF length simply because there was more fibre for nonlinear interaction. It is also shown that the three shortest fibres have a slightly worse conversion penalty at 1560 nm than the longest HNLF because they have a different dispersion profile. The HNLF of 50 m and 150 m have linear characteristics and do not experience Brillouin scattering. The 350m-long HNLF crosses the Brillouin threshold for pump powers above 21 dBm. The longest HNLF has the lowest conversion penalty for low pump powers but also starts to experience Brillouin scattering above 17 dBm of pump power. Therefore, we decided to use the longest 750m HNLF at low pump powers where a reasonable conversion penalty is still not influenced by Brillouin scattering. For the sake of simplicity, we did not use any Brillouin suppression methods such as pump phase modulation.

Conversion penalty [dB]												
HNLf length [m]	50			150			350			750		
Wavelength [nm]	154	155	156	154	155	156	154	155	156	154	155	156
	0	0	0	0	0	0	0	0	0	0	0	0
PB 15dBm	41.7	42	43.1	32.6	33.0	34.6	25.8	26.0	26.8	21.4	24.5	20.2
PB 16dBm	40.1	40.3	41.5	30.5	31.2	32.7	24.0	24.2	25.0	19.5	22.7	18.3
PB 17dBm	38.5	38.6	39.9	29.0	29.5	30.9	22.2	22.5	23.2	17.7	20.8	16.6
PB 18dBm	36.9	37.0	38.3	27.0	27.4	29.3	20.3	20.7	21.5	16.7	19.1	15.3
PB 19dBm	35.1	35.1	36.5	25.0	25.5	27.4	18.5	18.7	19.6	16.0	17.0	14.8
PB 20dBm	33.0	33.0	34.4	23.2	23.4	25.2	16.4	16.7	17.5	15.6	15.5	14
PB 21dBm	30.7	30.8	32.1	20.9	21.1	23.0	14.5	14.7	15.4	15.3	15.0	13.7
PB 22dBm	28.5	28.7	29.9	18.7	18.9	20.7	13.6	13.5	14.3	15.1	14.5	13.4
PB 23dBm	26.8	26.8	28.1	16.8	17.0	18.9	13.2	13.1	13.5	14.8	14.5	13.1

Table 10: Conversion penalties in dB for pump powers, wavelengths and HNLf lengths

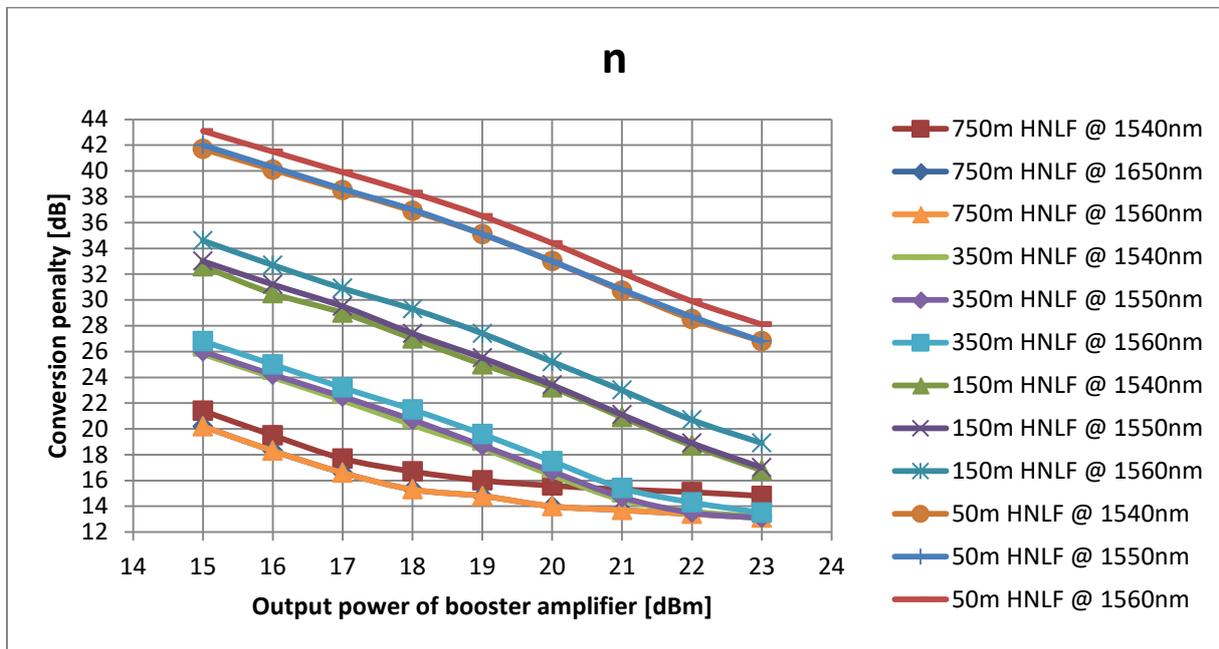


Figure 40: Conversion penalty for four HNLf fibres

7.6 Conclusion

The optical signal converter based on FWM was designed to support processing of Photonic services in an optimised setup with optimisation being addressed for each functional block of the converter. We selected optimal nonlinear media from the available materials based on conversion efficiency and other discussed parameters of the media. Conversion efficiency remains at similar levels in a spectral range of 1400 GHz (11.2 nm). We decided to retain a manual alignment of polarisation to keep signal amplification at low levels and we optimised pump power levels to minimise further conversion penalties. The final parameters of the converter were summarised in Table 11.

Parameter	Optimized value
HNLf fibre	750m HNLf (ZDWL=1518nm, Att=0.57dB, unidirectional)
Polarization control	Manual / Semi-manual (PC – Phoenix Photonics)
Amplification	Dual stage amplification (PB+PA)
Conversion product filtering	Double filtered (Santec – TBPF)
Wavelength conversion range	1400 GHz / 11.2 nm
Conversion Penalty	13-20 dB
Pump power range	15-23 dB

Table 11: Final parameters of the optical signal converter

8 Evaluation of the signal converter for temporal signal in optical network

As described in Chapter 3.4.3 the signal conversion may utilise a nonlinear FWM effect to create a copy of the original signal at a new frequency through the nonlinear interaction of light and dielectric media of optical fibre. The interaction of light and fibre has a finite efficiency that is translated as a negative penalty to the power of the copied signal. The penalty may decrease the OSNR signal and, thus, effectively shorten the total distance that the signal may travel. Nevertheless, in congested networks the wavelength conversion may be the only option for special applications and a proper design will minimise the penalty on OSNR. The selected application of time transfer is also very sensitive to any uncontrolled jitter in an end-to-end delay and, therefore, prevents classical electrical regeneration that utilises electrical buffering. We evaluated the signal conversion of a temporal signal from TTA in the signal converter based on the FWM effect in HNLf fibre.

In our experiment, the continuous wave laser source was used as a pump laser and two amplification stages adjusted the peak power levels of signals to the required levels. The experiment was performed as shown in Figure 41.

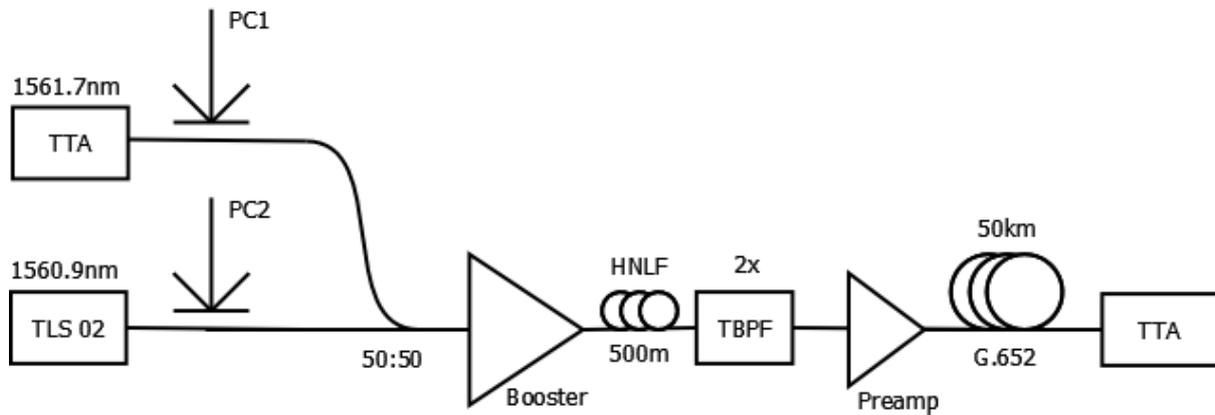


Figure 41: Experimental setup for the wavelength conversion of transferred temporal information

Tunable Laser Source (TLS) Cobrite provided a CW signal at a wavelength of 1560.9 nm which was noted as the pump signal. The Time Transfer Adapter, equipped with DWDM SFP transceiver at 1561.7 nm, supplied the seed signal transferring the timing information. Both signals had their polarisation states controlled by polarisation controller devices and were added together at a 50%/50% optical coupler. The signals were together amplified in a Keopsys optical amplifier to a total output power of 20 dBm that was shared between signals and ASE noise background. Amplified signals interacted with 750 m of Highly Nonlinear Fibre (HNLF) to create anti-Stokes and Stokes products.

Based on conversion efficiency, the second and third orders of Stokes and anti-Stokes products are produced with considerable lower peak powers that are unsuitable for signal conversion. The spectrum of nonlinear mixing is shown in Figure 42. The first order of the anti-Stoke product is then double filtered to suppress other signals and extract the desired new signal at 1560.1 nm, which subsequently had to be amplified up to 0 dBm of output power to give the signal the required margin to traverse 50 km of G.652D fibre spool and reach the detector. Since detectors respond to quite a broad wavelength range in the infrared part of the spectrum the temporal signal on new wavelength was well received.

