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Deliverable DJ1.2.2: State-of-the-Art Photonic Switching Technologies – Study and Testing

Deliverable DJ1.2.2

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Abstract

This document continues the investigations into state-of-the-art and emerging optical networking technologies documented in DJ1.2.1 in order to determine how GÉANT and the NRENs can develop their networks to meet future demands. It describes the tests conducted on 100G transmission technology; service restoration using GMPLS; alien wavelength; power consumption; a next-generation network solution based on the Alcatel-Lucent 1830 Photonic Service Switch platform; and time and frequency transfer tests in the context of Photonic Services.

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Executive Summary

This document continues the investigations into state-of-the-art and emerging optical networking technologies carried out by GN3 Joint Research Activity 1 Future Networks, Task 2 Photonic Switching and Experimental Photonic Facilities (JRA1 Task 2) documented in "Deliverable DJ1.2.1: State-of-the-Art Photonic Switching Technologies". Its objective is to prove and examine the implementation concept of six major state-of-the-art photonic technologies and services, to show how the implementations work in practice, and to share the experiences in order to make it easier for National Research and Education Networks (NRENs) to implement their chosen network technologies and services. The six areas covered are:

- 100G transmission technology (the terms 100G and 100 Gbit/s are used interchangeably throughout the document).
- Service restoration using GMPLS.
- Alien wavelength.
- Power consumption.
- A next-generation network solution based on the Alcatel-Lucent 1830 Photonic Service Switch platform.
- Time and frequency transfer tests in the context of Photonic Services.

100G Transmission Technology

With the structured development of 100G transmission technologies, falling 100G prices, and the efficiencies it brings in the optical layer, 100G is set to be the de facto standard for the foreseeable future. NRENs are therefore increasingly likely to consider the implementation of 100G channel capacities in their legacy Dense Wavelength-Division Multiplexing (DWDM) networks, and so they will find the results of investigation and field tests of 100G technology to be interesting and relevant.

The *100G Tests* chapter presents the 100 Gbit/s technology laboratory and field tests performed by the NRENs participating in JRA1 Task 2, including a brief description of the technology, facilities and equipment used, and their operational experience with regard to 100G. The tests feature solutions from Ciena and Alcatel-Lucent (ALU), who collaborated on the work.

The tests of the Ciena solution proved that a 10 Gbit/s DWDM infrastructure can be upgraded to 100 Gbit/s without disturbing the existing production traffic, and that wavelengths from different DWDM manufacturers can coexist successfully. The operational experience of installing the Ciena solution in an existing DWDM network resulted in a stable 100G circuit, with no alarms raised for one year. The tests of the ALU solution showed that a 100G coherent transmission system is resilient to many network impairments such as chromatic dispersion

(CD), polarisation mode dispersion (PMD), filtration and inter-channel interference, and that coherent systems can work over compensated networks with no known influence from the type of dispersion compensation; Fibre Bragg Grating should be preferred for chromatic dispersion compensation. New coherent systems can therefore be deployed in operational 10G Non-Return-to-Zero (NRZ) transmission systems as long as the network remains dispersion compensated. The tests verified that the ALU solution works with Cisco and CzechLight transmission systems within a multi-vendor environment; over single-fibre bi-directional transmission lines; and in parallel with photonic services such as atomic clock comparison.

GMPLS Implementations

Generalised Multi-Protocol Label Switching (GMPLS) is seen as one of the ways to achieve fully automated restoration and provisioning in the network, and is implemented by several DWDM vendors. The NRENs' interest in advanced control planes is related to the desire for Bandwidth on Demand solutions and to the general need for better control of complex networks. The *GMPLS in the Optical Domain* chapter describes the service restoration tests conducted on the production ADVA DWDM transmission system of an NREN network; services were restored in the optical domain using a modified version of GMPLS. The chapter describes the testbed environment and the goals of the tests, and discusses the signal flow configuration and requirements. The results cover service restoration times for: different types of faults, different numbers of switching services, switching with or without wavelength change, and switching with different path lengths.

The tests showed that service restoration in an ADVA transmission system is possible, with restoration taking approximately a few minutes. The restoration time depends heavily on the number of components that need tuning and equalising: adding ROADMs on the path causes an increase in restoration time of 30 seconds per ROADM. No differences in restoration time were observed to be caused by different physical fibre lengths between service termination points, different fault types (laser off, fibre cut) or different numbers of services.

Use of Alien Wavelength

Within the context of increasing demand for cross-border fibre (CBF) DWDM links between NRENs, the use of alien wavelengths via DWDM systems from different vendors, with no optical-to-electrical-to-optical (OEO) regeneration at the transition point, is an appealing concept. This approach reduces the cost per wavelength and offers a "greener" solution, while greatly simplifying the design of the intermediate Point of Presence (PoP) where the two DWDM systems interconnect, resulting in savings in both capital and operating expenditure (CAPEX and OPEX). The *Alien Wavelength* chapter describes the work carried out to establish an alien wavelength between Amsterdam and Copenhagen, from the first step of verifying optical line of sight to the complex task of validation and predicting performance using an advanced optical model for simulation of alien wavelength in multi-vendor, multi-domain DWDM scenarios.

The tests investigated the performance of the alien wavelength in terms of pre-Forward Error Correction Bit Error Rate (BER) for different values of the guard band between the alien wavelength and wavelengths carrying existing traffic. A near-optimum guard band of 150 GHz was found. The test results also determined a range of power for the 40 Gbit/s alien wavelength with negligible susceptibility to Self-Phase Modulation and acceptable BER performance. The simulation studies revealed that it is vital to use pre-studies – e.g. to identify the limiting factors in the system – to reduce computation time that can otherwise increase to days, and that even small inaccuracies in settings can effectively distort the signal beyond recovery. Work continues to predict and optimise the live system link more accurately, primarily in terms of launch power, channel spacing and the modulation format of neighbouring channels. A comparison of the CAPEX and OPEX of transmission systems with native (i.e. regenerated) and alien wavelengths showed that equipment costs dominate the cost of the transmission system at 98% of the total, with the second- and third-largest costs (energy and labour respectively) more than an order of magnitude less. In the most beneficial scenario with a 100 Gbit/s alien wavelength, CAPEX accounted for 98.7%, power 0.8% and labour 0.6%.

Power Consumption

Although the comparison mentioned above showed that energy costs for transmission systems are significantly less than the greatest cost (equipment), power consumption is nonetheless an important issue, for both environmental and cost reasons. The power consumption of network devices has increased steadily with the growth in Internet traffic and is approximately doubling every year. The *Power Consumption* chapter introduces the consumption indicator, which calculates power consumption for a core transport link from node A to node B based on basic link parameters; the indicator is given in the local currency per kilometre of link and year of service. It also shows the computation of the indicator for real examples and assesses the indicator's usefulness in comparing links.

The data shows that the open solution represented by OpenDWDM on the optical layer can reduce energy consumption by as much as three times. This in turn reduces operating expenditure, which may be a significant saving when considered over a five-year lease period with steadily increasing electricity costs.

NGN Solution Based on ALU 1830 PSS Platform

Chapter 6 describes an investigation of a next-generation network (NGN) solution to the delivery of photonic services based on the ALU 1830 Photonic Service Switch (PSS) platform. It provides an overview of the 1830 PSS series, discusses the different requirements for 40G and 100G solutions, and considers in detail the aspects of the 1830 PSS platform that make it an NGN architecture, particularly its colourless and directionless functionalities and dynamic reaction to network faults. It then describes the laboratory test environment and the following functional tests and results: measurement of channel spacing; chromatic dispersion (CD) resistance for coherent and incoherent transmission; and optical signal switching times.

The channel spacing measurement test showed that only coherent transmission for higher speeds (40G and 100G) can provide the spectrum width suitable for a 50 GHz ITU grid. The CD resistance tests compared 40G incoherent and 100G coherent signals; as expected, the errors were noticed first in the case of 40G transmission because the deployment of coherent transmission decreases the baud rate and spectral width and consequently provides higher resistance to signal dispersion. Testing of the optical signal switching times showed that when protection was forced by the Network Management System, the interruption time was approximately 0.3 ms; protection as a consequence of fibre cut took twice as long at 0.6 ms.

The introduction of 100G interfaces and new protection methods gives NGNs capabilities for restoration in the optical domain and guarantees of full capacity for primary and backup connections at all times. For optical transmission networks to be fully flexible, they should also feature colourless, directionless functionality, and base protection and restoration on advanced control planes, e.g. GMPLS. The advanced coherent modulation formats make the external dispersion compensation units (DCUs) obsolete, greatly reducing the losses and non-linear effects previously associated with the DCU. While coherent transmission and uncompensated optical lines are the optimum way to build DWDM networks, they prohibit the use of the large installed base of legacy DWDM systems and the associated 10G transponders with NRZ modulation format. Strong non-linear effects in non-zero dispersion shifted fibres can be limiting factors for the use of 40G and 100G transmission systems, and should still be taken into account when developing NGN networks.

Photonic Services

The *Photonic Services* (PS) chapter provides a description of PS – services between two or more points in an optical network, defined by their photonic path and allocated bandwidth – clarifying how they differ from alien wavelength and the GÉANT Lambda Service, and summarising their features and challenges. It goes on to consider examples of the demanding applications that require the quality of service delivered by PS, including interactive human collaboration, high-definition video, remote control of instruments and vehicles, comparison of atomic clocks, and ultra-stable frequency transfer, providing parameters and references for each. The chapter then presents the time and frequency transfer tests conducted by the JRA1 Task 2 NRENs, and concludes with a summary of the PS demonstrations they have carried out.

The demonstrations have confirmed that PS delivered over a well-controlled all-optical network without OEO conversion can meet the stringent requirements for low end-to-end latency and low latency jitter imposed by some NREN user applications. The time and frequency transfer tests produced similarly robust, ultra-stable results.

Conclusions

During the course of the GN3 project, optical networks have developed rapidly, to the point where coherent modulation formats for 40G and 100G are now commodity and advanced control planes are under development from almost all vendors, allowing restoration in the optical domain. The next steps with regard to capacity are 400G and 1T, while the concept of gridless Wavelength Selective Switch (WSS) components is gaining momentum, meaning that sub-band allocation (rather than channel allocation) may soon be the reality for newer DWDM networks, opening the way for more efficient use of the optical spectrum.

JRA1 Task 2 has investigated the developments that are of particular significance and relevance to the NREN community, and will continue to do so in Year 4 of the GN3 project. Planned topics include end-to-end provisioning of Photonic Services, transmission speeds above 100G, and extension and expansion of the alien wavelength tests. The Task will, however, remain flexible in order to respond to any changes in trends. It will also continue to work closely with vendors, to try to maintain the flow of ideas between NRENs and vendors, and to be well placed to provide the NREN community with information that will help them consider and implement their next-generation networks.

1 Introduction

The objective of this document is to prove and examine the implementation concepts of certain major state-of-the-art photonic technologies and services. The purpose is to show how the implementations work in practice and to share the experiences in order to make it easier for National Research and Education Networks (NRENs) to implement their chosen network technologies and services.

The document does not cover architectural or design models, or attempt to make a business case for applied solutions or technologies. The NRENs' focus is emerging technologies and the optimisation of operational and user experience. Neither does the document cover what NRENs in general have deployed when it comes to optical networks. Therefore it does not benchmark various technologies and architectural models against new emerging technologies and/or design recommendations coming from the industry.

The document covers six major areas as listed below:

- **100G transmission technology:** With emerging 100G transmission technologies and falling 100G prices, more NRENs will move towards implementation of 100G channel capacities in their Dense Wavelength-Division Multiplexing (DWDM) networks. The *100G Tests* chapter of this document covers a basic description of the equipment and facilities used in several test scenarios, including initial laboratory tests, experimental transmission tests and field tests.

- **GMPLS implementations:** Generalised Multi-Protocol Label Switching (GMPLS) is the enabling key to achieving fully automated restoration in the network. The *GMPLS in the Optical Domain* chapter describes the service restoration tests conducted by PSNC on the production ADVA DWDM transmission system of the PIONIER network; services were restored in the optical domain using a modified version of GMPLS. The chapter describes the testbed environment and the goals of the tests, and discusses the signal flow configuration and requirements. The results cover service restoration times for: different types of faults, different numbers of switching services, switching with or without wavelength change, and switching with different path lengths.

- **Use of alien wavelength:** The ongoing adoption of hybrid networking sparked the demand for cross-border fibre (CBF) DWDM links between NRENs. In this context, the use of alien (or foreign) wavelengths (also referred to in this document as lambdas) via DWDM systems from different vendors is an appealing concept. An alien wavelength is a DWDM wavelength that is set up between a transmitter and a receiver and then transported over the DWDM system of another vendor. In the case of a multi-domain alien wavelength, the alien wavelength is transported over multiple DWDM systems, of which one is from another vendor, where no optical-to-electrical-to-optical (OEO) regeneration is used at the transition between the two DWDM systems. This approach reduces the cost per wavelength compared to a 40 Gbit/s connection with regeneration, offers a “greener” solution, and greatly simplifies the design and operation of the intermediate Point of Presence (PoP) where the two DWDM systems interconnect. The *Alien Wavelength* chapter describes the work carried out to establish an alien wavelength between Amsterdam (SURFnet) and Copenhagen (DTU and NORDUnet), from the first step of verifying optical line of sight to the complex task of validation and predicting the performance utilising an advanced optical model for simulation of alien wavelength in multi-domain DWDM scenarios.

- **Power consumption:** The power consumption of network devices has increased steadily with the growth in Internet traffic and is approximately doubling every year [Neilson]. Today, the Internet consumes about 0.4% of total electricity in broadband-enabled countries [Tucker] and up to 8% in the USA [Bathula]. Such rapid growth of electricity consumption by large-scale distributed systems is becoming an issue. The *Power Consumption* chapter introduces the consumption indicator, which calculates power consumption for a core transport link from node A to node B based on basic link parameters. It also shows the computation of the indicator for real examples of core transport links and assesses the indicator’s usefulness in comparing links.

- **NGN solution based on ALU 1830 PSS platform:** Chapter 6 describes an investigation of a next-generation network (NGN) solution to the delivery of photonic services based on the Alcatel-Lucent (ALU) 1830 Photonic Service Switch (PSS) platform. It provides an overview of the 1830 PSS series, discusses the different requirements for 40G and 100G solutions, and considers in detail the aspects of the 1830 PSS platform that make it an NGN architecture, particularly colourless and directionless functionalities and dynamic reaction to network faults. It then describes the laboratory test environment and the following functional tests and results: measurement of channel spacing; chromatic dispersion resistance for coherent and incoherent transmission; and optical signal switching times.

- **Photonic services:** The *Photonic Services* (PS) chapter provides a description of PS, clarifying how they differ from alien wavelength and the GÉANT Lambda Service, and summarising their features and challenges. It goes on to consider examples of the demanding applications that require the quality of service delivered by PS, including interactive human collaboration, high-definition video, remote control of instruments and vehicles, comparison of atomic clocks, and ultra-stable frequency transfer, providing parameters and references for each. The chapter then presents the time and frequency transfer tests conducted by the JRA1 Task 2 NRENs, and concludes with a summary of the PS demonstrations they have carried out.

The document focuses on the implementation of the technologies and services; for the results of JRA1 Task 2’s initial study of photonic switching technologies, please see “Deliverable DJ1.2.1: State-of-the-Art Photonic Switching Technologies – Study and Testing” [DJ1.2.1].

2 100G Tests

2.1 Introduction

This chapter presents the 100 Gbit/s technology laboratory and field tests performed by the National Research and Education Networks (NRENs) participating in JRA1 Task 2, and their operational experience with regard to 100G. The tests feature solutions from Ciena and Alcatel-Lucent, who collaborated with the Task 2 team on the work.

100G represents the current state of the art for mature and available transmission technology. In contrast to the introduction of 40G, which suffered from a fragmented approach to its research and introduction, leading to multiple modulation formats and no economies of scale in the sub-supplier segment, the development of 100G has followed a framework created by the Optical Interworking Forum (OIF) and additional Multi-Source Agreements (MSAs). It is therefore expected that 100G will be the de facto standard for the foreseeable future, and that the price erosion will be faster than for 40G, yielding prices equal to five times 10G. In addition to the savings in the client layer connections (10G), 100G is ten times more efficient in the optical layer, releasing nine 10G optical channels per introduced 100G. For these reasons, investigation and field tests of 100G technology tests are of high interest and relevance for the NREN community.

2.2 Laboratory and Field Tests of Ciena 100G DWDM Solution

2.2.1 Introduction

This section presents a summary description of Ciena's 100 Gbit/s technology solution and an analysis of the 100 Gbit/s tests performed by RENATER during the second half of 2010 within the framework of the GN3 project.