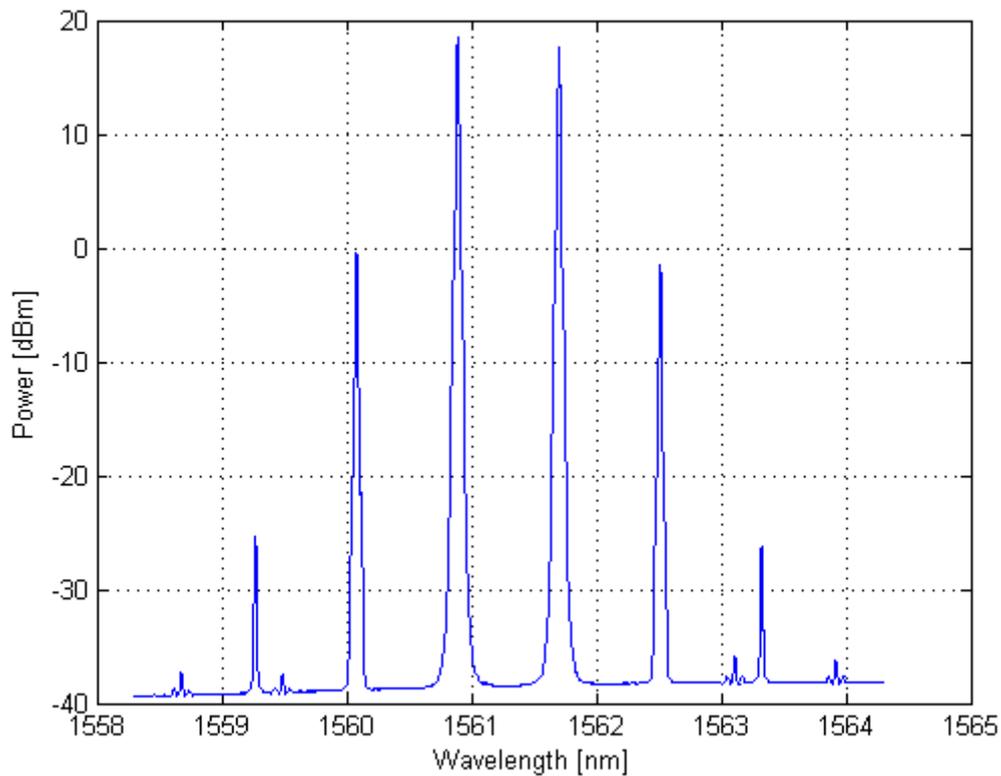


Figure 42: FWM in 500km of HNLF

8.1 Optimisation of long-haul time transfer

The maximal optical reach of time transfer depends on many link parameters including the noise figure of amplifiers, the attenuation of fibre spans, fibre types and amplification levels. We evaluated an ultra-long distance time transfer in a long-haul testbed made of 3000 km of G.652D fibre lit by the Czech Light Open DWDM transmission system which consists of 100km-long spans of G.652D fibre connected together through Czech Light inline amplifiers. A great advantage of this testbed is its customizability and fact that we may add span by span to estimate the limit, in optical reach, of the transmission system.

Czech Light Open DWDM transmission system was developed over last decade in CESNET to light CESNET backbone network. The development resulted in a number of utility models and functional samples that are listed in annexe A4. Utility models and functional samples were turned into turn-key network elements that light more than 3000 km of CESNET backbone network. These network elements made the basic framework of the long-haul testbed especially to amplify propagating signals and compensate for accumulated fibre dispersion.

The signal converter was placed between the Time Transfer Adapter and the testbed to demonstrate the stabilisation option through a change in a signal's wavelength.

8.2 Long-haul testbed description

At the beginning of the long-haul testbed, we arranged the Time Transfer Adapter to send a temporal signal into the Signal Converter that was able to change the wavelength of the temporal signal which entered the testbed and was amplified in the initial Power Booster amplifier. The booster amplifier accepts signals from -10 dBm and may provide a maximum output power of 23 dBm. Then, an amplified temporal signal entered the fibre span with spools of G.652D fibre. After each 100 km of fibre, the Inline amplifier improved the power budget of the signal and sent the signal to another fibre span until the signal reached the end of the line and was evaluated by another Time Transfer Adapter. Inline amplifiers accept signals from -30 dBm and may provide a maximum output power of 15 dBm. The basic setup is displayed in Figure 43.

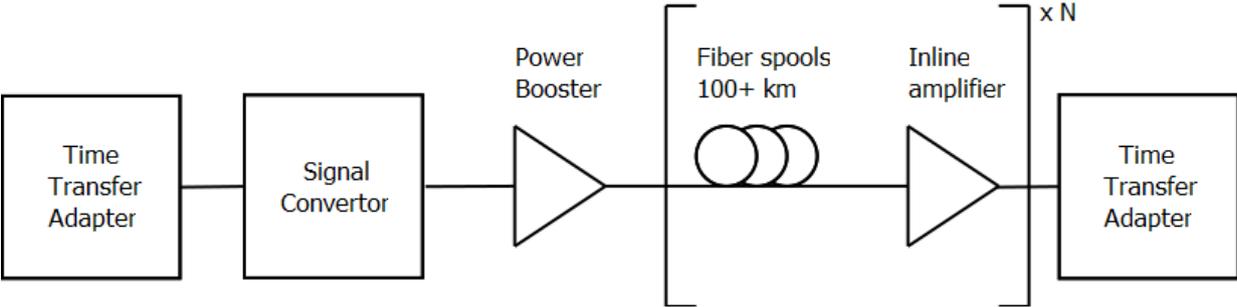


Figure 43: Time transfer experiment over a long-haul fibre testbed

8.3 Long-haul time transfer results

The temporal signal was sent by the Time Transfer Adapter at a wavelength of 1564.65 nm to the Signal converter where the temporal signal was mixed with a pump signal at 1563.85 nm to generate a new temporal signal at a wavelength of 1563.05 nm. We used 750m of HNLF inside the Signal Converter. The spectrum of mixing signals inside the Signal Converter is displayed in Figure 44.

The new temporal signal was amplified and fibre spans were gradually interconnected in the testbed to form a closed transmission system. Inline amplifiers were set to a fixed output power of 10 dBm. No dispersion compensation was inserted. The total transmission delay and power at the detector were measured before every testbed amplifier. Measured values are shown in Table 12.

The results clearly show that the total measured delay is linearly proportional to the testbed length with a delay of 4.97 ms per kilometre of optical fibre that matches the theory in equation (24) well. A standard deviation of 0.6 ms indicates that, although fibre spools are not of exactly the same length, the differences are fairly small. Power at the detector differed according to a slight difference between span attenuation and some additional local defects.

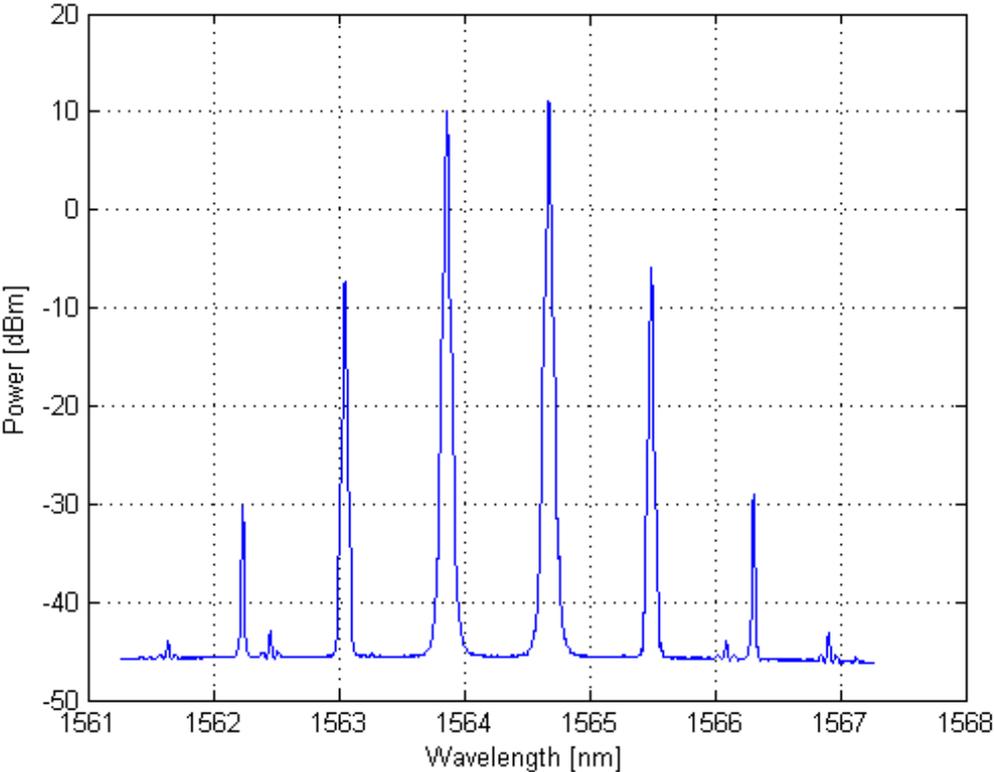


Figure 44: Spectrum of mixing signals in 750m HNLf a for long-haul testbed experiment

Testbed length [km]	Measured total delay [ns]	Power at detector [dBm]
0	4496.78	-4
50	252798.8	-14
100	501741.50	-13
200	998726.1	-11
300	1495750.9	-9.8
400	1992290.6	-9.9
500	2488870.95	-10.5
600	2985849.6	-10.3
700	3482654.6	-10.3
800	3979123.5	-11.2
900	4475882.9	-9.6
1000	4975076.5	-11.8
1100	5472018.2	-11.6

Table 12: Transmission delays according to fibre testbed length

8.4 Demonstration of the Signal converter in a traffic congestion scenario

We demonstrated the Signal converter in a real scenario. The scenario consisted of two optical fibre links of the total length of almost 2000 km. The first was 500 km and the second 1450 km long. The communication systems in our scenario employed 10 Gbps OOK DWDM signals to form up traffic of desired capacity. The 60 Gbps (denoted as 60G) traffic was therefore made of six DWDM signals of 10 Gbps and the 20 Gbps (denoted as 20G) traffic consisted of two DWDM signals. When all the traffic joined together after 500 km link, they formed the 80 Gbps (denoted as 80G) traffic. The real scenario schematic is shown in Figure 45. The temporal signal joined the link with the traffic of a 60Gbps communication system and overcame 500 km of the fibre link. Then another 20 Gbps system was added to the current traffic and the temporal signal had to be moved to a different optical channel in the Signal converter. All the traffic then overcame another 1400km of optical fibre link before being received at the destination.

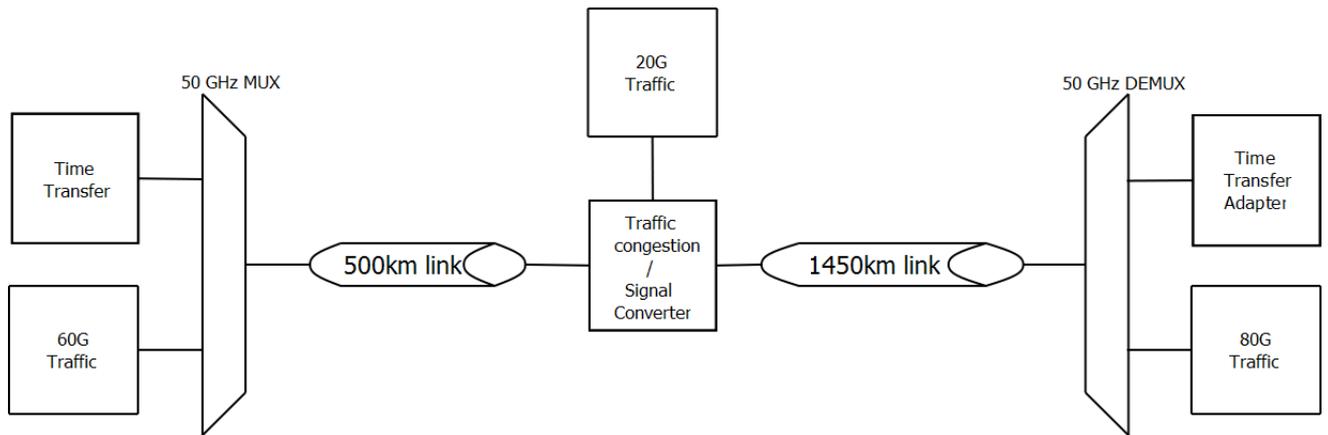


Figure 45: Demonstration of traffic congestion and signal conversion

Fibre links utilised in the demonstration were made up of 100 km fibre spools and inline EDFA amplifiers. Fibre spans of G.652D fibre have about 20 dB of attenuation. Inline EDFA amplifiers are devices from the CzechLight brand family designed in CESNET which compensate for link and connector losses. Ingress and egress points were equipped with 50 GHz MUX/DEMUX components. Details of the fibre links are in Figure 46.

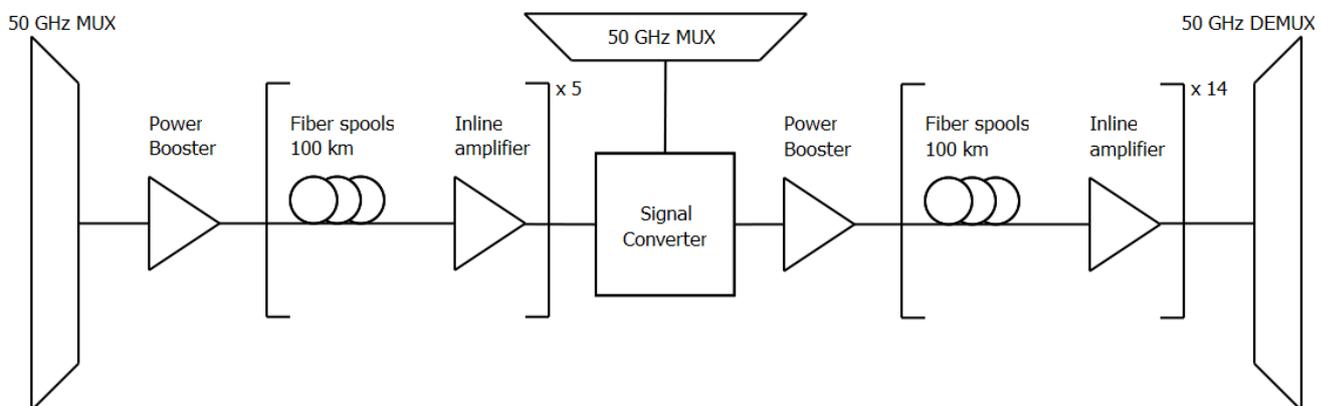


Figure 46: Details of fibre links in a demonstration setup

60 Gbps traffic is multiplexed with a temporal signal at the start of the setup and the optical spectrum plan is displayed in Figure 47. Black signals form the 60 Gbps communication system and green represents the temporal signal. All signals are aligned to a 50 GHz ITU DWDM grid. After 500 km of fibre link, other signals from 20 Gbps communication system join the multiplex, a spectral plan of which can be seen in Figure 48, and these signals are displayed in blue. The green temporal signal had to be moved to make space for the blue signals of 20 Gbps traffic and find a place among the black signals of 60 Gbps traffic. The signal converter thus resolved the traffic congestion by

moving the temporal signal to a free wavelength inside 60 Gbps traffic. The optical spectrum plan that resulted after resolving congestion is shown in Figure 49 with the temporal signal now marked in red.

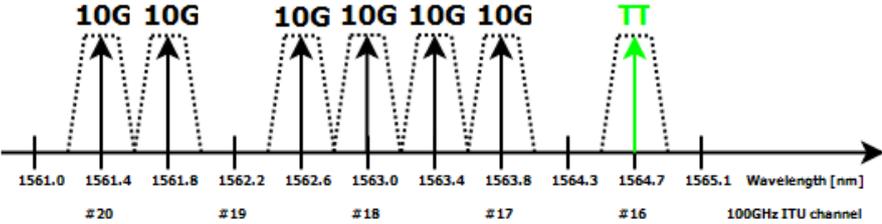


Figure 47: Optical spectrum plan at the start of setup

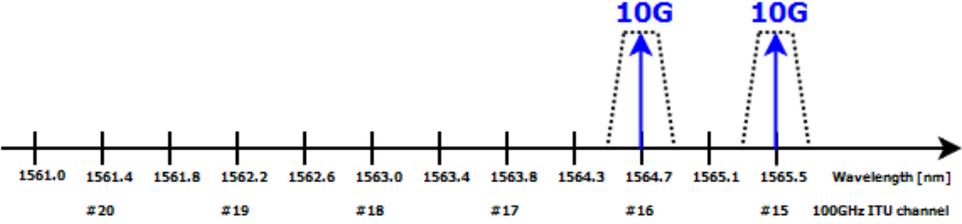


Figure 48: Optical spectrum plan of added 20G communication system

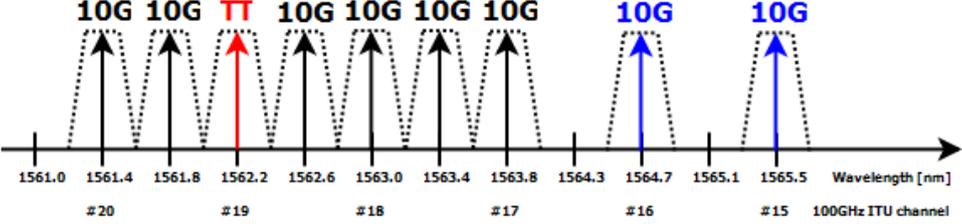


Figure 49: Optical spectrum plan of signals after resolving congestion

60 Gbps traffic was generated by an Avaya 7024XLS and merged with the temporal signal from the TTA at wavelengths according to the spectrum plan using a 50 GHz multiplexer resulting in the spectrum shown in Figure 50.

Signals propagated through the 500 km fibre link arrive at the congestion site with the spectrum shown in Figure 51. Here the temporal signal was dropped to the Signal converter and two signals of 20 Gbps traffic took its place.