Lab and field experiments were conducted in collaboration with the manufacturer Ciena, from whom 10 x 10 Gbit/s muxponders and Optical Multiservice Edge (OME) 6500 chassis (formerly from Nortel) had been leased. The muxponder features a 100 Gbit/s line-side interface, which is demultiplexed to 10 x 10 Gbit/s client interfaces.

The main purposes of the tests were:

- To validate the insertion of a 100 Gbit/s Dense Wavelength-Division Multiplexed (DWDM) wavelength on a live DWDM network based on 10 Gbit/s wavelengths, without any traffic disturbance or interruption.
- To gain experience in managing alien wavelengths. (Alien wavelengths were also the subject of a separate study, described in Chapter 4 on page 66.)
- To validate on the client side the expected, efficient and effective behaviour of each component involved in massive data transfers.

These aspects were evaluated over three stages. First, tests were performed at Ciena's laboratories to validate the experimental protocol defined for the field tests. Then, two field tests of 100 Gbit/s wavelength insertion were conducted on the RENATER backbone: between Lyon (Large Hadron Collider (LHC) Tier 1) and CERN (LHC Tier 0) on a Ciena CN 4200 link; and between Lyon and Dijon as an alien lambda (on Ciena equipment) on an Alcatel-Lucent 1696MS/1626LM link.

2.2.2 Ciena 100 Gbit/s Technology

The technology used during the tests had initially been developed by Nortel and is now used by Ciena. It is based on Dual Polarisation Quadrature Phase-Shift Keying (DP-QPSK) modulation associated with a coherent receiver. DP-QPSK lowers the baud rate of the system, using two bits per symbol and one symbol per polarisation plane. The optical spectrum is therefore four times narrower than if the baud rate had not been reduced.

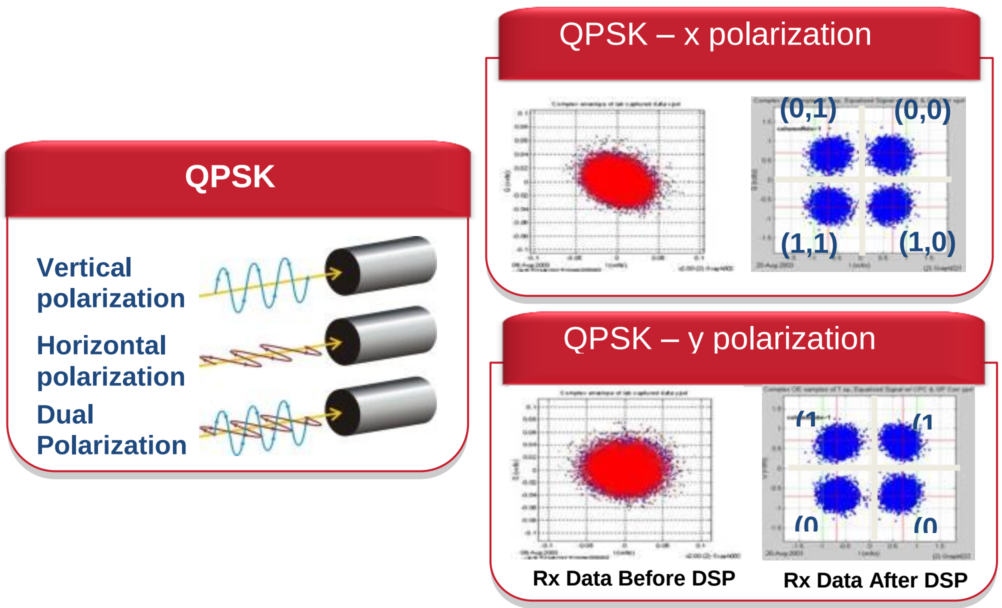


Figure 2.1: DP-QPSK in Ciena systems

The coherent receiver is able to lock into the frequency and phase of the incoming signal and is thus able to recover the incoming dual-polarisation QPSK bits appropriately. The coherent receiver allows a linear response in detecting the electric field, compared to the square law response of conventional photodetectors. With dispersion being a linear filtering phenomenon, the coherent receiver can now perform linear compensation to remove the dispersion factor from the signal.

Chromatic dispersion (CD) and mean Differential Group Delay (DGD) tolerance is thus better than on 10 Gbit/s DWDM systems, with +/- 30,000 ps/nm of CD tolerance and 20 ps for the mean DGD. In consequence, the addition of 100 Gbit/s signals on live 10 Gbit/s DWDM networks will not interfere with existing designs.

To transmit signals at a 100 Gbit/s rate, Ciena has implemented coherent Frequency-Division Multiplexing (FDM) of two DP-QPSK-modulated sub-carriers. The resulting signal carries the full 112 Gbit/s of payload within a single 50 GHz channel on the ITU DWDM grid, and is seen and operationally managed by the system as a single wavelength.

The Optical Spectrum Analyser (OSA) screenshot in Figure 2.2 below displays the spectrum of three 50 GHz spaced signals: 10 Gbit/s, 40 Gbit/s and 100 Gbit/s from Ciena.

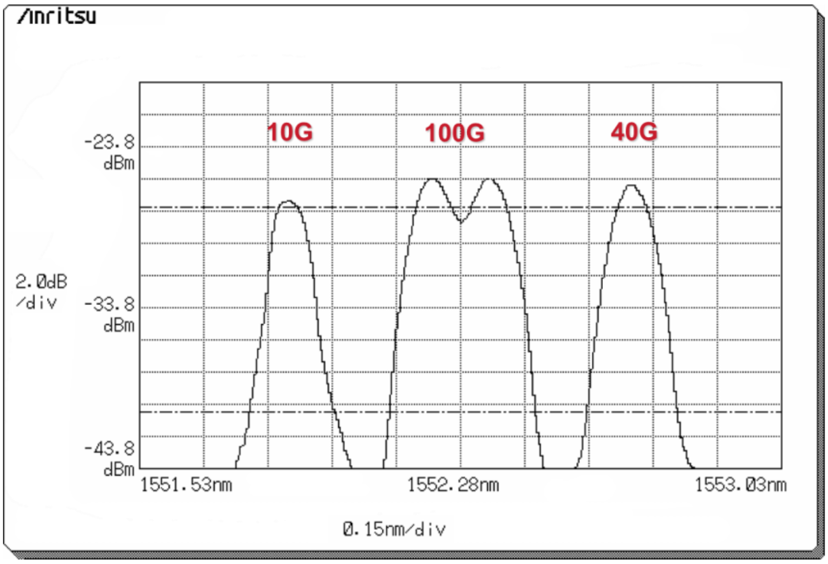


Figure 2.2: OSA screenshot with Ciena 10 Gbit/s, 40 Gbit/s and 100 Gbit/s signals

2.2.3 Test Simulation in Laboratories

This section covers the following aspects of the test simulations carried out in the Ciena laboratories:

- Testbed deployed:
  - Muxponder description.
- Test protocols and results:
  - 100 Gbit/s channel add.
  - Ethernet stability.
  - 100 Gbit/s wavelength shifting and guard band requirements.

- Optical Signal-to-Noise Ratio.
- Chromatic dispersion.

2.2.3.1 *Testbed Deployed*

To validate the experimental protocol to be applied during the field tests, the RENATER link Lyon1–Geneva was rebuilt as exactly as possible at Ciena's laboratories in London. This link had the advantage of being simple, while featuring the usual characteristics of RENATER links.

Two Ciena CN 4200 Classic chassis were used as terminal sites (Lyon1 and Geneva) to transmit two 10 Gbit/s DWDM wavelengths (channels (Ch.) 34 and 35) and one 1 Gbit/s DWDM wavelength (Ch. 36) on fibre rolls. As on the real Lyon–Geneva link, three fibre spans were available with CN 4200 In-Line Amplifiers (ILAs). A variable optical attenuator was available on a span to adjust signal strength. Additional dispersion compensation modules also made it possible to modify link properties.

Two 10 x 10 Gbit/s tunable muxponders, installed in a Ciena (ex-Nortel) OME 6500 chassis, were added to this DWDM system. The 100G muxponders were then connected directly to the optical multiplexers and co-propagated with channels 34, 35 and 36, which were already installed.

Figure 2.3 below shows a global view of the testbed deployed in Ciena's London laboratories.

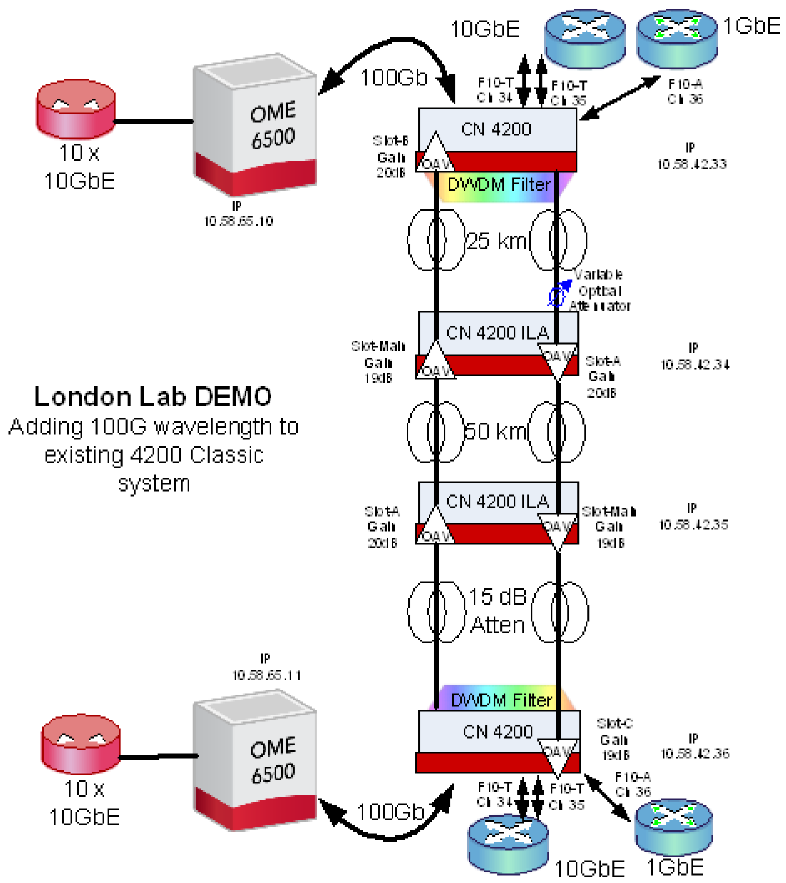


Figure 2.3: Testbed for protocol validation

Muxponder Description

Each Ciena muxponder is composed of two parts, as shown in Figure 2.4:

- On the left, a 2-slot line card called an OCLD (Optical Channel Laser Detector).
- On the right, a client card called an OCI (Optical Channel Interface), which features 10 x 10 GbE client interfaces.

Figure 2.4: Ciena 10 x 10 Gbit/s muxponders

The OCLD transmission and reception interfaces at the bottom of the card were connected to the CN 4200 multiplexers at link extremities.

The firmware release available in muxponders for the lab tests was not sufficient to reach 100 Gbit/s in line. It was therefore decided to inject a 10 Gbit/s Ethernet signal into the first port of a muxponder and to successively daisy-chain it to use eight ports on each terminal site, as described below.

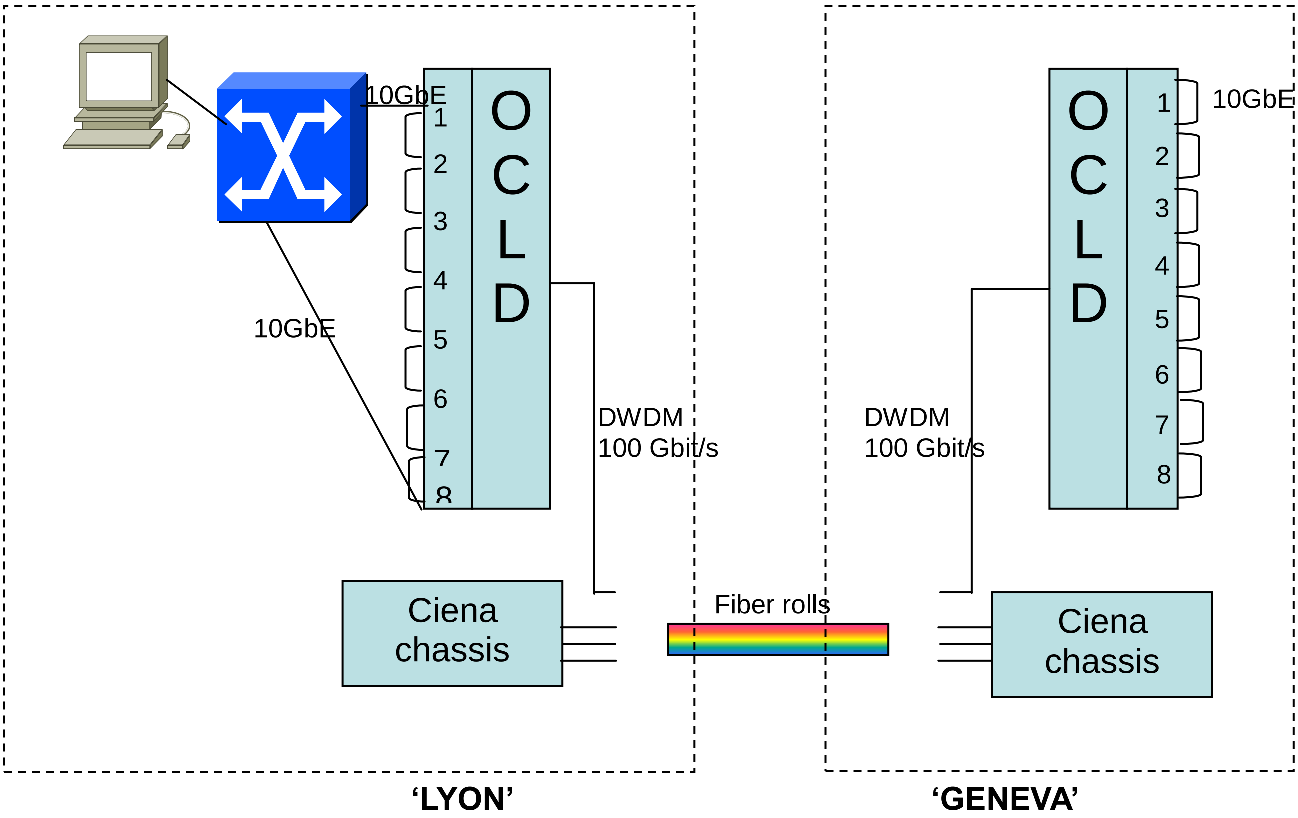


Figure 2.5: Daisy chain between points of presence during lab tests

2.2.3.2 *Test Protocols and Results*

Five types of tests were performed:

- 100 Gbit/s injection on Lyon–Geneva under normal conditions (100 Gbit/s wavelength at Ch. 52 and 1-10 Gbit/s at Ch. 34, 35 and 36).
- Ethernet stability, using Bit Error Rate (BER) and RFC 2544 tests.
- 100 Gbit/s wavelength shifting near 1 Gbit/s and 10 Gbit/s wavelengths (from Ch. 52 to Ch. 37) and guard band requirements.
- Optical Signal-to-Noise Ratio (OSNR) lowering to reach transmission limits.
- Addition of CD compensators.

100 Gbit/s Channel Add

The OSA screenshots in Figure 2.6 show the characteristics of the four wavelengths under normal conditions. On the left-hand side is the 100 Gbit/s wavelength, clearly distinguishable from the other signals of lower data rates. Although OSNR of 100 Gbit/s and 1-10 Gbit/s signals do not display equivalent emission levels, the situation is well-balanced on reception, as shown in the Figure 2.6 arrays.

The difference in OSNR between the Geneva and Lyon Rx readings is due to the lab setup. The link is not symmetrical with regard to amplifier spacing and amplifier settings, and, further, a Variable Optical Attenuator (VOA) is used in one of the directions (see Figure 2.3 – the VOA is marked just above the top ILA).