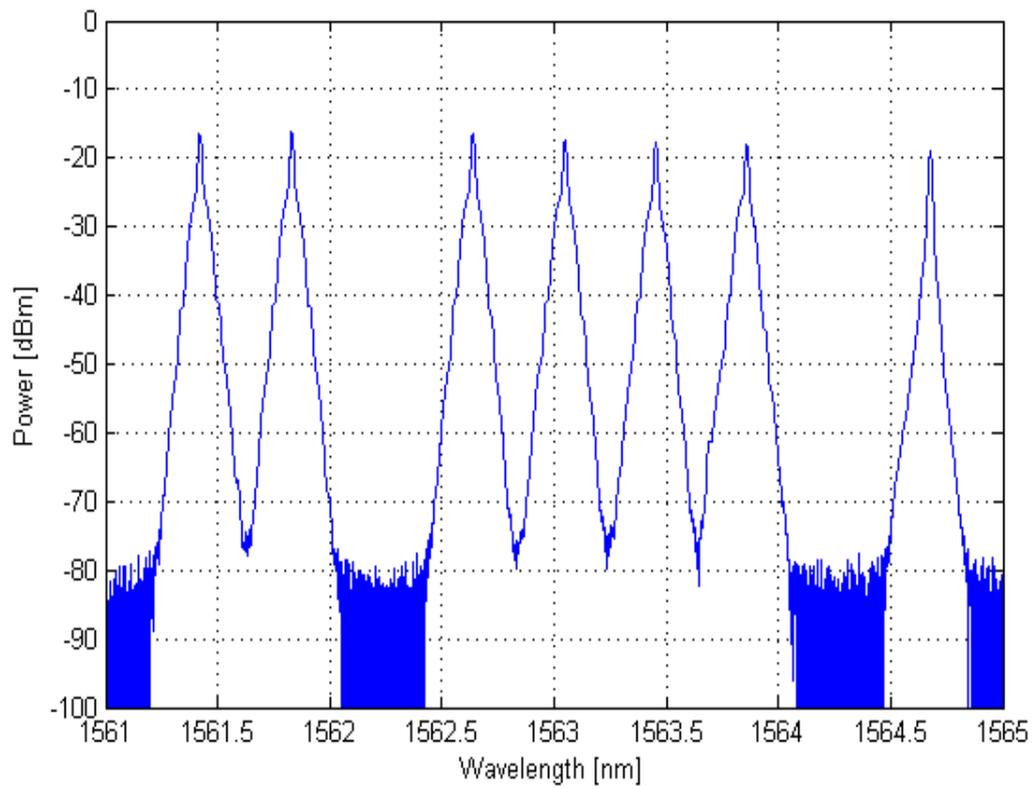


Figure 50: Measured spectrum after using the 50 GHz multiplexer

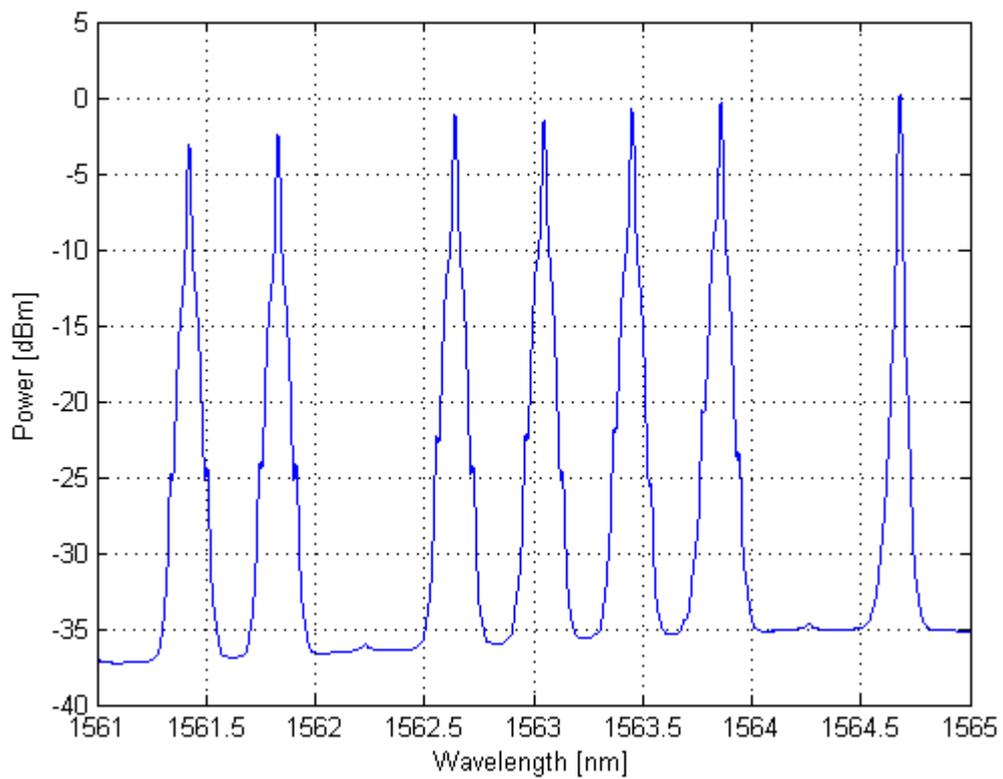


Figure 51: Measured spectrum after using the 500 km fibre link

The dropped temporal signal was amplified in the Czech Light EDFA to 15 dBm and mixed with the pump signal at 1563.4 nm at a level of 16 dBm. Both the pump and temporal signal interacted together in 750 m of HNLF to produce a new temporal signal at 1562.2 nm through FWM. The measured FWM spectrum is displayed in Figure 52. The new temporal signal was double filtered by Santec thin film filters and amplified by the Keopsys low noise EDFA preamplifier. The output of the Signal converter is shown in Figure 53. Congestion was resolved and the new temporal signal was again added to the combined traffic of the 60 Gbps and 20 Gbps systems. A new multiplex of signals had 7 closely spaced DWDM channels that entered the second fibre link with a total length of 1450 km. The new spectrum is shown in Figure 54.

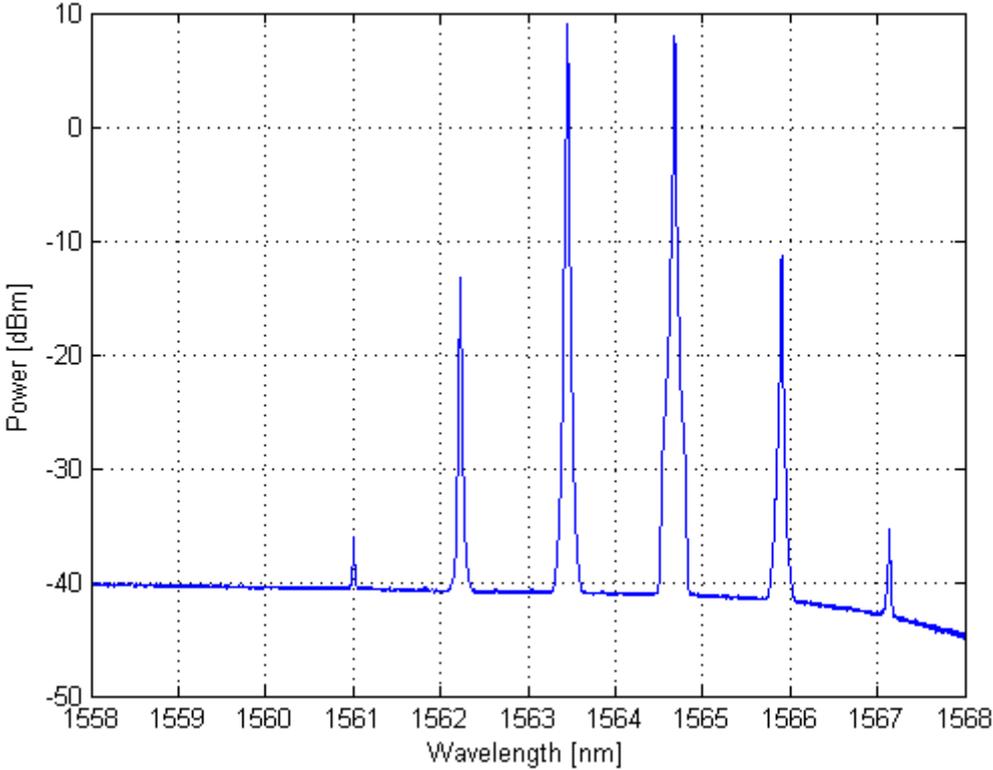


Figure 52: Measured spectrum of the FWM of the temporal signal

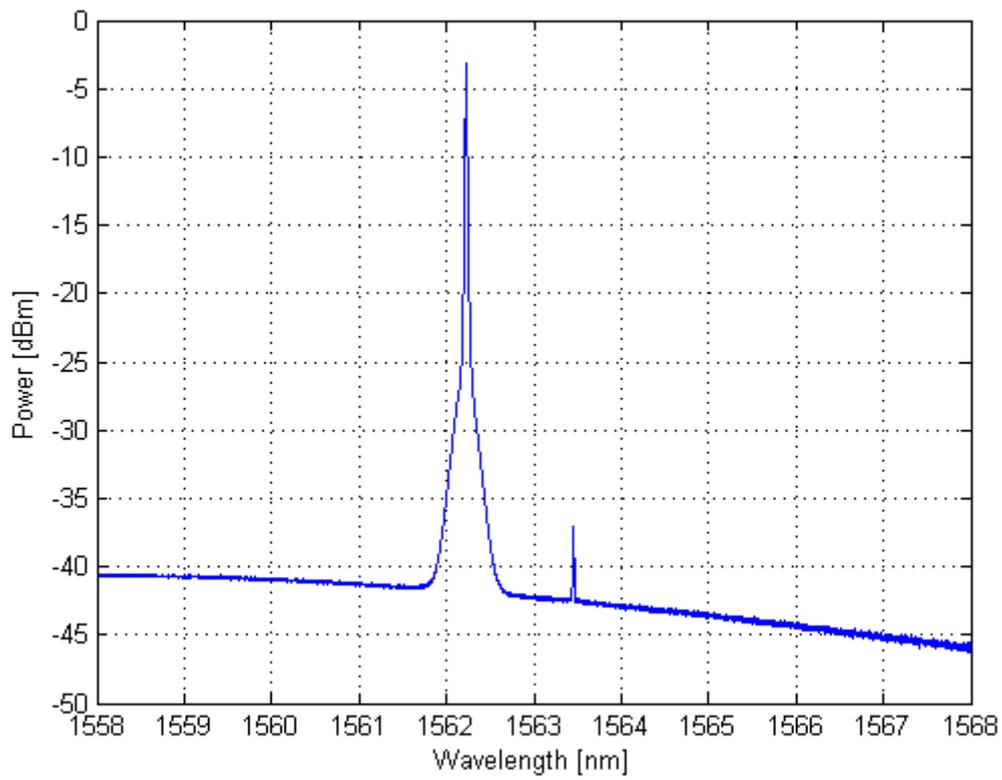


Figure 53: Measured spectrum of the converted temporal signal in the Signal converter

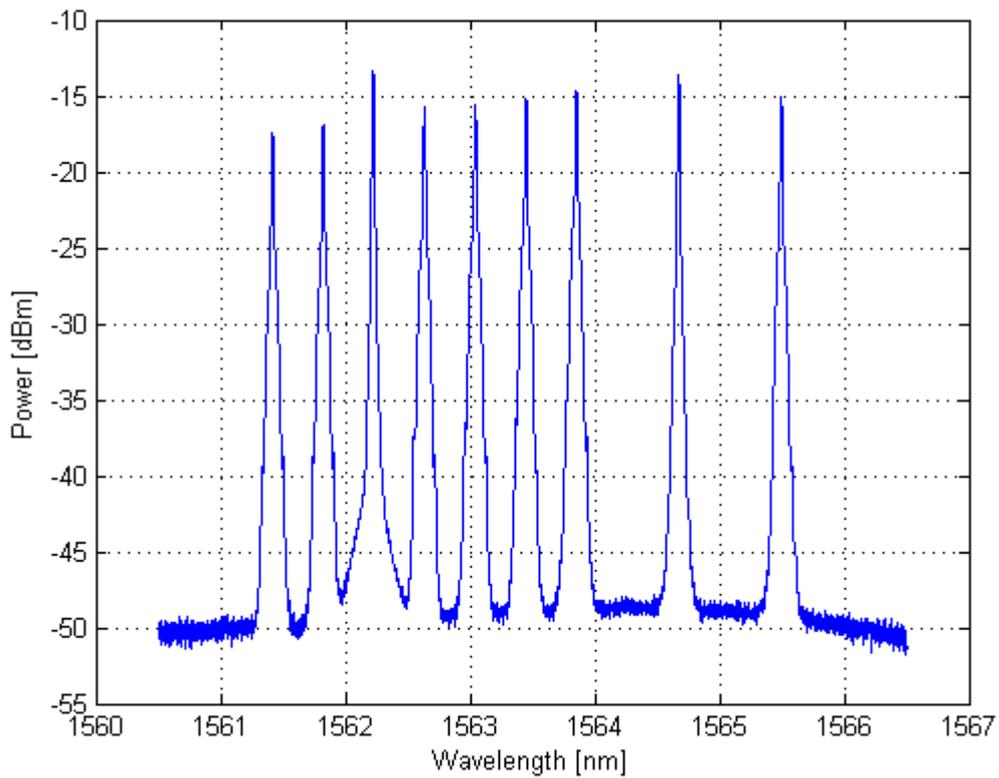


Figure 54: Measured spectrum of the multiplex after resolving congestion

The multiplex of data traffic and the temporal signal was carried over an optical link and the spectrum was monitored with measured spectra after 700 km and 1450 km of the second fibre link displayed in Figure 55 and Figure 56 respectively. It can be seen that the amplified spontaneous emission from the EDFAs is accumulated along the link and the optical spectrum is shaped according to the spectral gain of the EDFAs utilised. Although all EDFAs have flattening filter technology, a technology that should equalise the spectral gain distribution across the spectral multiplex with optical channels at longer wavelengths, the longer wavelength channels are still preferred after a small number of fibre spans. Clearly, a spectrum equaliser should be utilised every six or seven spans to keep the reasonably spectrum flat.

The total measured delay between the TTAs was 9.697656 ms that corresponds well to link length and the high number of EDFAs at the link as well as the long HNLF inside the Signal converter.

We have demonstrated a transfer of temporal signal over 1950 km that is crucially important for international applications of atomic clock comparisons. Moreover, traffic congestion has been resolved along the link by moving the temporal signal to a new wavelength in the Signal converter.

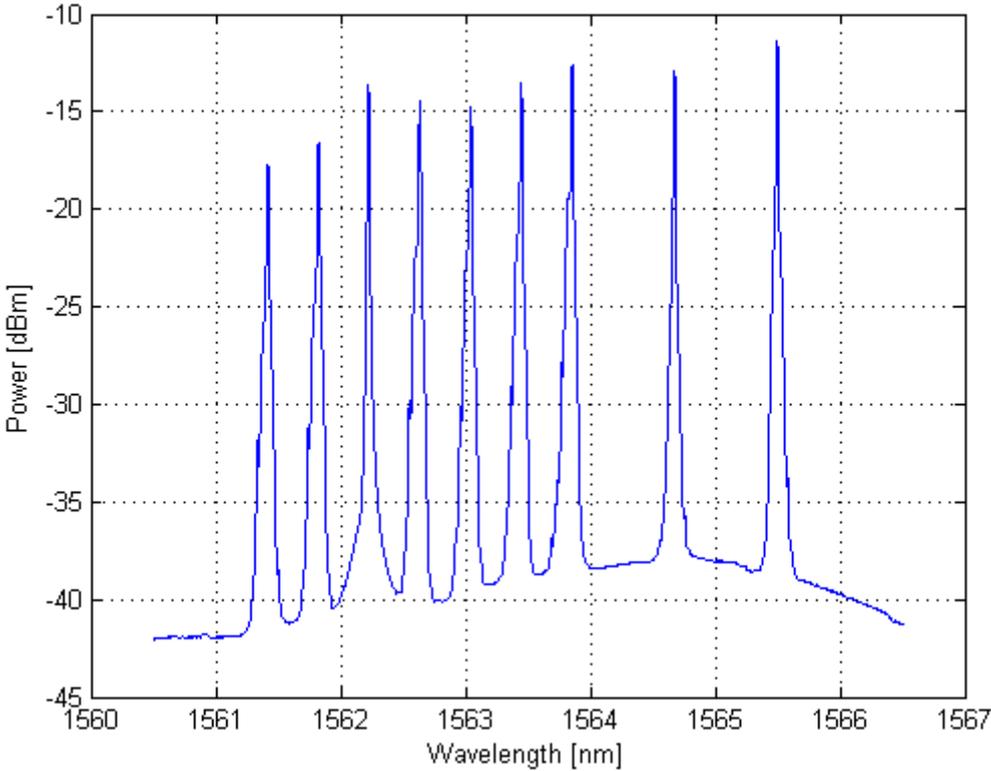


Figure 55: Measured spectrum after 700 km of the second fibre link

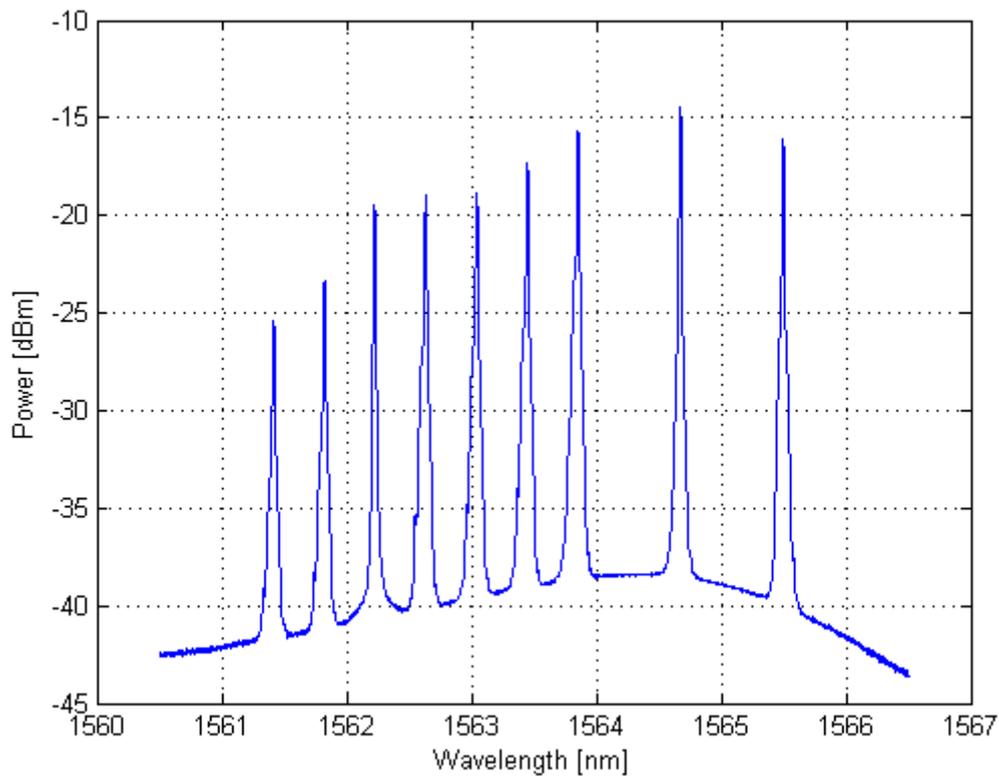


Figure 56: Measured spectrum after 1450 km of the second fibre link

8.5 Conclusion

The optical signal converter was first tested at a time transfer application over 50 km of the optical fibre on a spool. The time transferring application ran smoothly while reporting a propagation delay of 252.799 ms that matches the propagation theory. Since time transfer application is designed to connect two atomic clocks over a great distance, we verified signal propagation after its conversion in an optical signal converter, over an optical long-haul testbed. The long-haul experiment showed that the converter was capable of working over 1100 km of amplified optical links. Moreover, verifying the functionality of resolving wavelength contention in a network node we designed a real life experiment. The time transfer application shared spectra at the DWDM grid with 60 Gbps of traffic for 500 km to a node where another 20 Gbps of traffic were added and collided with the time transfer application. The optical signal converter moved the time transfer application to a free optical channel and all traffic travelled together another 1400 km to its destination. It was proven that the time transfer application could be converted to a different optical channel and carried over almost 2000 km. A further improvement in application performance may be achieved by stabilising

propagation delay. The optical signal converter may also be utilised to stabilise fast and slow propagation delay changes.

9 Stabilisation of the time transfer signal

The travel delay of the time signal between two TTAs fluctuates over time as a result of environmental changes around the optical link where the signal travels. The magnitude of fluctuations is dependent on the number of parameters of the fibre link, temperature and vibration changes and, especially, the length of the fibre link. The delay for the time transfer link between Prague and Vienna described in chapter 6.1 fluctuates in the range of 300 ns over a full year. This fluctuation is a superposition of fast and slow delay changes. Fast changes are explained by local events such as vibrations or stress at fibre link and have quite a small magnitude of only a few ns within a minute. Slow changes are, on the other hand, related to seasonal and day temperature changes and result in a large fluctuation of hundreds of ns.

9.1 Delay stabilisation through temperature conditioning

The dielectric medium of optical fibre slows propagating light down to a fraction of the speed of light according to the refractive index which is dependent on the actual temperature of the optical fibre and has a direct impact on propagation delay in the optical fibre. Such behaviour can be utilised to stabilise slow changes of delay in the optical fibre link. In order to evaluate temperature dependence of the refractive index for optical fibre, we enclosed a fibre spool in the temperature controlled environment. We conducted an experiment where the temperature of the controlled environment was changed from 6°C to 45°C and the temperature dependence of the total propagation delay was measured. The measurement had 6 fixed temperature points where the temperature was allowed to pervade the bulk material of the fibre spool. The fibre G.652.D delay dependence on temperature is shown in Figure 57.

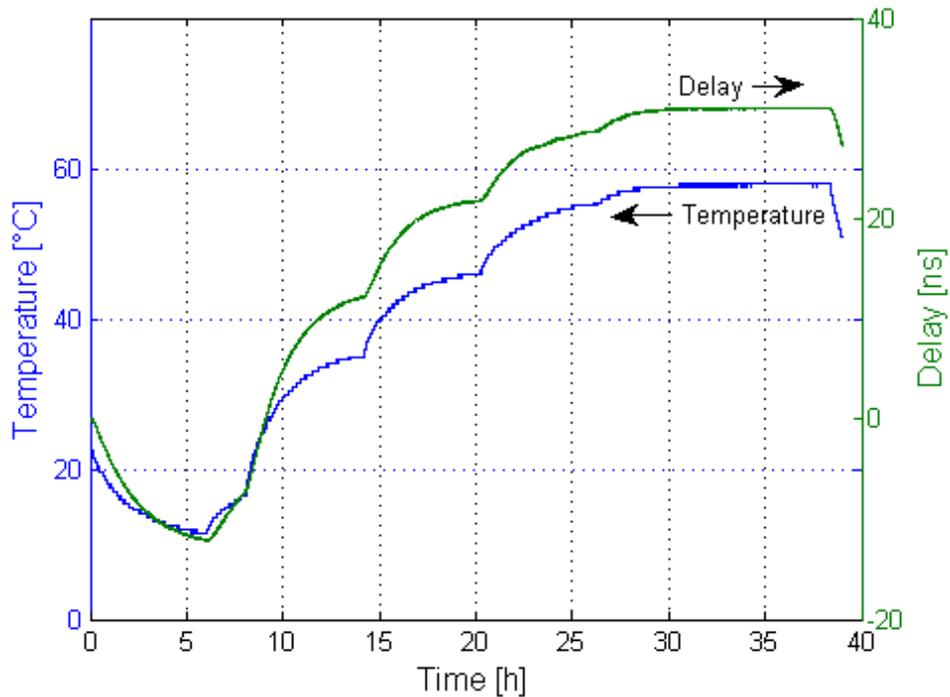


Figure 57: Delay dependence on temperature for G.652.D

Our temperature controlled environment took around 6 hours to stabilise at a fixed temperature point. We evaluated the three most common optical fibre types: a standard single mode fibre G.652D with dispersion around 17.5 ps/nm*km at 1550 nm, and two dispersion shifted fibres G.655.C and G.655.E with dispersions of 5 and -3 ps/nm*km respectively. Their temperature dependence is summarised in Table 13.