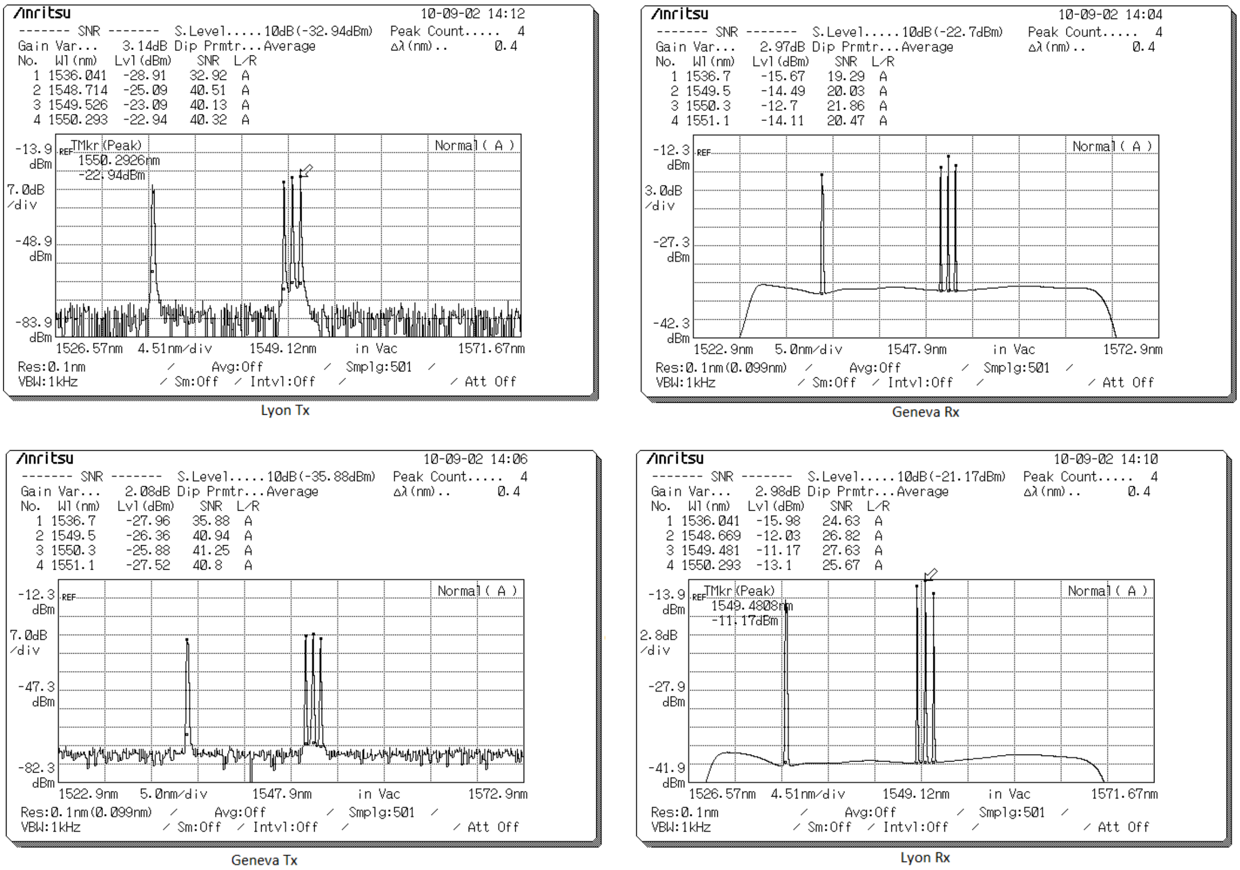


Figure 2.6: OSA screenshots on mux ports, on emission and reception sides

Ethernet Stability

The daisy-chained 10 GbE signal was monitored for two days to demonstrate the stability of the DWDM 100 Gbit/s interface.

The screenshot in Figure 2.7, taken during the tests, shows that no Ethernet errors were detected on the daisy chain during 15 hours of experiments.

Measurement Report

Test Result

PRINTED AT: **09/03/2010 09:34:55 AM**
Sunrise Telecom, Inc.
STT Ethernet+ version 03.01.0026
Firmware: **Ethernet+ 1 03.01.0026**
Elapse Time: **15:50:43**
Remaining Time: **Continuous**
Stop Date: **STILL RUNNING**
Ethernet Measurement - Slot #1
Current Port: **10GE-1**
Test Mode: **BERT**

Summary

Port 10GE-1 Status- NO ERRORS

Status

TX Rate:	**9771205632 bps**
TX Line Rate:	**9899943238 bps**
TX Utilization:	**99.00%**
RX Rate:	**9771190272 bps**
RX Line Rate:	**9899927768 bps**
RX Utilization:	**99.00%**

Signal

Vendor:	**SumitomoElectri**	
Wavelength:	**1310nm**	
RX Power:	**645.90uW**	**-1.90dBm**

Defects

Data Error	Count	Rate
IP Checksum	**0**	
Lost Frames	**N/A**	
FCS / CRC	**0**	
Out of Sequence	**N/A**	
Duplicate Packets	**N/A**	
Current Bit	**0**	
Bit	**0**	**0.000e+00**
Pattern Loss	**0**	

Figure 2.7: Ethernet test results after 15 hours

An RFC 2544 test was also run over one night without any errors, as shown in Figure 2.8:

Throughput

Frame Size	Throughput
64	**100.00%**
128	**100.00%**
256	**100.00%**
512	**100.00%**
1024	**100.00%**
1280	**100.00%**
1518	**100.00%**
9600	**N/A**
12000	**N/A**

Latency

Frame Size	Average (us)	Minimum (us)	Maximum (us)
64	**5291.60**	**5284.40**	**5298.90**
128	**5291.90**	**5284.50**	**5299.20**
256	**5292.90**	**5284.90**	**5300.90**
512	**5294.00**	**5285.60**	**5302.40**
1024	**5294.70**	**5286.70**	**5302.70**
1280	**5295.10**	**5287.30**	**5302.90**
1518	**5295.50**	**5287.90**	**5303.10**
9600	**0.00**	**0.00**	**0.00**
12000	**0.00**	**0.00**	**0.00**

Figure 2.8: RFC 2544 test results

100 Gbit/s Wavelength Shifting and Guard Band Requirements

Although Ciena’s experts recommend using a guard band of two 50 GHz DWDM wavelengths between a 100 Gbit/s signal and another signal with a lower data rate, the tests proved that it was possible to transmit a 100 Gbit/s signal directly adjacent to a small number of 1 Gbit/s and 10 Gbit/s DWDM wavelengths.

Figure 2.9 shows the behaviour of such signals after two re-amplifications: a 100 Gbit/s signal with both carriers is shown on the left-hand side; two 10 Gbit/s wavelengths with higher OSNRs and powers in the middle; and finally a 1 Gbit/s signal on the right-hand side.

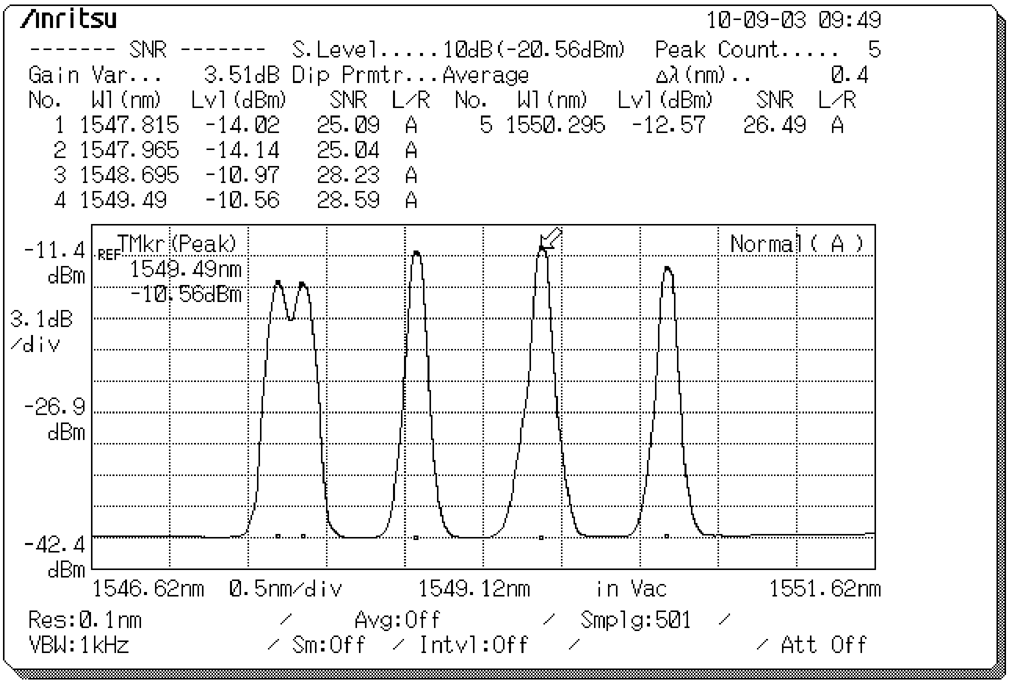


Figure 2.9: Adjacent 100 Gbit/s (on the left) and 10 Gbit/s wavelengths

Optical Signal-to-Noise Ratio

The OSNR tolerance of the 100 Gbit/s Ciena transmitter was evaluated by applying a Variable Optical Attenuator (VOA) within a span to degrade the multiplex arbitrarily. The VOA was increased (lowering the OSNR) to the point at which the 100G line and associated clients generated errors. The transmission threshold was determined at about 12.90 dB. This is shown in the screenshot in Figure 2.10, taken just before signal failure.

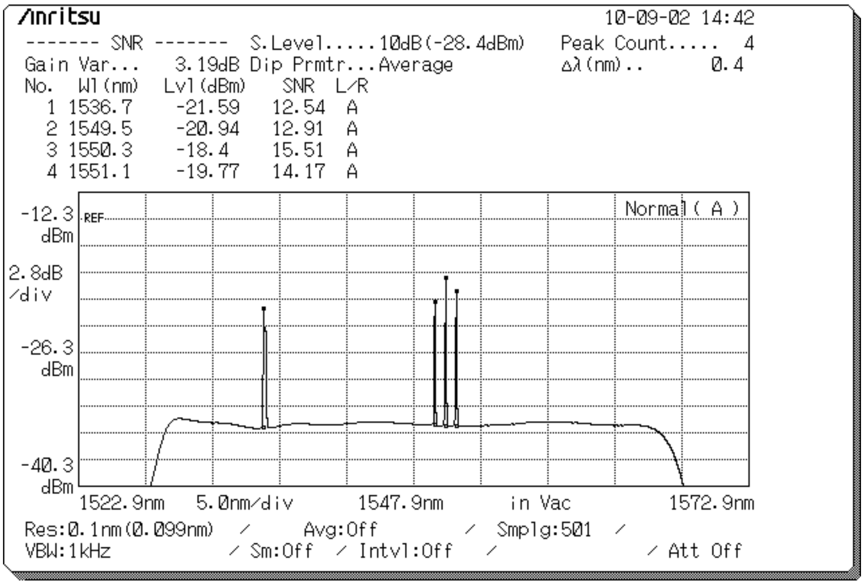


Figure 2.10: Transmission threshold of a Ciena 100 Gbit/s transmitter

Chromatic Dispersion

Finally, electronic compensation of chromatic dispersion was tested by placing Dispersion Compensating (DC) units on ILAs. It was noticed that the electronic Dispersion Compensation (eDC) functionality compensates the 100 Gbit/s signal to adapt it to the chromatic dispersion encountered in-line.

2.2.3.3 *Conclusion*

This evaluation in the laboratory made it possible to confirm that field tests could be performed on a live DWDM network with minimal risks, since:

- 100 Gbit/s wavelength insertion into the DWDM network did not cause any DWDM or Ethernet traffic interruption or disturbance.
- The ex-Nortel alien wavelength fits well within the existing 10 Gbit/s Ciena system, without any problems of power adaptation or dispersion compensation.

2.2.4 Field Tests

This section describes two field tests – the first undertaken between Lyon1 (IN2P3) and Geneva (CERN), and the second between Lyon1 (IN2P3) and Dijon – and presents the results with regard to Ethernet and DWDM.

2.2.4.1 *Lyon1 (IN2P3) – Geneva (CERN)*

The first field test took place between Lyon1 (Computing Centre of the National Institute of Nuclear Physics and Particle Physics (CC-IN2P3)) and Geneva (European Organisation for Nuclear Research (CERN)) (see Figure 2.11). The goal was to validate that 100 Gbit/s prototypes could be set up and run on a dark fibre in production, within conditions equivalent to those already tested in the laboratory. The field test environment was as follows:

- The link is composed of 3 spans of G.652 dark fibre, which represent a total distance of 224 km.
- Ciena CN 4200 are used in Lyon, Geneva and intermediate sites.
- Two 10 Gbit/s wavelengths are already in production on Ch. 34 and 35. These are injected in the fibre through a four-port coupler covering Ch. 34 to 37.
- The 100G signal was injected at Ch. 37, at 100 GHz from the nearest neighbour.

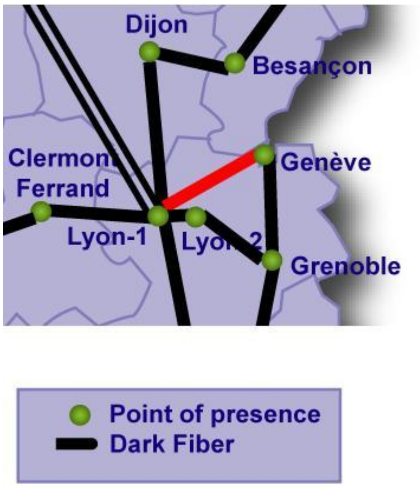


Figure 2.11: Lyon1–Geneva link

As this RENATER-5 DWDM link was initially deployed by Ciena, Ciena's experts were already familiar with the architecture parameters and consequently a theoretical simulation of the 100 Gbit/s wavelength transmission was easy to perform.

Several test steps had been defined:

- Insertion of 100 Gbit/s DWDM channel into the Lyon–Geneva fibre by Ciena's experts and handover to RENATER, IN2P3 and CERN for performance tests over a one-week period. The purpose of these tests (performed by IN2P3 and CERN) was to optimise 10 Gbit/s Ethernet port buffers on switches and LHC servers, in order to reach a throughput in the DWDM line as near as possible to 100 Gbit/s.
- 10 Gbit/s Ethernet traffic generated by the LHC switch and servers in Lyon, connected to one of the muxponder ports in Lyon, and then looped back in Geneva.
- 10 Gbit/s Ethernet traffic generated by the same LHC switch and servers, but daisy-chained five times to Geneva to fill the 100 Gbit/s DWDM channel, as shown in Figure 2.12.

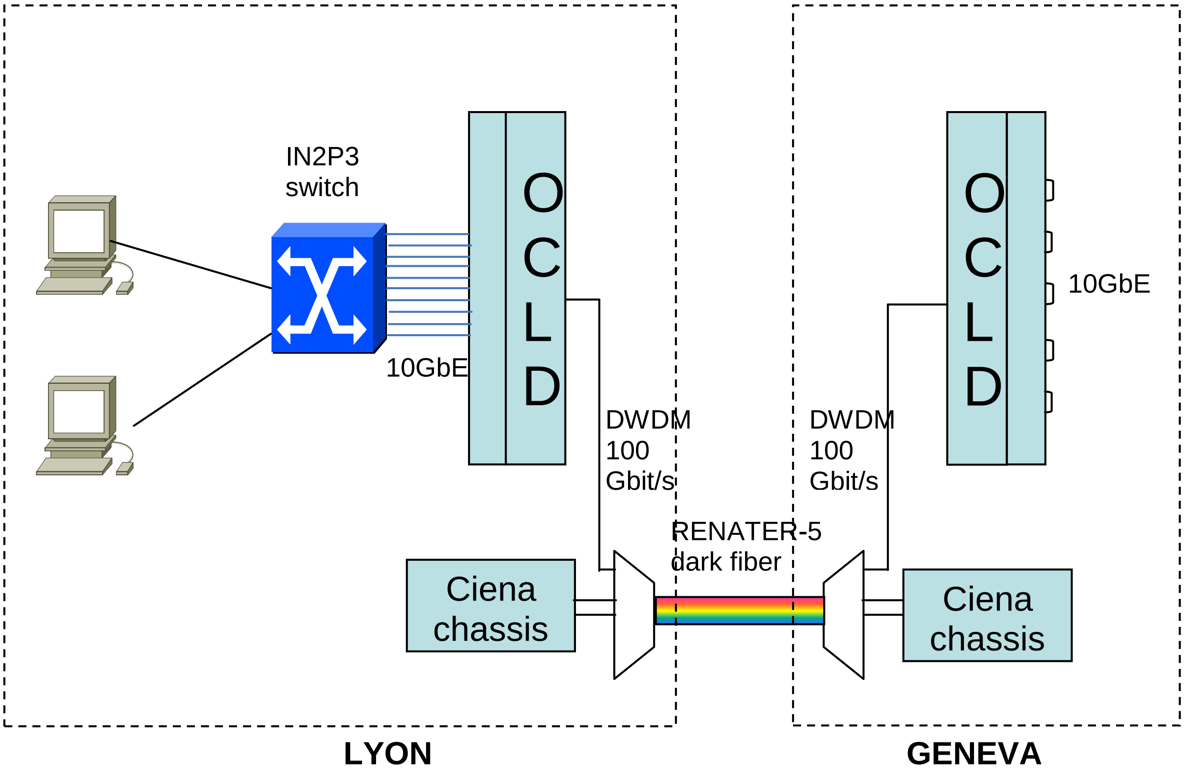


Figure 2.12: Daisy chain of 10 Gbit/s signals between Lyon and Geneva

- Temporary swap of the Worldwide LHC Computing Grid (WLCG) production traffic from RENATER's 10 Gbit/s channel to both 10 x 10 Gbit/s muxponders in Lyon and Geneva, as shown in Figure 2.13.