Temperature dependence of delay in optical fibres		
Fibre Type	Delay change of tested fibre spool with temp. [ns/K]	Delay of fibre [ps/km/K]
G.652D	0.9186	36.74
G.655.C	0.8994	35.96
G.655.E	0.9980	39.92

Table 13: Summary of temperature tests of optical fibres

The first column shows fibre type. The second column contains propagation delays through 25 km of the optical fibre at 30°C. Finally, the last column shows delays in picoseconds for one kilometre when the temperature is changed by 1 K. It shows that fibre with high zero dispersion wavelength, as in the case of our G.655.E, has slightly stronger temperature dependence.

Although there is a considerable time constant for a fibre spool to change its temperature, the aim of this method is to compensate for the slow effects that follow a single trend. Fast effects are compensated by the stabilisation method described in the next section.

9.2 Delay Stabilization through Wavelength Tuning

Light propagation theory in optical fibres shows that the total delay of propagation is dependent on the length of line L and the refractive index of the fibre as

$$\Delta L = \frac{c}{n(\lambda)} \Delta t \quad (23)$$

where c stands for the speed of light, $n(\lambda)$ is the wavelength dependent refractive index and Δt is the measured delay. Since the propagation delay depends on the refractive index that is a function of the wavelength, there is a difference in propagation delay ΔT between any two signals having different wavelength by $\Delta\lambda$. We may calculate it as

$$\Delta T = D \cdot \Delta\lambda / n(\lambda) \quad (24)$$

where D stands for fibre dispersion and L is the length of the line. The dispersion is also dependent on the wavelength of signals but may be considered constant for a small number of channel tunings.

We performed a simple wavelength conversion experiment where the time signal was tuned at a range of several hundred GHz ITU channels and then sent over the optical link. The setup is shown in Figure 58 where TTA stands for the Time Transfer adapter, TLS is the Tunable Laser Source and WC is the Wavelength Converter. The TTA produces a signal with a time stamp that is recognised by other TTA that evaluate the total delay between TTAs. Both TTAs were synchronised from a single time source. The WC in the experimental setup utilised a nonlinear Four Wave Mixing (FWM) process in Highly Nonlinear Fibre that tunes the time signal from TTA to a new wavelength according to the actual wavelength of the TLS. The tuned time signal propagates through a 50 km link of G.652 to be received at destination TTA. The first measurement was taken as a reference with a tuned time signal at 1550.12 nm and the total delay measured was 251361.1 ns. Then we tuned the signal by 200 GHz and 800 GHz to measure the total delay of 251359.51 ns and 251367.0 ns respectively as shown in

Table 14. The table shows that the delay difference per channel difference and 50km of fibre link are about 0.72ns.

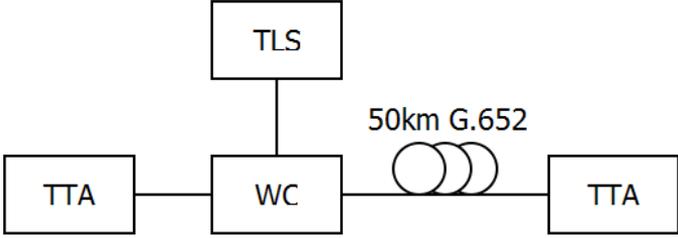


Figure 58: Simple wavelength conversion setup

Detuning [channels]	Delay [ns]	Channel difference [channels]	Delay difference [ns]
2	251361.1	Reference point	Reference point
3	251359.51	2	1.41
-2	251367.0	8	5.9

Table 14: Summary of wavelength conversion of the temporal information experiment

The measured values reflect our expectations in theory, where the distance travelled by light through a dielectric medium of the optical fibre with a refractive index of 1.468 (ITU G.652) in 251361.1ns follows equation (24).

9.3 Stabilisation methodology rules

The stabilisation of time transfers involves a combination of multiple methods to enhance the performance of a time transfer. Methods include optical delay lines, temperature conditioning and wavelength tuning. An Optical delay line represents a reasonably compact device with quick response time to changes in transmission delay. Unfortunately, it offers just a limited range and, therefore, limited stabilisation range. Temperature conditioning is a method for addressing slow delay changes and its effect depends on optical fibre length inside the controlled environment. Lastly, wavelength tuning may address both fast and slow delay changes. Its efficiency depends on the length of the optical link beyond the optical signal converter and the amount of signal detuning. The efficiency of each method is summarised in Table 15.

The methodology may be easily applied to the traffic congestion scenario described in Chapter 8. If we added, for instance, 100 km of temperature conditioned fibre at the beginning of the scenario, and then we would be able to stabilise 60 ns of slow delay changes. The optical signal converter was able to change the signal wavelength prior to 1400 km of the optical link. It offers up to 294 ns of slow stabilisation and 8.4 ns of fast stabilisation. In this scenario, we would be able to stabilise as much as 260 ns of delay changes.

Optical delay line		Temperature conditioning 60°C		Wavelength tuning 0.2 channel		Wavelength tuning 7 channels	
Distance [mm]	Delay [ns]	Spool [km]	Delay [ns]	Link distance [km]	Delay [ns]	Link distance [km]	Delay [ns]
1	0.003	50	30	50	0.3	50	10.5
300	1	100	60	100	0.6	100	21
500	1.66	200	120	200	1.2	200	42
1000	3.32	400	240	400	2.4	400	84
		500	300	500	3	500	105
				600	3.6	600	126
				800	4.8	800	168
				1000	6	1000	210

Table 15: Stabilisation methodology – efficiency of evaluated methods

9.4 Conclusion

The performance of the time transfer application is based on the stability of the end-to-end propagation delay. The propagation delay variation of optical links depends on many factors closely connected to the technologies used during the fibre link deployment. Despite the source, delay variations can be as fast as seconds and as slow as days. The fast variations are small in amplitude while slow variations have a larger scale. We combined the temperature conditioning device with wavelength tuning in the optical signal converter to address propagation delay stabilisation. In combination, they are able to stabilise propagation delays from units of nanoseconds for fast changes, to hundreds of nanoseconds for slow changes. Clearly, a lot of innovation can be done at the optical layer if the optical network is open and flexible enough to accommodate new ideas. Based on our experience, we propose the following methodology when designing academic optical networks.

10 Proposal of a new methodology for implementation of Photonic services

Optical research and educational networks are very different from commercial networks due to the multitude of differences in their purposes. This fact implies that the optimal design of the Photonic Services within academic networks has to be based on different priorities.

The main difference of these networks is in the number and character of customers. While commercial networks are highly capacity oriented to deliver standard services to a massive amount of users, academic networks have to support various novel networking concepts as described in Chapter 2. Also, the character of service requests is usually very different. Commercial networks establish and terminate services for users on an everyday basis, but academic networks are much more static with changes occurring on a scale of days. Another principal dissimilarity is in the network utilisation. Commercial networks feature a very high utilisation of network capacity since unused resources reduce available profit. Academic networks are funded for their availability to community users and they usually have a large percentage of unused capacity. The last notable difference is in their flexibility in adding new services. Academic networks are in place to provide a community with an environment enabling the demonstration of new applications in their early stages. Commercial networks, on the other hand, implement new services with the intention of making a profit and enlarging the customer base.

The principal differences impact the main traits of network designs. These traits are summarised in Table 16.

Network	Owner requirements	Design traits
Commercial	Serves a huge customer base Schedules standard services on request Utilises most of the capacity of optical networks Introduces new services according to roadmaps	Maximum capacity High-level network management High network utilisation Standard network parts/protocols
Academic	Small number of users/customers/partners Rather static network settings Low network utilisation Flexible enough to set up new services	Large area covered No need for complex management Simple network capacity design Full control over network

Table 16: Traits and differences of optical networks

Clearly, the implementation of Photonic Services in academic networks requires a network operator to digress from traditional leased circuits and capacity and to adapt new beneficial concepts that will be discussed in following chapters. Firstly, we do recommend implementation of dark fibre infrastructure concept that ensures network operator control over the underlying fibre infrastructure. This concept is further described in Chapter 10.1.

Once there are network resources available for the network operator, an optical fibre transport system may be freely chosen. This gives the network operator desired freedom to select the transport system that suits the best to the purpose of the network, and type of customers. Implementation of Photonic Services requires flexible spectrum allocation through network nodes and flexibility of the transport system. It is, generally, quite challenging to find the transport system with flexibility and functions outside the standard features delivered to commercial networks. Exceptionally, the network operator may negotiate an exclusive contract with a small optical transport system vendor to provide extra flexibility, but more likely the flexibility has to come from an open character of a DWDM network solution. The Open DWDM system concept is more discussed in chapter 10.2. This has been implemented in the open DWDM system called Czech Light, where the author of the thesis has been participating.

With the full control over an optical network infrastructure and transport system, the network operator may adopt cost-effective networking concepts of Nothing in Line (NIL) that allow single hop transmission over more than 200km and Single Fibre Transmission (SFT) that uses just one fibre for bidirectional communication. NIL is explained in chapter 10.3 and SFT in chapter 10.4.

Academic networks with low network utilisation may explore various concepts of sharing network resources with local partners. Sharing models are described in chapter 10.5.

Lastly, some applications for REC require all-optical network design to successfully implement Photonic Services. All-optical network concept is discussed in chapter 10.6.

10.1 Dark fibre infrastructure concept

Dark fibres represent a concept that allows the network operator to design and set up the optical network entirely according to the wishes and desires of the network operator. NREN network infrastructure may be built from leased capacity circuits and leased wavelengths that will bring considerable savings but renders NREN remains fully dependent on the capacity of the provider with minimal possibilities to introduce new network services. It is, therefore, essential for NRENs to base

their networks on dark fibres to reach the full access and control over an optical fibre infrastructure in order to allow NRENs to deploy any technology on top of it, particularly a technology that suits the best. Such dark fibre infrastructure concept allows NREN to build on top of the dark fibre infrastructure a future-proof network that allows implementation of Photonic Services and is flexible to REC requests. The dark fibre infrastructures may be either leased or owned as it is summarised for several types of network infrastructure in Table 17. However, it is clear that Photonic Services, defined at optical layer, are not supported by leased circuits or wavelengths.

Infrastructure Type	Cost	Flexibility	Photonic Services
Leased circuit or capacity	Low	Minimal	Not supported
Leased wavelength (lambda services)	Medium	Average	Not supported
Leased optical fibre (dark fibre)	High	Excellent	Supported
Owned optical fibre (dark fibre)	Extreme	Excellent	Supported

Table 17: Types of infrastructure and their costs, flexibility and ability to implement Photonic Services

10.2 Open photonic network devices concept

A communication network that is required by the REC should flexibly react to community needs to fulfil its role. The flexibility of networks strongly depends on the nature of the network and the expertise of the NREN’s staff. Expertise can be gained from proper training in networking, but hands-on experience is best obtained through practice with transport system’s hardware. Most optical network vendors deliver turn-key systems suitable for telecommunication operators seeking maximum network capacity at the price of its customization and flexibility. NREN network that allows nothing more than a network of ISPs and telecommunication operators may be easily considered redundant or even competition to the private sector. Therefore, the added value of NREN network flexibility should be evident. It translates into the nature of the network that is best shaped if network devices are open to modifications and enable added value through new services for REC. A great example is the pilot project described in Chapter 6. The openness of photonic network devices could be referred to similar approaches in open sources, open standards and open information [98]. This approach ensures access to all information about the device and creates the opportunity for end-users, such as NREN experts, to customise it to suit whatever application is requested by the REC. Open photonic network devices usually have a modular design so any part can be replaced by the latest model or desired manufacturer, as presented in [101]. All technical documentation is freely available and supported by the community [99]. The author took part in the design of Czech Light

open DWDM transmission system, a full family of network devices that can form an optical transport system to follow the latest trends [100][102]. Flexibility and openness of optical transport system simplify the implementation of Photonic Services.

10.3 Nothing-in-line concept

Most vendors have optimised their optical systems for maximum capacity and the customer has to provide housing for network equipment every 80 km to maintain optimal OSNR of signals under standard network conditions. Such a request can be complicated or even impossible in some places. For instance, it would be challenging to provide secure housing with electricity in the middle of a barren land [103]. The control over both optical infrastructure and optical transport layer discussed in previous chapters enable the network operator to use nothing-in-line concept and overcome single spans of lengths around 200 km. It has been successfully demonstrated [104] and an example is given in Chapter 6 for the Brno-Vienna link. The more detailed schematic is available in **Figure 59**. Xenpak-DWDM denotes ports located at the respective locations. The dashed blue lines that are coming out of multiplexers shows passing channels. DCU stands for dispersion compensation units made of fibre Bragg gratings to compensate for the link dispersion. CLA PB02 shows the locations of preamplifier and booster amplifiers that compensates for link attenuation. The fibre link has 50 dB of attenuation that is close to the limit of EDFA amplification technology for DWDM and becomes also the reason for having DCU between amplifiers and multiplexers, though Raman assisted amplification or hybrid EDFA-Raman technology will show better results [105]. Moreover, the majority of optical CzechLight links of CESNET have fibre spans in the range of 100-200 km. The Open DWDM system Czech Light was designed to support spans as long as around 200 km. The degradation of OSNR of Photonic Services is acceptable for countries with maximum optical path length lower than 1000 km.

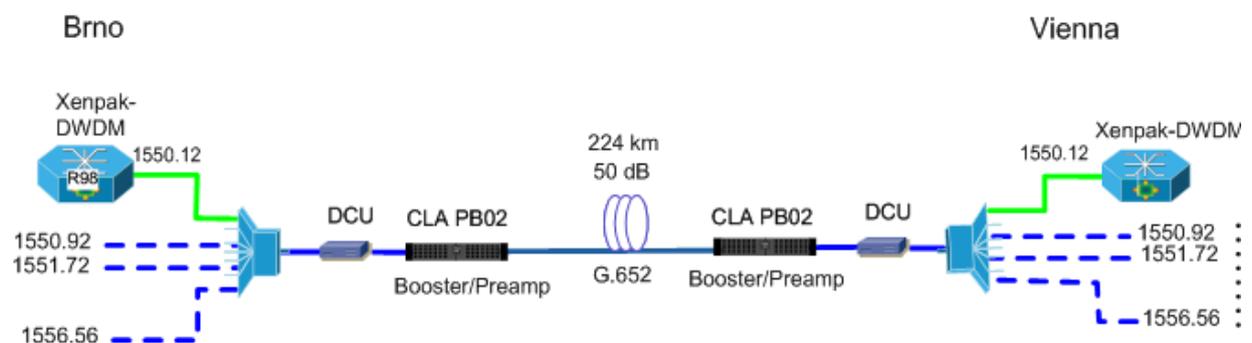


Figure 59: Nothing-in-line design of the cross-border optical link between Brno and Vienna

10.4 Single fibre transmission concept

The optical communication system usually requires a pair of optical fibres, one for each direction. Sharing just a single optical fibre for both directions has been commercially available for quite some time, but it was seldom deployed in the field. It is mainly because the market is oriented to telecommunication networks providers needs and there is usually a large fibre plant available. Still, the annual rental of fibre pairs in central Europe is about 0.2-1 EUR/metre/year [106][107] and the rental of a single fibre comes at 60% of the price of a fibre pair. The annualised cost of a commercial transmission system is about 0.12 EUR/metre/year for 4 years amortisation and 10 Gbps transmission rate, and from 0.035 to 0.047 EUR/metre/year for Czech Light open DWDM transmission systems [106]. Bidirectional SFT has just half the capacity of fibre pair, but if it is considered more than 70 optical channels, at 100 GHz grid, just within the C-band then one can easily have 350 Gbps data flows in both directions with well matured 10Gb NRZ transceivers. Since that capacity is not as often required by any NREN, I can see bidirectional SFT as a promising approach for emerging NRENs with limited resources. Photonic Services may be implemented also over single fibre transmission links.

10.5 Cost-effective Fibre sharing concept

Academic networks generally have a large percentage of free capacity that can be shared to reclaim some cost of the network. Some of them may find a legal way to share one network system with a commercial company that utilises otherwise unused capacity. The rest have an option to use some cost-effective concepts if they oversee their optical infrastructure. Academic networks may save close to 40% of infrastructure costs if they deploy SFT in their network. SFT will limit the capacity of a link to one-half, or around 40 channels of 10G or 100G signals if only C-band is used, which is usually more than sufficient for most academic network links. SFT may use interleaved signals according to their direction or reserve “blue and red” bands for separate directions. Nowadays optical systems have the capacity to transmit in the C-band and L-band. That opens the option to separate users from their respective frequency bands with most monitoring capability guaranteed. Sub-band spectrum sharing is now being piloted in academic networks with the granularity of optical channels based on the Alien wave technology discussed in Chapter 5.2. There are a few novel techniques that use Multicore fibres [108] and Few-mode transmission [109], but they have been still just being researched and developed and are not expected to reach the market soon. The methods discussed are summarised in Table 18. For each sharing concept, we specified resource needed, multiplex used

and system isolation. We have also proposed a number of users sharing the resource and assesses the maturity of sharing concepts. Photonic services require an available spectrum slice throughout the network and are therefore compatible with the band and sub-band sharing concepts.

Concepts	Multiplex	Insulation	Resource	Users	Maturity
SFT	spatial	Perfect	Single fibre	2	Commercial
Multicore fibres	spatial	crosstalk of cores	Single fibre or pair	<10	Research
Multimode	Modal	crosstalk of modes	Number of modes	<10	Research
Band	Frequency	Guard band	Frequency band	<3	Commercial
Sub-band	Frequency	Guard band	Frequency sub-band	<10	Pilot
Interleaved	Frequency	Direction	Half capacity	2	Commercial

Table 18: Fibre sharing methods for academic networks

10.6 All-optical networks concept

Once an NREN acquires a dark fibre infrastructure, they have to select whether they will use open, commercial or multivendor systems. Clearly, commercial systems allow only features that vendors are aware of and are prone to fast modifications to REC requests. In contrast, open systems permit all modifications and give a full hands-on experience to NREN experts who shape the network according to current needs. Therefore, it is possible to form truly all-optical network layer that can establish a light-path between any locations in the network. Such a network satisfies even the most demanding REC requests, such as atomic clock comparison [110], and is suitable for any other application with strict requirements on latency jitter. All-optical networks are limited in their reach by the lack of all-optical regeneration that remains a challenge for the research community.

10.7 Conclusion

The traits of commercial and academic networks differ in many aspects. Although it is generally possible to build a flexible academic network from commercially available systems, special attention has to be paid in its design. Most of the flexibility required from an academic network is based on controlling the physical infrastructure. Without a dark fibre infrastructure, it is very difficult to obtain a well-tailored system for the needs of an academic network as moments arise when innovation is delayed by the cumbersome roadmaps of optical system vendors. Access to open optical systems that offer the full flexibility of network functions is increasing and will allow network operators to run

single fibre optical systems or links operated in a nothing-in-line regime. Many academic networks are also considering sharing their networks with partners to lower operational costs and increase network utilisation. This is generally considered to be a good choice unless it limits the potential of network innovation.

11 Thesis summary

The thesis has two main objectives. The first one is to propose a new methodology how to include special applications in optical backbone networks and while recommending design features for research and education networks to allow them to introduce special applications effectively in their networks. And the other objective, in order to validate the first aim, to design, optimise and demonstrates an optical signal processing device for solving wavelength contention in optical backbone networks.

The current state of optical research and education networks was discussed with an emphasis on the European community. A number of special applications, which are generally supported only by research and education networks, were presented to specify network requirements for such applications in detail. The special application of time transfer for optical networks was selected to demonstrate its coexistence with standard data traffic. Techniques for optical signal regeneration and processing were studied to select FWM as a suitable nonlinear method for processing of special optical signals. This specific optical processing device has been designed to prevent signal contention with data traffic by an all-optical processing method.

The concept of **Photonic Service**, a technique to include special applications to optical networks, has been defined. It reserves optical spectrum and optical light-path for each special application to maximise network transparency and is compared to concepts of Alien Wave and Lambda Service.

A special application of the time transfer was piloted in Czech research and education network with superior results to the traditional GPS method. The time transfer pilot was designed as an international Alien Wave and the stability of the transceivers used and their influence on the special application was measured.

A signal converter was designed to maximise the transparency to signal characteristics by employing the nonlinear four-wave mixing effect in a highly nonlinear optical fibre. The functional blocks of the signal converter were optimised to maximise conversion efficiency while maintaining a simple design which emphasised nonlinear media efficiency, polarisation alignment and pump power level.

The optical parameters of signals processed by the optical signal converter in long-haul optical fibre testbed to reach almost 1200 km were evaluated. A realistic solution to traffic congestion of IP data traffic with the temporal signal of the time transfer was demonstrated as the signal converter effectively changed the carrier wavelength of the temporal signal to prevent wavelength contention. The demonstration was performed over two links with a total length of 2000 km.