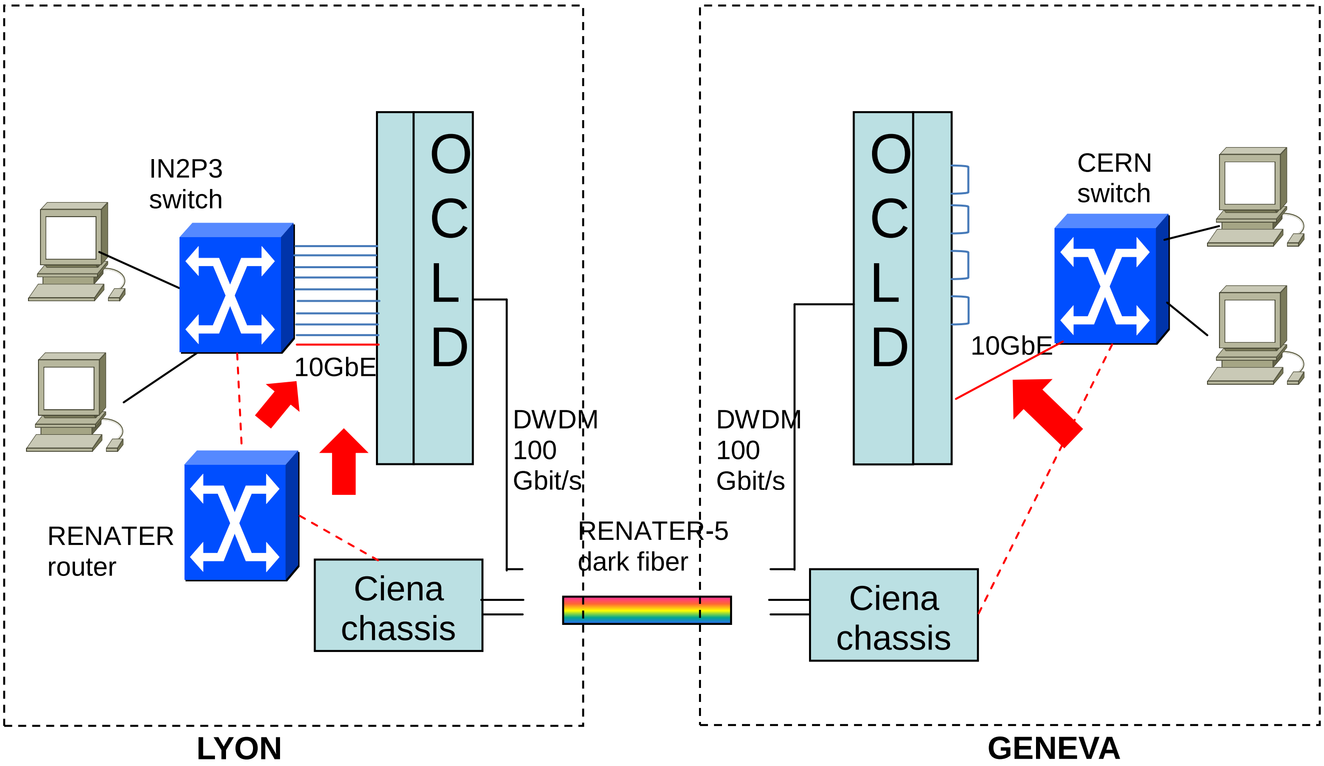


Figure 2.13: WLCG production traffic swapping

2.2.4.2 *Lyon1 (IN2P3) – Dijon*

After the first field test, ex-Nortel devices were moved from Geneva to Dijon.

The Lyon1–Dijon link is quite different from Lyon1–Geneva, being composed of four spans of G.655 dark fibres over 280 km (Figure 2.14). Theoretically it is more sensitive to non-linear effects than the Lyon1–Geneva link, which is based on G.652 fibres. Two 10 Gbit/s wavelengths (Ch. 42 and 44) were already in production on this link, injected into the fibre by an eight-port filter (Ch. 42 to 50, without Ch. 46). Ch. 50 was selected to transmit the 100 Gbit/s signal, thus being 250 GHz away from the nearest neighbour.

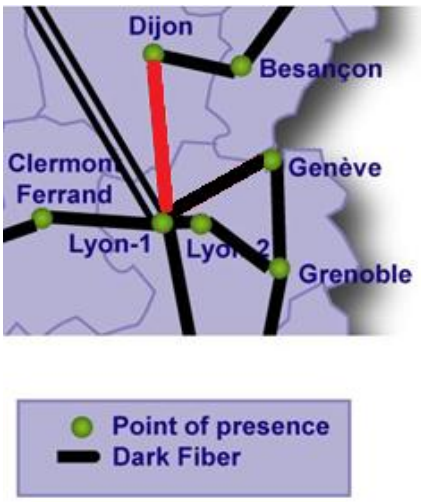


Figure 2.14: Lyon1–Dijon link

As in the first field test, the 100 Gbit/s channel was injected in RENATER production traffic, but this time as a foreign lambda on an Alcatel-Lucent infrastructure (1696 MS and 1626 LM). A preliminary simulation had been performed by Ciena based on the signal powers on each card of the system.

As Dijon University is not involved in scientific projects requiring high transfer network capacities, the tests were concentrated on a daisy chain with loopbacks in Dijon, as shown in Figure 2.15.

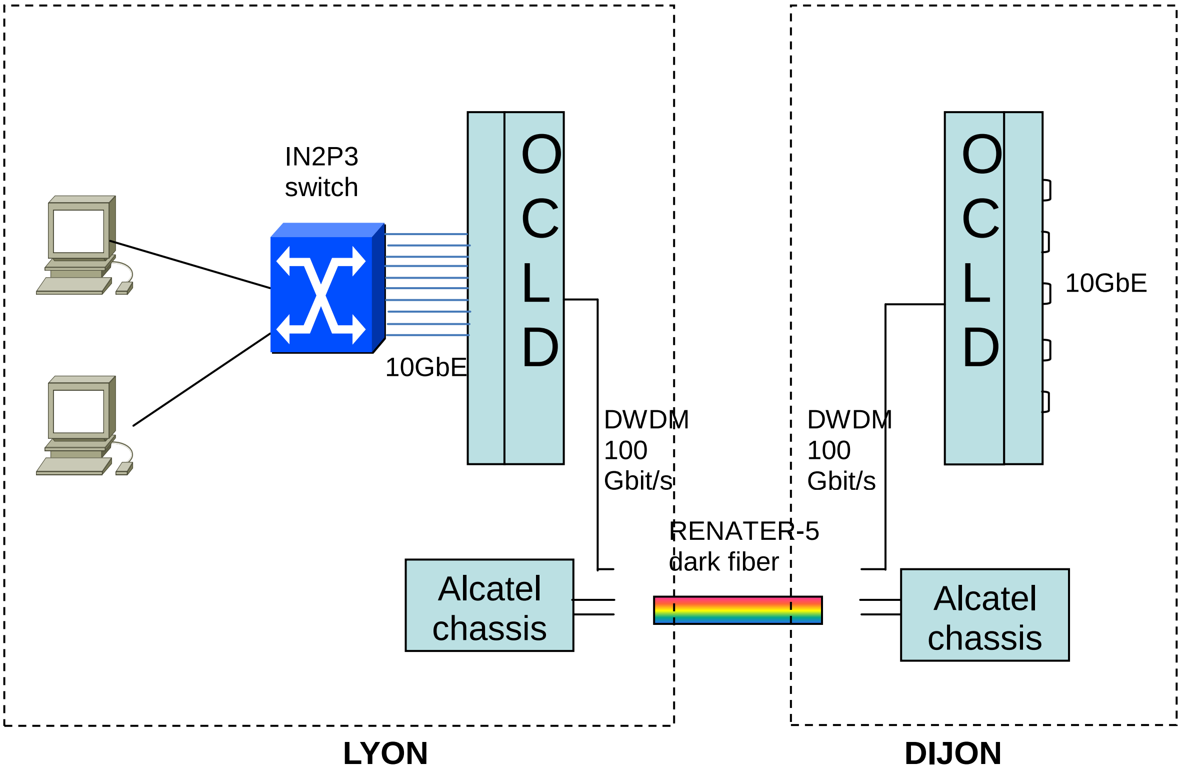


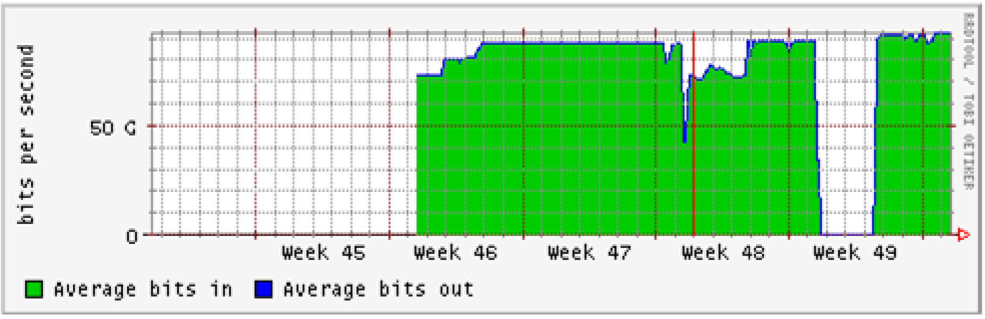
Figure 2.15: Daisy chain of 10 Gbit/s signals between Lyon and Dijon

2.2.4.3 *Results*

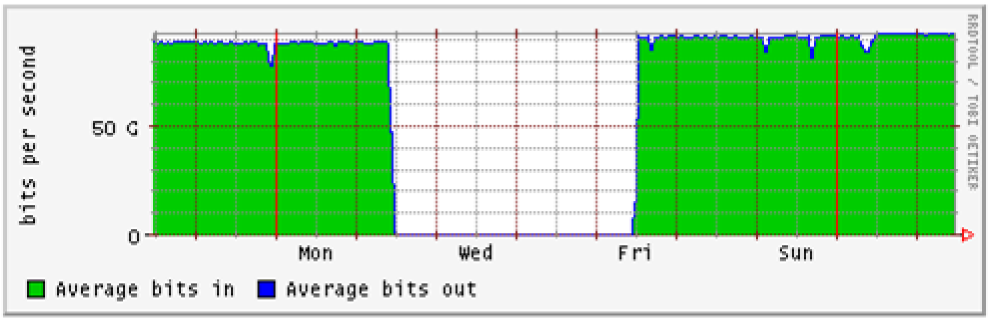
Ethernet

Both 100 Gbit/s channel insertions on the RENATER-5 infrastructure were successful. Alien wavelength transmissions were transparent for the CN 4200 and 1696 MS / 1626 LM systems supervised by the RENATER Network Operations Centre (NOC) (no alarm was detected in the optical domain).

As shown in Figure 2.16, the buffers of the IN2P3 switch that provided the 10 GbE signal were first tuned in week 48 in order to get the best data rate from the three LHC servers that were to transmit the data on the link. This resulted in a data rate of 95 Gbit/s (see end of week 48). Note that the data transmission unit used in the graph is Gibit (i.e., 230 bits). Statistics are not available for Wednesday and Thursday of week 49, owing to transportation of the ex-Nortel chassis and transceivers to Dijon University. At the end of week 49, the 100 Gbit/s alien wavelength was operational on the Lyon–Dijon link.



beginning of tests after red line



week 49

Figure 2.16: Ethernet statistics during the tests

DWDM

By using the Nortel supervision platform, it was possible to control the 100 Gbit/s alien wavelength parameters and see the link characteristics estimated by the OCLD and used to compensate the DWDM signal:

- Fibre length was correctly estimated, i.e. 220 km (the real distance is 224 km).
- While the state of the 100G transponder is “In Service”, the estimated instance of DGD is 4 ps, dispersion of received signal is -525 ps. Thus the 100G transponder is able to work without any problem on a link optimised for 10G wavelength transmission.

This is shown in Figure 2.17 below.

Name ▲	Primary State	Secor State	Optical System Identifier	Tx Path Identifier	Tx Power (dBm)	Tx Actual Power (dBm)	Rx Actual Power (dBm)	Rx FEC Format	Tx FEC Format	Tx Wavelength (nm)	Pre-FEC Signal Fail Threshold (dBQ)	Pre-FEC Signal Fail Threshold (BER)	Pre-FEC Signal Degrade Threshold (dBQ)	Pre-FEC Signal Degrade Threshold (BER)	Rate	Port Mode
OTM4-1-4-1	IS			-	-1.0	-1.0	-7.6	PFEC	PFEC	1547.72	0.00	3.80E-03	0.50	1.36E-03	112G	SDH

ODU Monitoring	Estimated Fiber Length (km)	Estimated Instance Of DGD	Rx Last Acquired Dispersion	Supported Mean DGD	Reach Specification (km)	Trace Tx	Associated Far End Rx ID	Echoed Trace Rx
No	220	4	-525	10	1800	OME-RENATER-2-1-4-1	OME-RENATER-1-1-4-1	OME-RENATER-2-1-4-1

Figure 2.17: Link characteristics on Nortel platform during Lyon–Geneva tests

The OSA screenshot in Figure 2.18 below shows the foreign wavelength on the left-hand side, and both RENATER 10 Gbit/s channels already up and running on the Lyon–Geneva link.

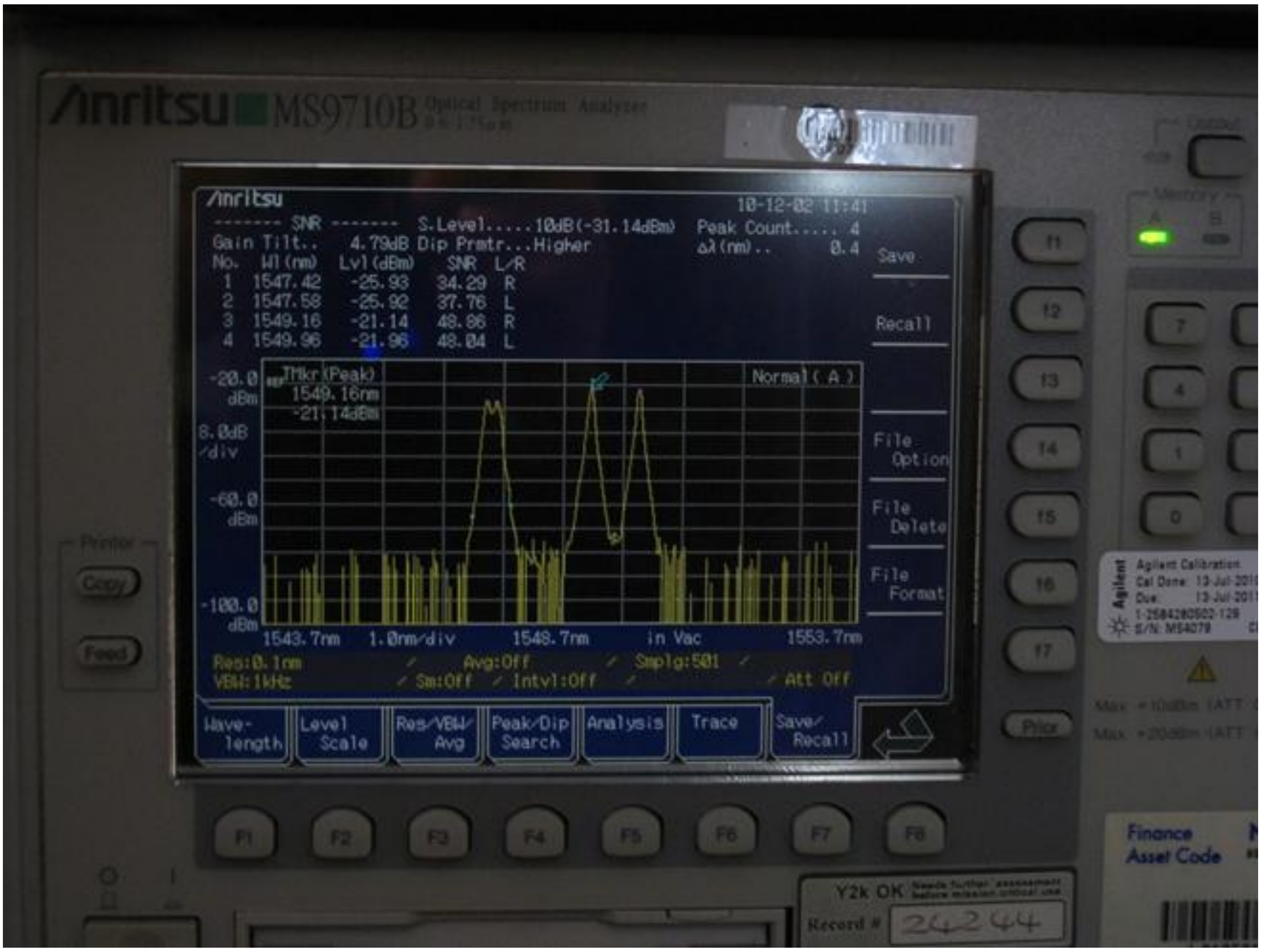


Figure 2.18: OSA screenshot during the tests

The power levels of each DWDM card on both links were measured and stored before, during and after the tests, as shown in Figure 2.19 and Figure 2.20 below.