Finally, a new methodology for implementation of Photonic services was finalised with respective concepts of dark fibres, nothing-in-line, single fibre transmission, open photonic devices and flexible photonic layer. An analysis of cost-effective fibre sharing methods was proposed with the advantages of the flexible photonic layer being emphasised.

The author took a part in the design and development of Czech Light open DWDM transmission system for backbone networks that was also used during the demonstration of the traffic congestion scenario. The full list of utility models and functional samples developed can be found in annexe A4.

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Annexe

A1. List of lighting technologies in European National Research and Education Networks

NREN name	Country	DWDM Lighting technology
ACONET	Austria	Alcatel-Lucent
AMRES	Serbia	
ARNES	Slovenia	Adva
BASNET	Belarus	
BELNET	Belgium	
BREN	Bulgaria	
CARNET	Croatia	leased services
CESNET	Czech Republic	Cisco, Open(CzechLight)
CYNET	Cyprus	
DFN	Germany	ECI
EENET	Estonia	
FCCN	Portugal	Huawei
FUNET-CSS	Finland	NSN, Ciena-Nortel
GARR	Italy	Huawei
GRNET	Greek	Alcatel-Lucent, ADVA
HEANET	Ireland	Adva
JANET	Great Britain	Ciena-Nortel
KAZRENA	Kazakhstan	
LITNET	Lithuania	Adva, Transmode
MARNET	Macedonia	
MREN	Montenegro	
NIIF	Hungary	Alcatel-Lucent
NORDUNET	Scandinavia	
PIONER	Poland	ADVA
REDIRIS	Spain	Alcatel-Lucent
RENAM	Moldavia	
RENATER	France	Alcatel-Lucent, Ciena
RESTENA	Luxembourg	

RoEduNet	Rumania	Ciena-Nortel
SANET	Slovakia	
SigmaNet	Latvia	leased services
SURFNET	Netherlands	Ciena-Nortel
SWITCH	Switzerland	Sorrento, BTI
ULAKBIM	Turkey	Ciena-Nortel
UOM-CSC	Malta	
URAN	Ukraine	

Table 19: Transmission system vendors of European NREs

A2. Author's impacted journal papers related to doctoral thesis

1. J.Vojtech, M. Slapak, P. Skoda, J. Radil, O. Havlis, et al., „**Joint accurate time and stable frequency distribution infrastructure sharing fibre footprint with research network**“, Opt. Eng. 56(2), 027101 (Feb 06, 2017). <http://dx.doi.org/10.1117/1.OE.56.2.027101>
2. P. Skoda, J. Radil, J. Vojtech, M. Hula, „**Analyses of 100 Gbps Coherent System Performances**“, Radioengineering, 2013, vol. 22, n. 2, s. 632-637. ISSN 1210-2512
3. P.Honzatko, A.Kumpera and P.Skoda, „**Effects of Polarization Dependent Gain and Dynamic of the SOA on Performance of the Ultra Nonlinear Interferometre Gate**“, Opt. Express, vol. 15, 2541-2547,2007

All authors hold equal share in the joined publications.

A3. Author's impacted journal Papers not related to doctoral thesis

1. B. Kelleher, C. Bonatto, P. Skoda, S. P. Hegarty, and G. Huyet, „**Excitation regeneration in delay-coupled oscillators**“, Phys. Rev. E 81, 036204, 2010

All authors hold equal share in the joined publications.

A4. Author's utility models and functional samples related to doctoral thesis

1. M. Karásek, J. Vojtěch, J. Radil, P. Škoda, „**Modular building box for all-optical conversion and copying of optical signals for the spread of the Internet and other networks**“, Utility Model, CESNET, 2011
2. P. Škoda, J. Vojtěch, V. Smotlacha, J. Radil, „**CL-WC-FWM, Czech Light wavelength converter for special applications**“, Functional Sample (in registration process), CESNET, 2016
3. J. Vojtěch, M. Hůla, V. Smotlacha, P. Skoda, „**CLA BIDI O/E, Czech Light amplifier for interleaved bidirectional channels**“, Functional Sample, CESNET, 2012
4. J. Vojtěch, T. Uhlář, M. Karásek, M. Hůla, P. Škoda, J. Radil „**CL TLS, Czech Light Tunable Laser Source**“, Functional Sample, CESNET, 2009

5. J. Vojtěch, M. Hůla, J. Radil, M. Karásek, S. Šíma, P. Škoda, "**CL DS-WSS, Czech Light Dual Stage Wavelength Selective Switch**", Functional Sample, CESNET, 2010
6. J. Vojtěch, P. Škoda, M. Hůla, T. Uhlář, J. Radil, M. Karásek, S. Šíma, "**CL VMUX/VDEMUX, Czech Light colorless Variable Multiplexer/Demultiplexer**", Functional Sample, CESNET, 2009
7. J. Vojtěch, M. Hůla, P. Škoda, J. Radil, S. Šíma, T. Uhlář, "**CL DGD, Czech Light Differential Group Delay emulator**", Functional Sample, CESNET, 2011
8. J. Vojtěch, M. Hůla, P. Škoda, S. Šíma, V. Smotlacha, "**CLA I BIDI, Czech Light Amplifier for bidirectional amplification**", Functional Sample, CESNET, 2011
9. J. Vojtěch, T. Uhlář, M. Hůla, P. Škoda, M. Altmann, M. Karásek, S. Šíma, J. Radil, "**CLM 4x8, Czech Light Multicasting Switch 4 inputs 8 outputs**", Functional Sample, CESNET, 2009
10. M. Karásek, J. Vojtěch, J. Radil, P. Škoda, "**CL WC MZI, Czech Light Wavelength Converter utilizing Mach-Zehnder structure**", Functional Sample, CESNET, 2009

All authors hold equal share in the joined utility models and functional samples.

A5. Author's utility models and functional samples not related to doctoral thesis

1. M. Komanec, P. Škoda, S. Zvanovec, "**Pulse Fibre Ring Laser**", Functional Sample, ČVUT v Praze, 2011

All authors hold equal share in the joined utility models and functional samples.

A6. Author's peer-reviewed conference papers related to doctoral thesis

1. P. Škoda, M. Altmann, J. Vojtěch, J. Radil, V. Smotlacha and P. Škoda, "**Propagation delay stabilization to address fast and slow delay changes,**" 2016 10th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), *Prague*, 2016, pp. 1-4.
2. P. Munster, J. Vojtěch, T. Horvat, O. Havlis, M. Slapak, P. Skoda, J. Radil, M. Hula, R. Velc, "**Coexistence of access and backbone networks with sensor systems,**" 2016 International

- Workshop on Fibre Optics in Access Network (FOAN), Lisbon, 2016, pp. 1-5.
doi: 10.1109/FOAN.2016.7764538
3. J. Vojtech, J. Radil, O. Havlis, M. Altmann, P. Skoda and V. Smotlacha, "**Resilience of semiconductor optical amplifier with holding beam injection to reflections in bidirectional reciprocal operation**," 2016 18th International Conference on Transparent Optical Networks (ICTON), Trento, 2016, pp. 1-3. doi: 10.1109/ICTON.2016.7550629
 4. R. Velc, R. Vohnout, J. Vojtěch, P. Škoda, *et al.*, "Pre-Commercial Procurement in Optical Networking domain," *2016 18th International Conference on Transparent Optical Networks (ICTON)*, Trento, 2016, pp. 1-4. doi: 10.1109/ICTON.2016.7550485
 5. J. Vojtech, M. Šlapák, P. Skoda, J. Radil, O. Havlis, M. Altmann, P. Munster, V. Smotlacha, J. Kundrat, R. Velc, L. Altmannova, M. Hula, „**Joint accurate time and stable frequency distribution infrastructure sharing fibre footprint with research network**“, Proc. SPIE 9977, Remote Sensing System Engineering VI, 99770F (September 19, 2016);
doi:10.1117/12.2237205.
 6. J. Vojtech, V. Smotlacha, P. Skoda, „**Simultaneous transmission of accurate time and stable frequency through bidirectional channel over telecommunication infrastructure with excessive spans**“, Proc. SPIE 9598, Optics and Photonics for Information Processing IX, 95981A (September 9, 2015), doi:10.1117/12.2186959.
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doi: 10.1109/OGC.2015.7336835
 8. J. Vojtěch, V. Smotlacha, P. Skoda, „**Shared optical infrastructure for precise time transfer**“, International Conference on Information Engineering, Volume: 49, March 2014,
DOI:10.2495/ICIE20130121
 9. P. Škoda, E. Camisard, „**Time and frequency transfer over optical network**“, Proceedings of the Asia-Pacific Advanced Network 2013 v. 35, p. 20-27., 2013
 10. J. Vojtech, V. Smotlacha, P. Skoda, „**Transmission of Timing Sensitive Information Using Photonic Services**“, Applied Mechanics and Materials, Vols. 321-324, pp. 2343-2347, 2013
 11. J. Vojtěch, V. Smotlacha, P. Škoda, „**Transmission of Accurate Time Information Using Photonic Services**“, Advanced Materials Research Vol. 717 (2013) pp 870-874, Thailand, 2013
 12. J. Vojtěch, V. Smotlacha, S. Šíma and P. Škoda, "**Photonic services**," *2012 14th International Conference on Transparent Optical Networks (ICTON)*, Coventry, 2012, pp. 1-4. doi: 10.1109/ICTON.2012.6253805

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14. P.Škoda, J. Vojtěch, „**Fibre Pair Sharing**“, NORDUnet Conference 2012
15. Pavel Škoda, Jan Radil, Josef Vojtěch, Miloslav Hůla, „**Results of 100G Coherent DP-QPSK System Tests Performed in CESNET**“, OK 2012
16. R. Vohnout, L. Altmannova, S. Sima, P. Skoda, „**Infrastructure Overview with Focus on Exprimental Facility**“, 8th International ICST Conference, TridentCom 2012, Thessanoliiki, Greece, June 11-13, proceedings pp 11-17, 2012
17. J. Vojtech, V. Smotlacha, P. Skoda, S. Sima, J. Radil, M. Hůla, „**Photonic Services Enables Real-time Applications over Long Distances**“, ICP 2012 Proceedings, Malaysia, 2012
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20. P. Škoda, J. Radil, L. Altmannová, M. Hůla, S. Šíma, J. Vojtěch, „**Innovative photonic devices for emerging NRENS**“, UbuntuNet Alliance Proceedings 2011, KENET, ISBN: ISSN 2223-7062
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All authors hold equal share in the joined publications.