Because the Ciena and ex-Nortel transceivers are shooting in fibres at almost the same power levels, no configuration adjustment was needed to transmit the 100 Gbit/s signal between Lyon and Geneva properly. No significant change in power levels was noticed along the link, before (data on the 25th of November in Figure 2.19) or during the tests (on the 26th and after in Figure 2.19 and Figure 2.20) on the CN 4200 systems.

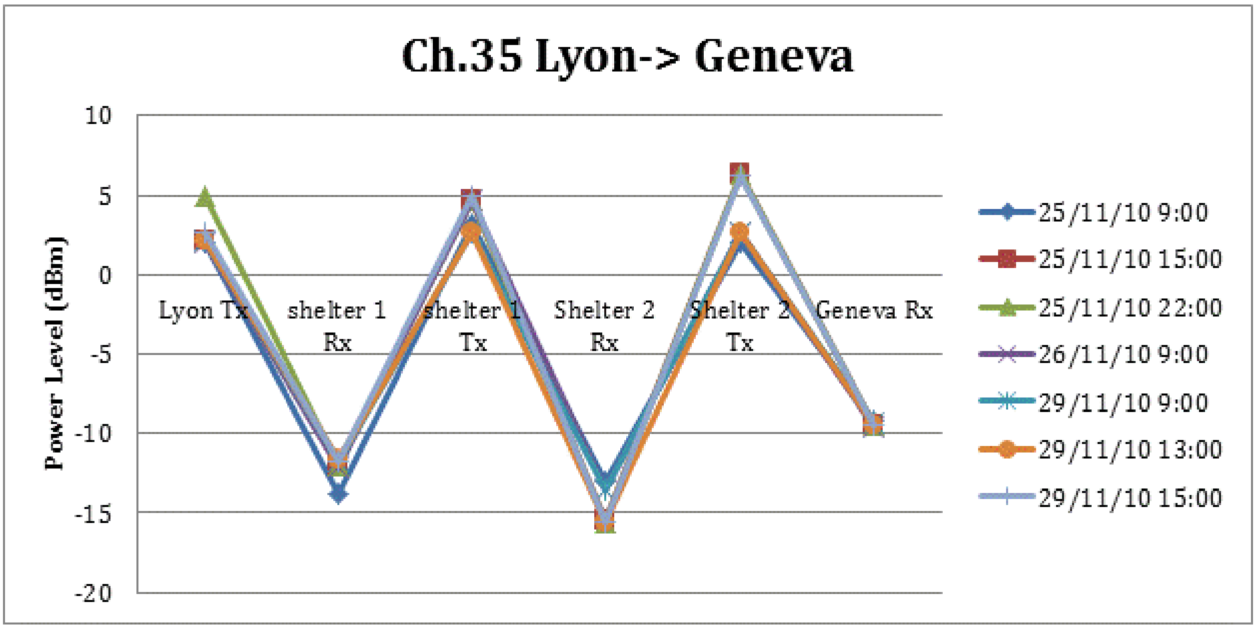


Figure 2.19: Power levels on Lyon–Geneva link during link commissioning

However, the situation was not the same on the Lyon–Dijon link because Alcatel shoot their DWDM signals at a lower level than Ciena/Nortel. When the 100 Gbit/s channel was inserted (green lines and dots on 9/12/10 16:20 in Figure 2.20), overall power levels increased on the link and especially in ILAs where the maximum powers at first and second stages were reached. To protect the Alcatel system, the power levels on the 100 Gbit/s channel were quickly decreased to achieve more acceptable levels (purple lines and dots on 9/12/10 16:30 in Figure 2.20). This new configuration was maintained during the test week without any disturbance.

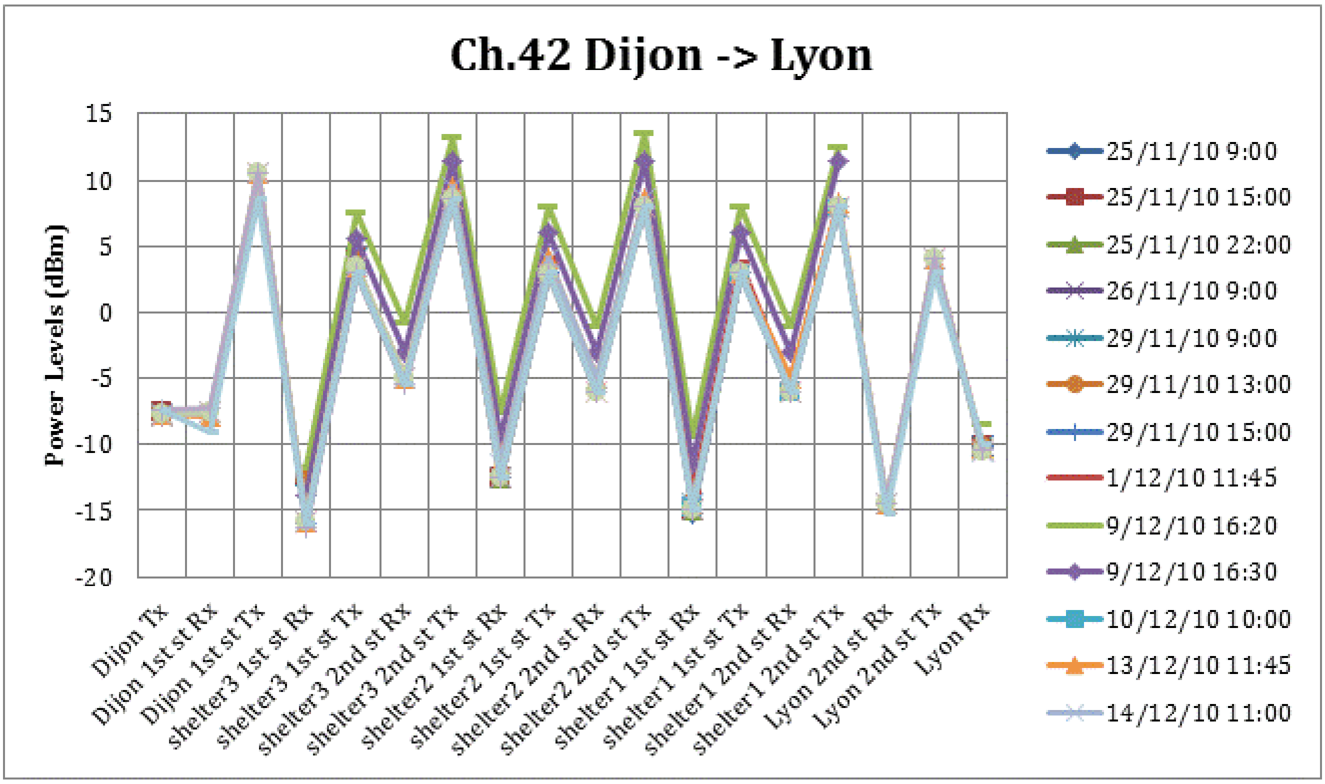


Figure 2.20: Power levels on Dijon-Lyon link

2.2.5 Conclusions

This sequence of tests, performed both in the laboratory and within a live NREN backbone network, proves that a simple existing DWDM infrastructure designed for 10 Gbit/s using a few channels can be upgraded to 100 Gbit/s without disturbing the existing production traffic. The coexistence of wavelengths from two different major DWDM manufacturers (Alcatel-Lucent and Ciena) was also successful.

It has also been noticed that the running conditions of 10 Gbit/s and 100 Gbit/s DWDM wavelengths were quite similar, with a good adaptation of 100 Gbit/s transponders to a network designed for 10 Gbit/s wavelength transmission.

This opens the way to further investigations (likely more quantitative) on upgrade conditions such as:

- Impact of the existing 10 Gbit/s channel amount on the 100 Gbit/s channel characteristics.
- Comparison of 10 Gbit/s and 100 Gbit/s performances in terms of span number, powers and OSNR of each signal, and non-linear effects.
- 100 Gbit/s channel performance in terms of its position on the spectrum.
- Influence of G.652 and G.655 utilisation on 100 Gbit/s channel performance.

2.3 Operational Experience of Ciena 100G DWDM Solution

2.3.1 Introduction

This section describes RoEduNet's operational experience of installing and running a 100G lambda within an existing DWDM network. It covers RoEduNet's approach to the 100G lambda installation, its DWDM network and the Ciena solution for 100G lambdas, implemented using cards developed for the Optical Multiservice Edge 6500 platform. It then describes the 100G circuit deployment in more detail, addressing: path selection; optical design, simulations and approval; optical equipment and software activities; 100G circuit provisioning and installation; environment considerations; and networking equipment requirements.

2.3.2 Background

2.3.2.1 *Approach*

As part of its contribution to JRA1 Task 2 activity, RoEduNet planned to install a new 100G lambda within its existing DWDM network. The initial plan was to operate a testbed for a few months, and then to decide whether such a circuit should be installed for production operations within the national network. To this end, RoEduNet initiated discussions with Nortel, the manufacturer of the optical equipment, in Q3 2009. In December 2009, Nortel announced the commercial availability of a 100G optical solution (interface card) for the Optical Multiservice Edge (OME) 6500 platform [Nortel100G]. The new card was suitable for installation within the existing RoEduNet optical network provided that many OME 6500 with existing 10G lambdas were already in operation. Discussions to establish a testbed in RoEduNet's network with help from Nortel specialists were interrupted when Ciena bought Nortel's optical business. The proposed testbed was therefore delayed until the second half of 2010.

Taking into account the ratification of IEEE 802.3ba (the standard supporting speeds greater than 10 Gbit/s in Ethernet applications) in June 2010, and that Ciena's optical solution for 100G lambda complied with these standards, RoEduNet decided to acquire and install a new 100G lambda and omit the test procedure. This approach was also influenced by development plans for the entire RoEduNet network, which proposed that four 100G lambdas should be installed to connect four major nodes of the network to the national NOC, using existing 10G lambdas as backup connections. According to this plan, the first circuit would connect the regional node in Iasi (in the north-east part of Romania – see Figure 2.21) with the national NOC.

At the end of 2010, the first 100G circuit between two major academic cities within Romania (Bucharest and Iasi) was installed. The 100G circuit is about 500 km long, following a path with 8 segments, and uses RoEduNet's DWDM network, which is based on Ciena/Nortel equipment and leased optical fibre (a partnership with SC Telecomunicatii CFR SA (TcCFR), a Romanian Railway company division).

2.3.2.2 *RoEduNet DWDM Network*

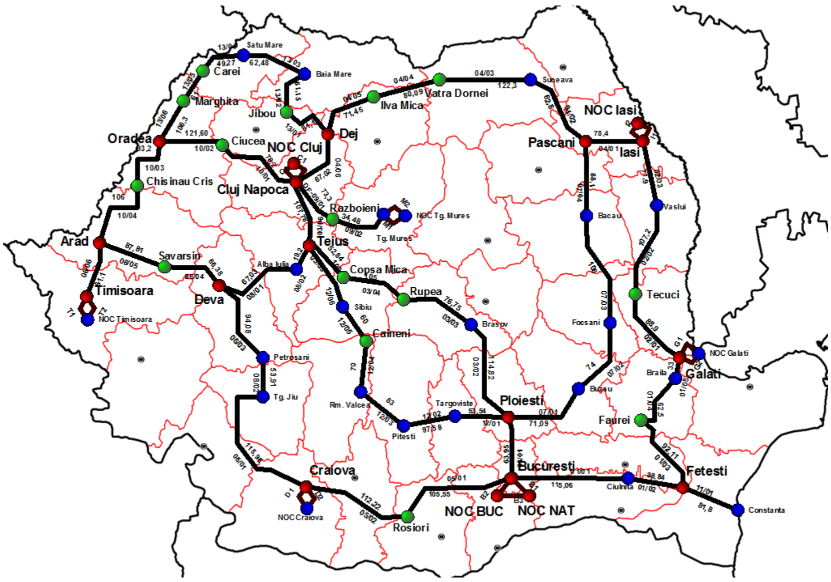


Figure 2.21: RoEduNet DWDM network 2008 – dark fibre footprint

The RoEduNet DWDM network was installed at the end of 2008 and has about 170 network elements (NEs) and 4238.8 km of leased pairs of G.652 optical fibres. The topology of the dark fibre (DF) network is presented in Figure 2.21. The RoEduNet DWDM 100 GHz-spaced network uses Ciena/Nortel optical equipment: the photonic layer is managed by Common Photonic Layer (CPL) devices and the service layer has circuits terminated within equipment such as OME 6500 and OM 5200/5100. There are 46 fibre segments connecting 56 sites: 18 Reconfigurable Optical Add-Drop Multiplexer (ROADM) capable, 23 OADM and 15 equipped only with amplifiers.

Network nodes with more than 2 directions are ROADMs with Wavelength Selective Switch (WSS). Also, there are several special ROADM nodes in RoEduNet NOCs from Bucharest, Iasi and Cluj that have 2 directions or are terminal nodes. To reduce the costs, there is no optical protection, but this capability was requested in the tender process and can be installed if necessary. However, the number of lambdas available for each regional NOC and the physical path by which each one reaches these nodes provide protection at Layer 3 (OSI) and traffic balancing, if necessary.

All provisioned lambdas are 10G, the majority of them being used to carry 10G Ethernet circuits between Ciena/Nortel OME 6500 equipment located in RoEduNet NOCs, and 10 x 1 Gbit/s Ethernet between neighbouring 5200/5100 equipment installed at optical points of presence (PoPs) located in TcCFR premises and RoEduNet NOCs. Four types of lambdas are installed (see Figure 2.22):

- 100 Gbit/s Ethernet (thick orange path).
- 10 Gbit/s Ethernet (red paths).

- STM64 used by RoEduNet's partner TcCFR (green paths).
- Another type of 10G lambdas that consist of 10 x 1G using Ciena/Nortel service cards available for 5200/5100 equipment (blue paths).

There are 79 10G lambdas in production:

- 35 10G Ethernet regional.
- 3 STM64.
- 41 10 x 1G multiplexed in one 10G circuit.

It should be noted that because of the mapping of 1 Gbit/s Ethernet circuits into the optical transport system, the last type of card permits 9 1 Gbit/s Ethernet encapsulated circuits plus one 155 Mbit/s Ethernet encapsulated.

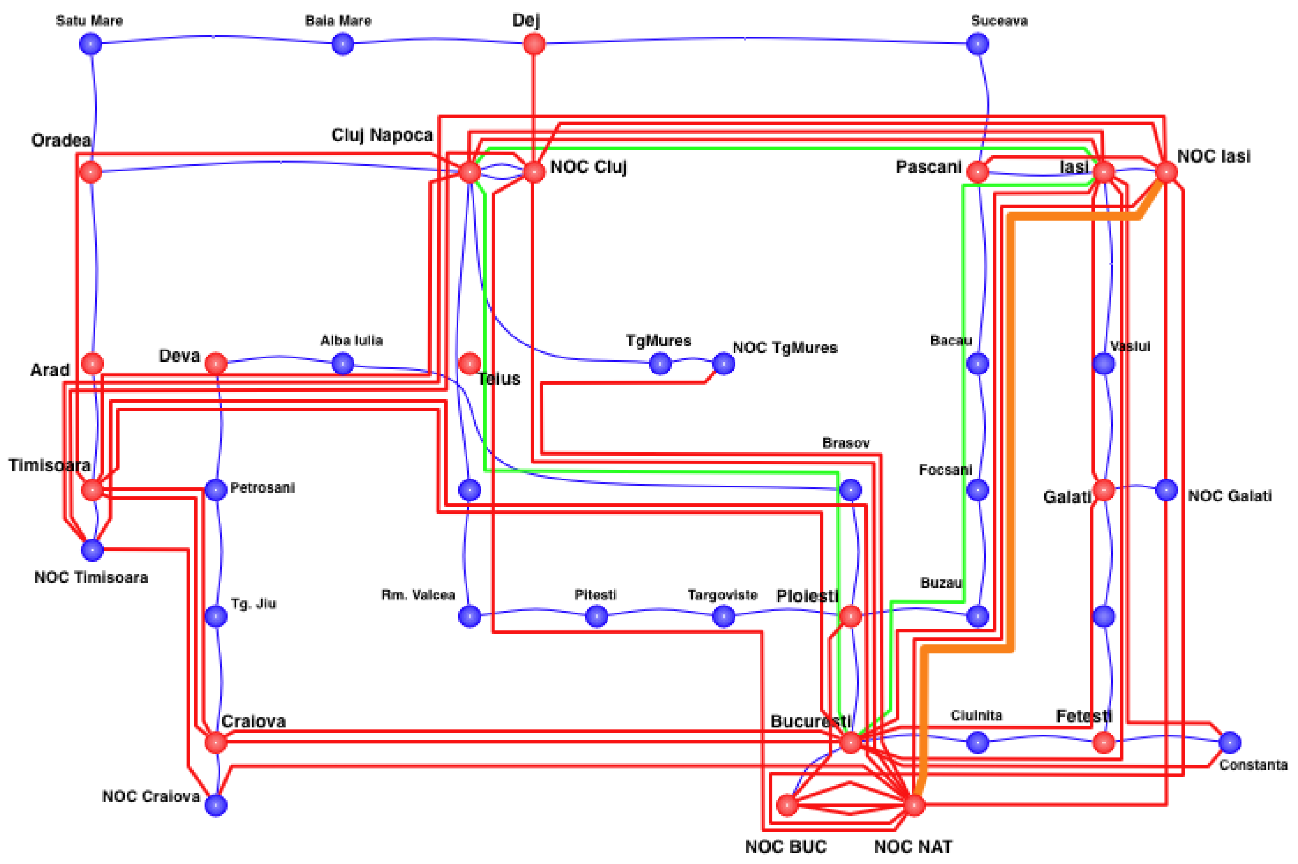


Figure 2.22: RoEduNet2 optical network – lambdas

The RoEduNet DWDM network is realised using two layers: photonic (Common Photonic Layer (CPL)) and optical service. Due to budgetary constraints it was not possible to use only one type of hardware platform for the optical service layer. As a result, two types of optical service platform are used: OME 6500 and OM 5x00. This approach also fits the hierarchy of the network; the optical network provides two types of lambdas:

regional and local. Regional lambdas are used to interconnect regional nodes and their lengths range from a few hundred kilometres to more than one thousand. Local lambdas are used to connect local PoPs to regional nodes, with lengths varying from a few tenths of kilometres to less than two hundred. The main difference between OME 6500 and OM 5x00, besides the fact that OME 6500 is the new generation of equipment, is that OME 6500 uses electronic Dispersion Compensation (eDC), which automatically compensates the chromatic dispersion of the link, and OM 5x00 does not use this technology. Using eDC makes Dispersion Compensation Modules (DCMs) unnecessary on the fibre span. Eliminating DCMs results in a number of advantages, particularly for high-rate lambdas using DP-QPSK modulation:

- Increased performance: inserting DCMs increases the span loss and thus reduces OSNR.
- DCMs accentuate non-linear effects affecting PSK signals.
- Reduced costs: the cost of compensating the chromatic dispersion is included in the cost of the cards and is paid per lambda installed. It should be noted that inserting DCMs adds additional costs to amplifiers to compensate the additional loss added by DCMs.

Unfortunately the RoEduNet DWDM network has spans that are partially compensated using DCMs to compensate chromatic dispersion for lambdas provided by OM 5x00 for links that exceed 90 km. For example, a fibre segment of 110 km is compensated using a DCM30. Although the presence of DCMs is needed for traditional modulation formats (e.g. OOK-NRZ), it is a drawback when coherent modulation formats are being used, as they introduce attenuation and non-linearities. Regional lambdas provided by OME 6500 do not need DCMs. Future upgrades of the network remove such DCMs completely.

Network management is performed using 2 redundant servers (master-slave) running Optical Manager Element Adapter (OMEA). These are located in 2 different datacentres, and operated using Site Manager software installed in several locations.

2.3.2.3 *Ciena/Nortel 100G Solution*

The Ciena/Nortel solution for 100G lambdas has been implemented using cards developed for the OME 6500 hardware platform. The solution is based on Coherent Optical Frequency-Division Multiplexing (CO-FDM) using two 58.2G subcarriers within one 50 GHz ITU channel. The transmission system uses these two 14.55 Gbaud subcarriers, DP-QPSK spaced at 20 GHz, and combined using an optic coupler. On the receiver side, an optical splitter separates each subcarrier and an Erbium Doped Fibre Amplifier (EDFA) is used as a pre-amplifier to compensate the losses introduced by the splitter. It should be noted that all the components mentioned are part of the line card and that there is no separate hardware.

A simplified schematic for a subcarrier transmitter and receiver used in CO-FDM for 100G interface cards is presented in Figure 2.23. The signal from the laser source is split into four components using a splitter (Spl), two for each polarisation (horizontal and vertical) used as a carrier in the modulation units (Mod1 to Mod4) for logic signals Dx1 to Dx4. The polarisation shifter (Pol) rotates one signal, then both are combined (at Com) and transmitted. On the receiver side, the signal received from the transmitter carrying the information and a signal from a local laser source are both split into two components using couplers (Spl) and polarisation shifters. Components from both sources go through two 90-degree hybrid mixers, optical detectors and transimpedance amplifiers to obtain logic signals Dx1 to Dx4.

The data signals represented in Figure 2.23 on the transmitter side are Optical Transport Network (OTN) frames that pass through a Forward Error Correction (FEC) encoder and then a QPSK multiplexer (MUX); on the receiver side, data signals will go to an Analog/Digital Digital Signal Processor (A/D DSP) and then to an FEC decoder, delivering OTN frames.

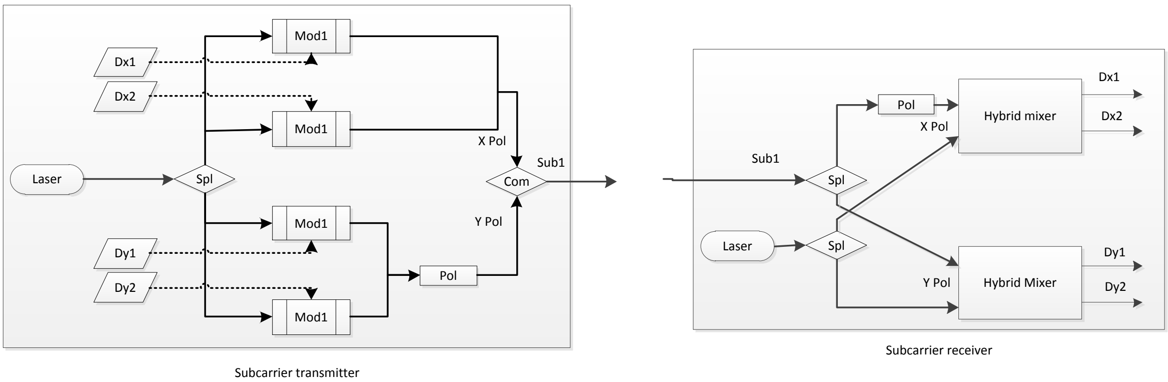


Figure 2.23: Simplified schematic for a subcarrier transmitter-receiver system

100G services for OME 6500 use a pair of cards: one for line side, called an Optical Channel Laser Detector (OCLD), and another one for client side (Optical Channel Interface (OCI)). Using this solution, the following transparent wavelength services can be deployed:

- 100G Ethernet using 100G IEEE802.3ba-compliant OCI card and 100G OCLD card on the line side.
- 10 x 10GE LAN PHY by using a 10 x 10GE MUX card on the client side and 100G OCLD card on the line side.
- Transparent STM64/OC-192, 10GE and OTU2 using a 10 x 10GE MUX Card and 100G OCLD card on the line side.

A particular case is 100G regeneration using a 100G OCLD pair connected back to back.

The most important characteristics of the cards used for 100G circuits are:

- Use two subcarriers spaced at 20 GHz.
- 14.55 Gbaud.
- Compatible with ITU 50 GHz spacing grid.
- Use eDC and compensate ± 32000 ps/nm.
- Reach more than 1000 km.
- OTU4 line rate.
- 20 ps mean Differential Group Delay (DGD).

2.3.3 100G Circuit Deployment

The 100G lambda installation between NOC NAT (National Network Operations Centre) and NOC Iasi (located in the north-east part of the country, as shown in Figure 2.24) took place at the end of 2010,. The RoEduNet DWDM network and the final path of the 100G circuit are represented in Figure 2.24. The 100G circuit passes through 7 intermediary sites. It should be noted that the topology presented in Figure 2.24 was used by Ciena throughout the process of design and simulation before installing the new lambda. Red circles represent ROADM-capable nodes, blue circles are OADM nodes (i.e. Optical Add-Drop Multiplexing nodes that are *not* reconfigurable) and yellow circles are used for amplifier sites.

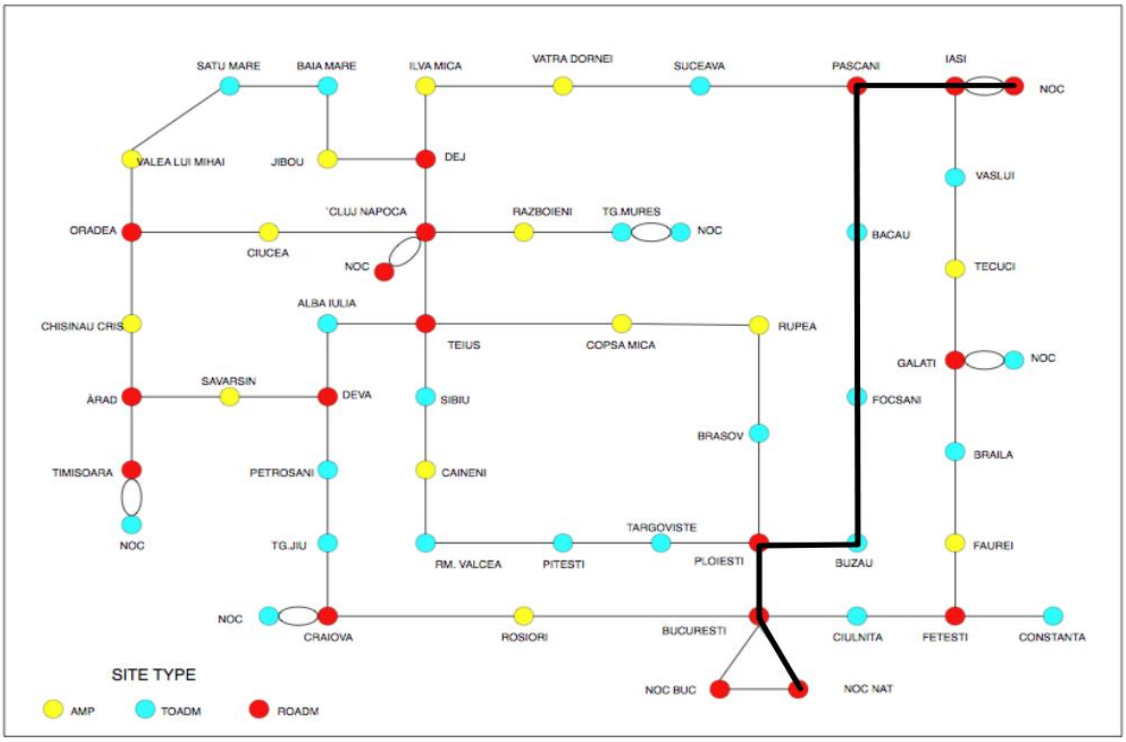


Figure 2.24: Path of 100G circuit (thick black line)

Several steps were necessary in order to complete this activity, including:

- Path selection.
- Optical design, simulations and approval.
- Optical equipment and software activities.
- 100G circuit provisioning and installation.

Each of these is described below, together with environmental considerations and networking equipment requirements.

2.3.3.1 *Path Selection*

The new 100G circuit was requested between NOC NAT and NOC Iasi (Figure 2.24). There are two feasible paths to link these nodes:

- Through Fetesti and Galati, ten fibre segments with a total length of 622.5 km.
- Through Ploiesti and Pascani, eight fibre segments with a length of 500.5 km.

RoEduNet asked for a flexible solution, so that the new circuit could be moved from one path to another when necessary. At the time of installation the first option was dropped because there were problems with the fibre on the Ciulnita–Fetesti segment. These were caused by the fact that the railway segment is under reconstruction, with works ongoing along the fibre path; consequently fibre cuts and degradation of fibre span characteristics were expected. Also, this path is 122 km longer than the other option, although the number of lambdas per segment is lower. Another reason not to use this path is the future network evolution. Three local PoPs need to be installed and connected to Ciulnita and Braila or Fetesti. These extensions could have forced RoEduNet to have downtime, i.e. lambdas out of service for certain periods of time.

The second path option was preferred not only because it was shorter and more stable, but also because it was more challenging due to the greater number of other (10G) lambdas configured on the Bucuresti–Ploiesti span, which is the busiest from this point of view. On the other hand, it should be noted that all possible PoPs on this path are already connected to the optical network; there is only one extension to be added in the future, but the necessary circuits for the new location are already installed.

2.3.3.2 *Optical Design, Simulations and Approval*

Optical design for the new 100G lambda was undertaken by Ciena, and took into account the existing lambda usage plan, node types along the route and optical domains traversed by the circuit. The Ciena/Nortel equipment uses a DWDM grid that is divided into several groups. To offer an affordable option for sites that need a small number of wavelengths to be added and/or dropped, Ciena/Nortel has Channel Mux/Demux (CMD) filtering equipment with 4 or 8 lambdas, respective to 100 GHz or 50 GHz DWDM grid spacing. The egress optical signal from these CMDs feeds a Group Mux/Demux (GMD) that has 9 ports, giving a total of 36 or 72 available lambdas.

Although it is not a problem to have 10G, 40G and 100G lambdas configured within the same lambda group, as demonstrated in Ciena's lab, there was a preference to install 100G within a separate group to facilitate differential provisioning later, if needed. The 100G lambda traverses eight fibre segments providing different services (10G Ethernet lambdas, 10 x 1G Ethernet and STM-64) and many intermediary sites are using GMDs. To preserve the lambdas for these sites it was preferred not to use any of these lambdas and to install 100G within a separate group instead.

Table 2.1 presents details of the nodes and fibre spans through which the 100G circuit passes, with distances between the intermediary nodes and lambdas already installed on each segment. It is important to note that the same lambdas may appear on several spans but can be part of different circuits. The 100G lambda is highlighted with green.

Length/ Service	NOC NAT	7 km	BUCURESTI	63.95 km	PLOIESTI	71.09 km	BUZAU	74 km	FOCSANI	106 km	BACAU	88.10 km	PASCANI	78,40 km	IASI	5 km	NOC Iasi
10G																1531,12	
10G				1532,68													
10G														1534,25			
100G		1542,14		1542,14		1542,14		1542,14		1542,14		1542,14		1542,14		1542,14	
10G				1546,12		1546,12		1546,12		1546,12		1546,12		1546,12			
10G		1546,92		1546,92												1546,92	
10G		1547,72		1547,72										1547,72		1547,72	
10G														1548,51		1548,51	
10G		1549,32		1549,32		1549,32		1549,32		1549,32		1549,32		1549,32		1549,32	
10G				1550,12		1550,12		1550,12		1550,12		1550,12		1550,12		1550,12	
10G		1550,92		1550,92													
10G		1551,72															
10G				1554,13										1554,13		1554,13	
10G		1554,94		1554,94										1554,94			
10G		1555,75		1555,75										1555,75			
10G				1556,55		1556,55		1556,55		1556,55		1556,55		1556,55			
10G				1557,36		1557,36		1557,36		1557,36		1557,36		1557,36			
10G				1558,98													
No. of lambdas		8		14		6		6		6		6		12		8	

Table 2.1: 100G circuit path information

The installed Ciena/Nortel CPL equipment uses a wavelength plan that is compliant with ITU G.694.1 and G.698.1 recommendations. To simplify some management and configuration operations, the available wavelengths are divided into 9 groups with either 4 lambdas per group and 8 skipped lambdas in some applications (for 100 GHz spacing) or 8 lambdas per group and 16 skipped lambdas (for 50 GHz spacing). OME 6500 supports all 44 available channels for the 100 GHz grid. This grouping permits differentiated configuration parameters for more sensitive carried circuits, such as 40G or 100G, when needed. In these cases, there is a preference for circuits with similar needs to be placed within the same lambda group.

2.3.3.3 *Optical Equipment and Software Activities*

After the design phase, the following optical equipment and software activities were required in order to install the 100G circuit:

- Purchase of a new OME 6500 with SP-2 shelf-processor for NOC NAT. This was necessary because no free slots were available on the existing system (special positions within the OME 6500 slots are needed); the necessary slots (3–6) were available in NOC Iasi.

- Upgrade (replacement) of the shelf processor from SP to SP-2 on the OME 6500 for NOC Iasi, in order to support 100G cards (a 100G circuit requires more computational speed from the shelf-processor).
- Upgrade of software for all DWDM network equipment to alleviate possible problems if only the 2 involved OME 6500 were upgraded. It should be noted that the software upgrade was performed not only for all OME 6500 but also for all CPL equipment on the whole network. CPL was installed in 2008, when the network was deployed, and because 100G circuits were not available at that time CPL software was not “aware” of these types of lambdas. Two options were available: not to perform a software upgrade (lower cost) and to install 100G lambda as a “foreign lambda”, or to do the upgrade. The second option was the safest but this was not the only reason for upgrading the software: there are plans to install some other 100G lambdas within the network and the management of the whole network could become very difficult. A third option was also available: to upgrade only the CPLs in the optical domains traversed by the new lambda. However, this option was not feasible because of the possibility of unpredictable behaviour affecting the management of the entire network.
- Purchase of two sets of 100G OCLD (line side) and OCI (client side) cards, including C Form-factor Pluggable (CFP)-compliant modules. In order to have a usable 100G circuit transponder, 2 cards are needed at each end (one OCLD and one OCI), the client side being separated from the line side (as described in Section 2.3.2.3).

Further details about these activities are presented in Appendix A.1 on page 139.

2.3.3.4 *100G Circuit Provisioning and Installation*

Due to the layered separation of photonic and service components, installing a new circuit within an operational environment is not very difficult, once design documentation (output from Ciena’s Optical Modeler tool) is available for use. The Site Manager software was used in order to complete the software configuration steps described in Appendix A.2 on page 142.

2.3.3.5 *Environment Considerations*

In cases where 2 card sets (OCLD+OCI, OCLD+OCLD) are installed in the same OME 6500, power requirements must be verified carefully because 60A feeds are needed. Also, cooling demand is higher, so high-flow cooling fan modules are needed. Typical and maximum electrical power requirements for the OME 6500 cards needed for a 100G lambda circuit installed in RoEduNet are presented in Table 2.2 below.

	Typical Power Consumption (W)	Maximum Power (W)
SP shelf processor	20	20
SP-2 processor	40	42
100G OCLD card	285	316
100G OCI card CFP module	78 21	94 24

	Typical Power Consumption (W)	Maximum Power (W)
Total power for one transponder (OCLD + OCI + CFP)	384	434

Table 2.2: Power consumption for 100G components

2.3.3.6 *Networking Equipment Requirements*

The requirements for the networking (Layer 3) part of the 100G installation are as follows:

- Existing Carrier Routing System (CRS) upgrade to CRS3 in NOC NAT, in order to support 100G Ethernet interfaces (Modular Service Card (MSC) with 140 Gbit/s line rate throughput).
- One CRS3 for NOC Iasi.
- 100G cards with 100Gbase-LR4 CFP modules compatible with Ciena/Nortel client side.

These were not acquired because it was too late, in 2010, to organise a new tender for Layer 3 equipment. Unfortunately, in 2011, the necessary resources were not available to buy the new routers; instead, the tender is to be launched at the start of 2012. The lack of Layer 3 equipment did not affect the tests performed on the optical layer, but made the CFP interworking test and the planned Cisco router test impossible.

2.3.4 Conclusions

The 100G circuit installation within RoEduNet was performed at the end of 2010, involving hardware and software changes on the installed DWDM equipment. New hardware was needed to accommodate the 100G cards in the National NOC and NOC Iasi, and a more powerful shelf processor was installed in the Iasi node. Because of the novelty of the 100G card, equipment and management software installed in the RoEduNet DWDM network back in 2008 had to be upgraded to versions that support the new circuit cards and corresponding new services.

The NOC Iasi OME 6500 equipment hosting the 100G cards can be seen in Figure 2.25: NOC Iasi OME6500 and 100G cards (OCI card in slots 3-4, OCLD card in slots 5-6; slots are numbered from left to right). Also present are two types of 10G transponders (600 km (regional) on slots 11-14 and 1600 km (premium) reach on slots 9-10), carrying 10G Ethernet on different length circuits; these are used to connect NOC Iasi to other RoEduNet nodes.

Figure 2.25: NOC Iasi OME6500 and 100G cards

The 100G circuit was stable, with no alarms raised by the optical network monitoring software for one year. With the exception of one restart (required by a firmware upgrade recently performed on OME 6500), no other events were observed for the 100G circuit end components.

Apart from the necessary software upgrade, the installation and operation of the 100G technology from Ciena was straightforward. The cards were standard production cards (not beta releases), supported by the Ciena optical simulation tool and installed on OME 6500 hardware as with all other regular cards. No special training was required and the alarms seen in the management system followed standard Ciena and OTN terminology.

2.4 Laboratory and Field Tests of Alcatel-Lucent100G Solution

CESNET conducted extensive testing of the Alcatel-Lucent (ALU) 1830 Photonic Service Switch (PSS) platform. The test report presented here includes a basic description of the equipment and facilities used, initial laboratory tests, experimental transmission tests, field tests over multiple scenarios, and conclusions.

2.4.1 Equipment and Facilities Used

This section presents brief descriptions of the following equipment and facilities used in the tests:

- ALU 1830 Photonic Service Switch platform.
- EXFO PSO-200 Optical Modulation Analyser.

- APEX-T AP2443B Optical Complex Spectrum Analyser.
- Cisco ONS 15454 Multiservice Transport Platform.
- CzechLight OpenDWDM.
- CESNET2 Network.
- CESNET Optical Laboratories.

2.4.1.1 *ALU 1830 Photonic Service Switch Platform*

The Alcatel-Lucent 1830 Photonic Service Switch (PSS) is the metro/regional Wavelength-Division Multiplexing (WDM) platform purpose-built for flexible and automated WDM networking. The new 100Gbit/s platform's signals rely on complex Dual Polarisation Quadrature Phase-Shift Keying (DP-QPSK) coherent modulation that fits into the 50 GHz ITU frequency grid. Signal resiliency to transmission impairments is well supported by the advanced Forward Error Correction (FEC) mechanism, which makes the signals resistant to most negative linear effects such as chromatic dispersion or polarisation mode dispersion. (The 1830 PSS is also discussed in Chapter 6 *NGN Solution Based on ALU 1830 PSS Platform* on page 99.)

Figure 2.26: ALU 1830 PSS

2.4.1.2 *EXFO PSO-200 Optical Modulation Analyser*

The EXFO PSO-200 Optical Modulation Analyser is designed for testing transceivers with a large variety of coherent modulation formats. The device coherently detects modulation signals and displays constellation and eye diagrams of the received signals as well as their most important parameters. PSO-200 does not support forward error codes and therefore displays modulation symbols rather than transmitted data.

Figure 2.27: EXFO PSO-200 Optical Modulation Analyser

2.4.1.3 *APEX-T AP2443B Optical Complex Spectrum Analyser*

The APEX-T AP2443B Optical Complex Spectrum Analyser achieves unmatched resolution of 0.04 pm (5 MHz) with a close-in dynamic range of 60 dB. This next-generation device achieves such excellent parameters thanks to new interferometric principles.

Figure 2.28: APEX-T AP2443B Optical Complex Spectrum Analyser

2.4.1.4 *Cisco ONS 15454 Multiservice Transport Platform*

The Cisco ONS 15454 Multiservice Transport Platform (MSTP) is the most-deployed metropolitan-area and regional DWDM solution in the world, featuring two- through eight-degree Reconfigurable Optical Add/Drop Multiplexer (ROADM) technology that enables wavelength provisioning across entire networks and eliminates the need for optical-to-electrical-to-optical (OEO) transponder conversions. The ONS 15454 MSTP interconnects with Layer 2, Layer 3 and storage area network (SAN) devices at rates up to 40 Gbit/s. It delivers any service type to any network location and supports all DWDM topologies.

Figure 2.29: Cisco ONS 15454 MSTP

2.4.1.5 *CzechLight OpenDWDM*

The CzechLight OpenDWDM is a complete family of network devices for optical core networks designed to increase the adaptability and flexibility of a core network to suit the demanding needs of the Research and Education (R&E) community. CESNET uses OpenDWDM in about 40% of the backbone network.

2.4.1.6 *CESNET2 Network*

The CESNET2 network is the production part of the CESNET optical core network, utilising systems and devices from Cisco Systems. Cisco DWDM equipment covers about 60% of the CESNET optical core network, serving the biggest cities. Both Cisco DWDM and OpenDWDM perform without any errors in a multi-vendor environment. The network performance is monitored at [CESNET2Perf]. For a map of the CESNET2 network, please see Figure 2.43 on page 51.

2.4.1.7 *CESNET Optical Laboratories*

The CESNET optical laboratories play a crucial role in CESNET's applied research. CESNET invests considerable effort in research activities with the aim of improving the flexibility of the optical core network and so meeting the needs of the R&E community. Currently CESNET is performing module-to-system research in cooperation with Czech universities and research institutions.

Figure 2.30: CESNET optical laboratories

2.4.2 Initial Laboratory Tests

The initial laboratory tests of the Alcatel-Lucent 100G solution focused on:

- Power budget.

- Filtration of optical spectra.
- Non-Linear effect threshold.

Each of these is described below.

2.4.2.1 *Power Budget*

The power budget of the 100G DP-QPSK system from Alcatel-Lucent was tested to establish the maximum attenuation that can be overcome without optical amplification. A pseudorandom sequence from Bit Error Rate Testing (BERT) was multiplexed in the ALU system onto a 100G coherent signal. The 100G signal passes only a variable attenuator from EXFO before demultiplexing and retrieving a pseudorandom sequence for BERT, as shown in Figure 2.31.

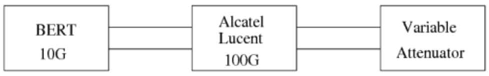


Figure 2.31: Power budget test setup

Owing to the advanced Forward Error Correction (FEC) embedded in the ALU system, the system is able to overcome attenuation of almost 3 orders of magnitude (28.2 dB) without any amplification.

2.4.2.2 *Filtration Test*

Filtration of optical spectra takes place at many optical elements throughout every network. Also, the slight misalignment of the central wavelengths of optical elements is a common problem and therefore the resilience of the system to filtration effect is an important parameter. The 100G ALU system was fed by a pseudorandom sequence from BERT. The 100G signal was then double-filtered by two tunable filters from Santec (“A” in Figure 2.32 below) and JDSU (“B”), before it was sent back to the 100G ALU system. Double filtering was used to increase the slope of the resulting optical filter and thus impose stricter constraints on the 100G system. Optical spectra were observed using a high-resolution optical spectrum analyser from APEX Technologies, as shown in Figure 2.32.

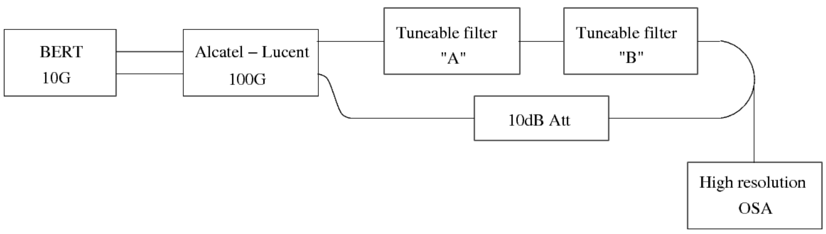


Figure 2.32: Setup of filtration test

The 100G signal was filtered by 100 GHz, 50 GHz and 30 GHz filters, as can be seen in the left-hand column of Figure 2.33. 30 GHz filtering was subsequently performed asymmetrically by detuning the filter 40 GHz to the left and right of the central wavelength of the respective ITU channel. Finally, the spectrum of the double-filtered signal at its central wavelength is displayed at the bottom of the right-hand column of Figure 2.33. There was no impact on transmission BER for the filtering scheme provided that filter detuning did not increase beyond 40 GHz. The advanced FEC performance was not monitored due to time constraints.

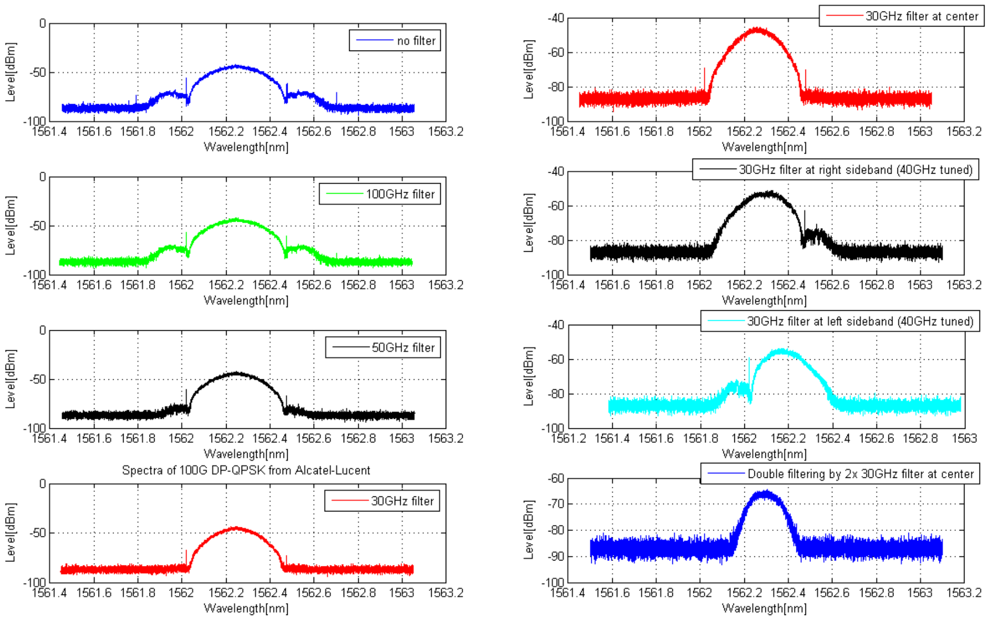


Figure 2.33: Spectra of 100G signal with applied filtering

2.4.2.3 *Non-Linear Effect Threshold*

Non-linear effects start to appear if the optical power level in the optical fibre exceeds a certain limit. The most significant effect for a 100G modulated signal in the CESNET setup is a self-phase modulation (SPM), which adds spurious phase modulation to the signal while broadening the signal spectrum. As shown in Figure 2.34, a 100G signal from the ALU system was amplified by a booster amplifier from Keopsys and sent through 100 km of G.652. The optical spectrum was monitored by APEX OSA before the signal returned to the ALU system.

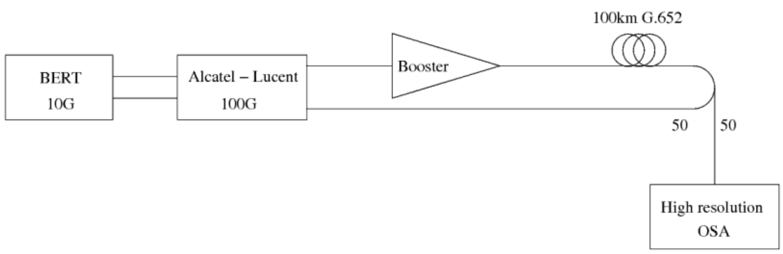


Figure 2.34: Setup for non-linear threshold test

The output power of the optical amplifier was increased from 10dBm to 27dBm. The system did not produce any errors until the output power reached 22dBm. Optical spectra for several amplifier output powers are shown in Figure 2.35. It can be seen that powers over 20dBm induce SPM, considerable broadening of the main peak and vanishing of sidebands. Therefore the use of amplifiers with high output power requires careful planning.

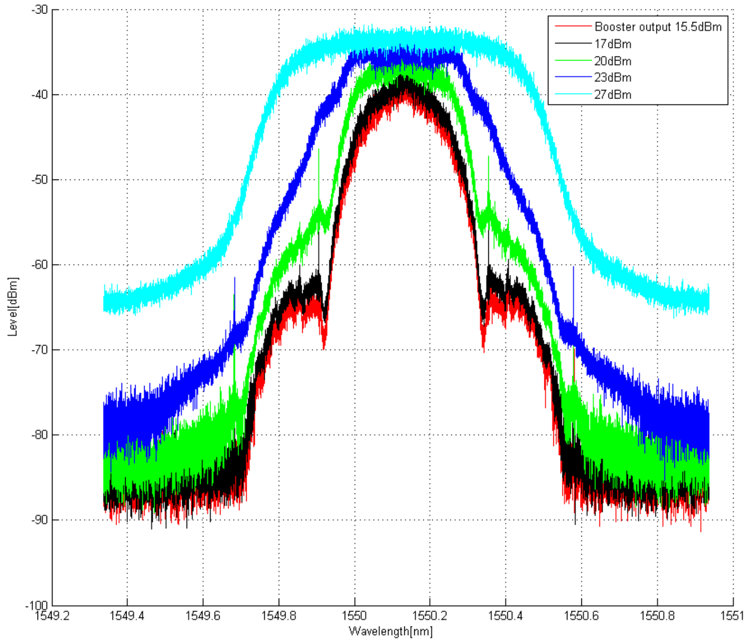


Figure 2.35: Non-linear spectrum broadening as a function of booster output power

2.4.3 Experimental Transmission Line Tests

The experimental transmission line tests investigated:

- Transmission.
- Interference,
- Constellation diagrams.

Each of these is described below.

2.4.3.1 *Transmission Test*

The transmission test covered a distance of 600 km utilising both G.652 and G.655 fibre spans available in the laboratory. The parameters of the fibre spans used can be found in Table 2.3 below. The test was set up using

Dispersion Compensating Fibres (DCF) and long spans to explore possible effects of the ALU system on traditional transmission links with DCFs. Having started with DCF as the dispersion compensation element, some of the DCFs were then replaced with Dispersion Compensating Modules (DCM) that utilise Fibre Bragg Gratings (FBG), to prove that 100G technology can work together with standard systems.

DCFs are spools of dispersion compensation fibre lengths have the opposite dispersion to the desired span of fibre line. Their disadvantages are smaller fibre core (about four times smaller) and therefore stronger non-linear effects, together with considerable attenuation (more than 5 dB extra per typical 80km-long span) and cost. DCMs are short fibres with inscribed periodical structures called Bragg Gratings that shape their transmission parameters and can be designed or even tuned for dispersion compensation. It should be mentioned that the latency of DCMs is lower than that of DFCs, which is why DCMs in general are a better choice for creating “fast” networks, optimising the performance of various protocols, e.g. TCP, and the user/system experience for interactive services.

Two 100G signals from ALU systems were combined with 12 standard 10G channels in a multiplexer and sent to the first amplification stage. The spectrum after multiplexing is shown in Figure 2.37 below. Double-stage amplifiers with gain-flattening features were used in this experiment. All amplifiers except the first had a dispersion compensating element in between their stages. The whole setup can be seen in Figure 2.36.

ID	Type	Length (km)	Att (dB)	CD (ps/nm)
A1	G.652c	100.7	20.1	1611.2
A2	G.652c	103.7	20.7	1659.0
A3	G.652c	101.1	20.2	1618.0
B1	G.655	95.4	19.1	19.4
B2	G.655	100.3	20.1	401.2
B3	G.655	100.6	20.1	402.4

Table 2.3: Fibre spans used in laboratory experiment

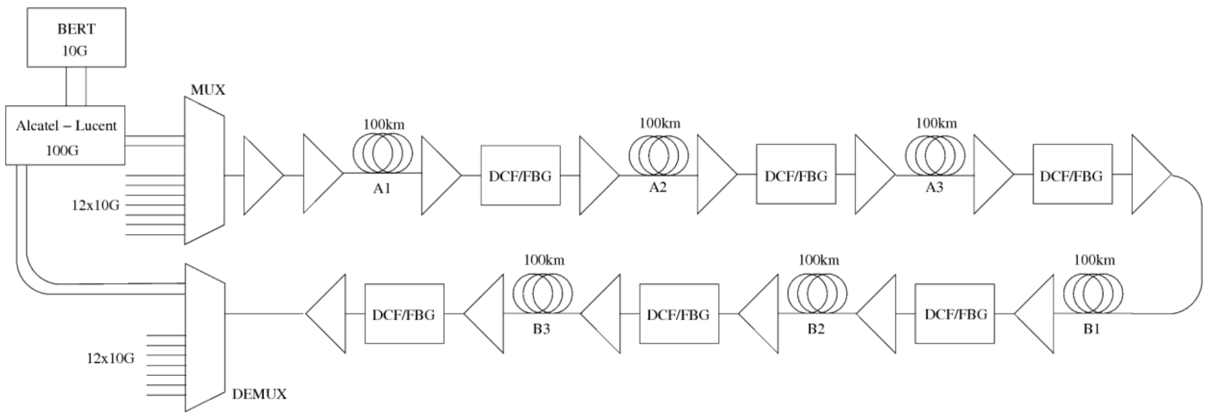


Figure 2.36: Experimental setup of 600 km transmission

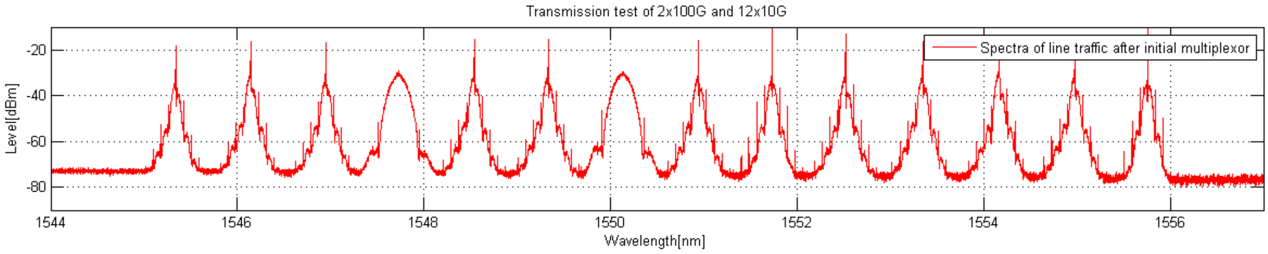


Figure 2.37: Spectra of 2 x 100G and 12 x 10G after initial multiplexing

Both 10G and 100G systems worked without errors with proper dispersion compensation. In the case of the DCFs, the systems worked with 844 ps/nm uncompensated dispersion without errors. With some of the DCFs changed for DCMs, similar uncompensated dispersion of 814 ps/nm was achieved. In this case some errors in BERTs were experienced. The conclusion drawn from this test is, therefore, that FBGs have an advantage with regard to length when compared to DCFs, but that the dispersion must be compensated more accurately. Noise added by the ALU amplifier after 7 amplifications was estimated to be about 5.5dB per amplifier.

2.4.3.2 *Interference Test*

The mutual influence of adjacent optical channels is undesirable in DWDM systems. Inter-channel interference testing is therefore of high importance for optical network planning. CESNET set up a 600 km long transmission line with 12 x 10G optical channels at 100 GHz grid spacing and fitted two 100G channels at 50 GHz grid spacing in between the 10G channels. The performance of one 100G channel was measured by monitoring advanced Forward Error Correction (AFEC) at 15 minutes intervals. AFEC experienced 1144 million corrected frames for adjacent 12 x 10G channels in the system, as can be seen in the red section of Figure 2.38 below. However, once three adjacent 10G lambdas were removed to reduce interference, the AFEC corrections immediately increased to 2282 million corrected frames, as shown in the blue section of Figure 2.38. This effect seems counterintuitive and is still being studied; however, it is thought that the drop in system performance can be attributed to a change of transmission power balance in combination with the automatic power control of the amplifiers along the transmission line. In other words, exclusion of three channels might result in a lower pump current of optical amplifiers where they might experience greater phase noise which is detrimental to coherent signals but has no influence on other NRZ modulated signals.

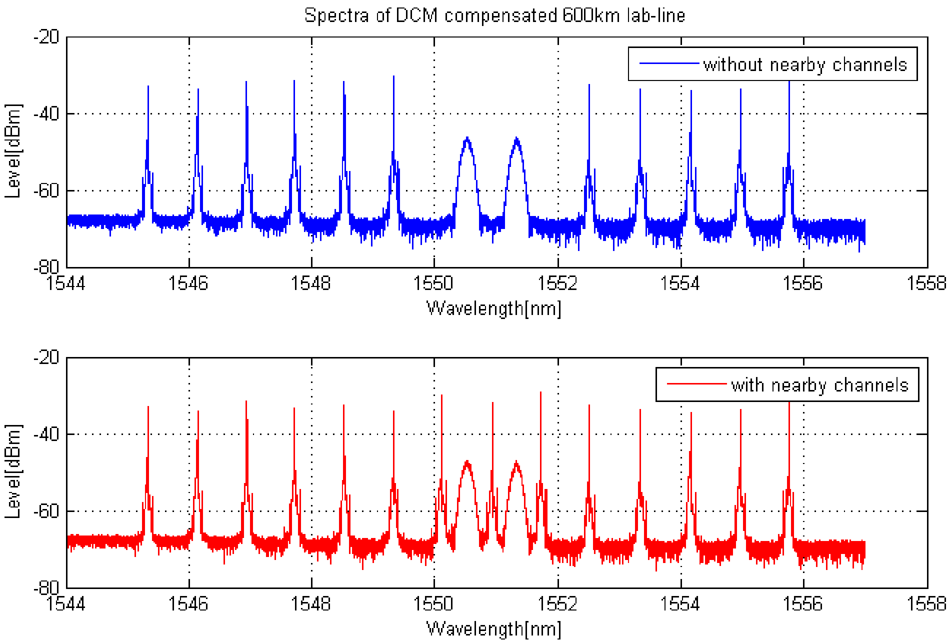


Figure 2.38: Spectra of interference test without adjacent 10G channels (blue) and with adjacent 10G channels (red)

2.4.3.3 *Constellation Diagram Test*

An eye diagram is an effective means of displaying simple modulation schemes. A skilled engineer can easily judge signal quality and its parameters. More complex modulations such as DP-QPSK are better represented by constellation diagrams, which show symbols detected in the complex plane. DP-QPSK is a coherent modulation exploiting both phase and polarisation to represent modulation symbols. Transceivers work at a symbol rate of about 25 GBaud/s, which translates to about 50 Gbit/s for four-state QPSK in one polarisation. The second polarisation carries the same amount of information, resulting in total throughput of about 100 Gbit/s.

The Optical Modulation Analyser PSO-200 from EXFO can detect and display various advanced optical modulation schemes. The analyser is dedicated to coherent transceiver testing at equipment production companies and therefore unable to correct transmission impairments. The CESNET transceiver was analysed with PSO-200. A clear constellation diagram of 100G DP-QPSK is shown in Figure 2.39. The figure displays constellation diagrams for both orthogonal polarisations and related eye diagrams of demodulated bit streams at the detector. In the next test, 10 km of G.652 with precise DCF to compensate chromatic dispersion was added; only limited signal distortion was observed (see Figure 2.40). The fibre link was therefore extended to 100 km of G.652 and a tunable dispersion compensation module based on FBG was used to optimise the performance of the PSO-200. A partial signal distortion can be seen in Figure 2.41 due to accumulated Amplified Spontaneous Emission (ASE) from the amplifiers in the setup and some PMD. Figure 2.42 shows the performance of the PSO-200 in the presence of 170 ps/nm of uncompensated chromatic dispersion. Real long-haul fibre lines usually experience more noise from multiple amplifier stages and larger PMD than fibre spools, which prevented us from carrying out constellation analysis of real lines. The reason for the difference in PMD between deployed fibre and fibre spools is that the PMD effect is based on the birefringent nature of optical fibre which is enhanced by the mechanical stress put on optical fibre which in turn is increased by fibre plant deployment. It should be highlighted that PSO-200 is not designed for system testing.

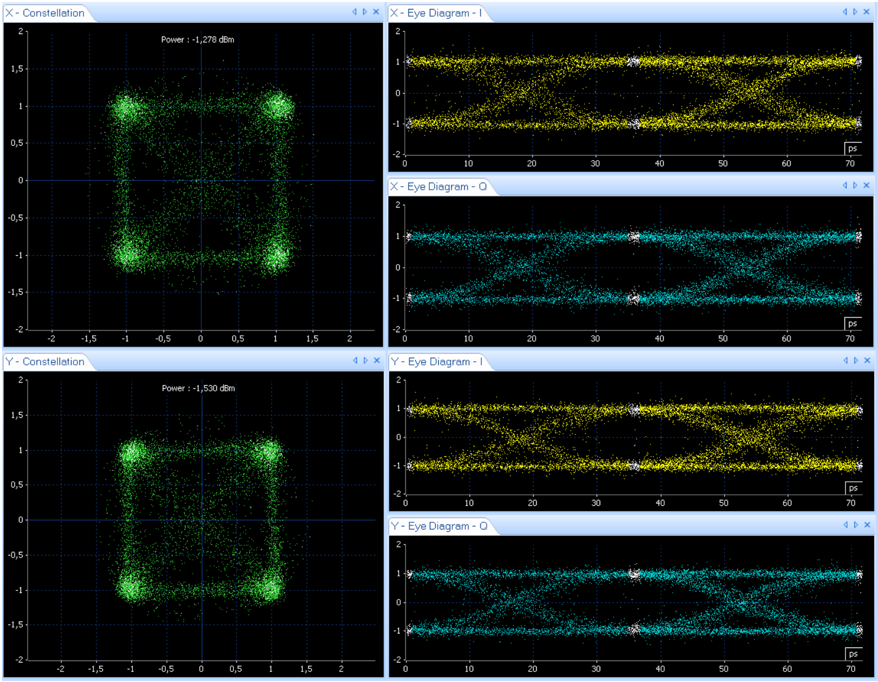


Figure 2.39: Constellation diagram of 100G DP-QPSK directly after transceiver

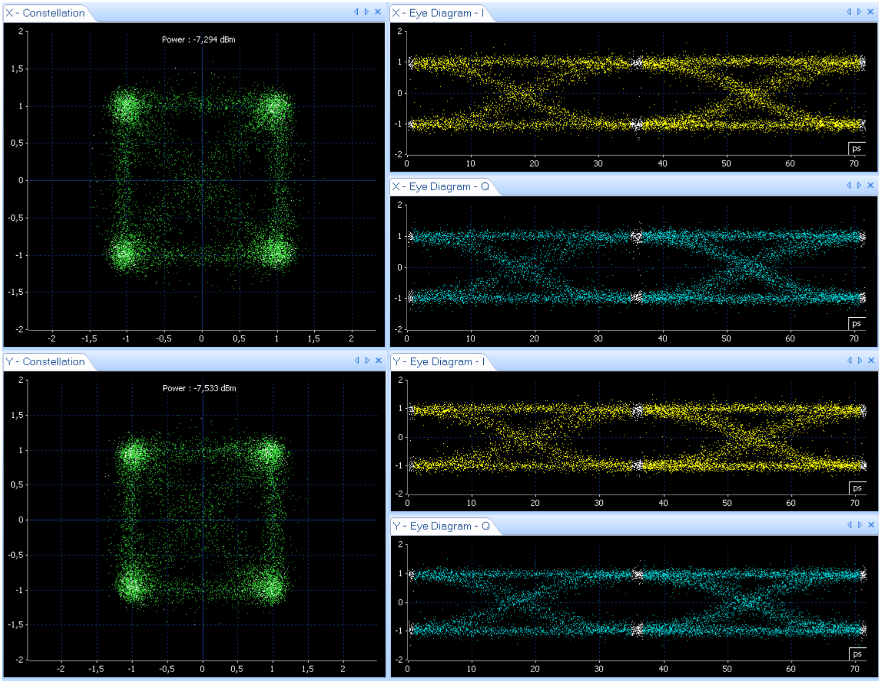


Figure 2.40: Constellation diagram of 100G DP-QPSK modulation after 10 km of fibre with precise dispersion compensation

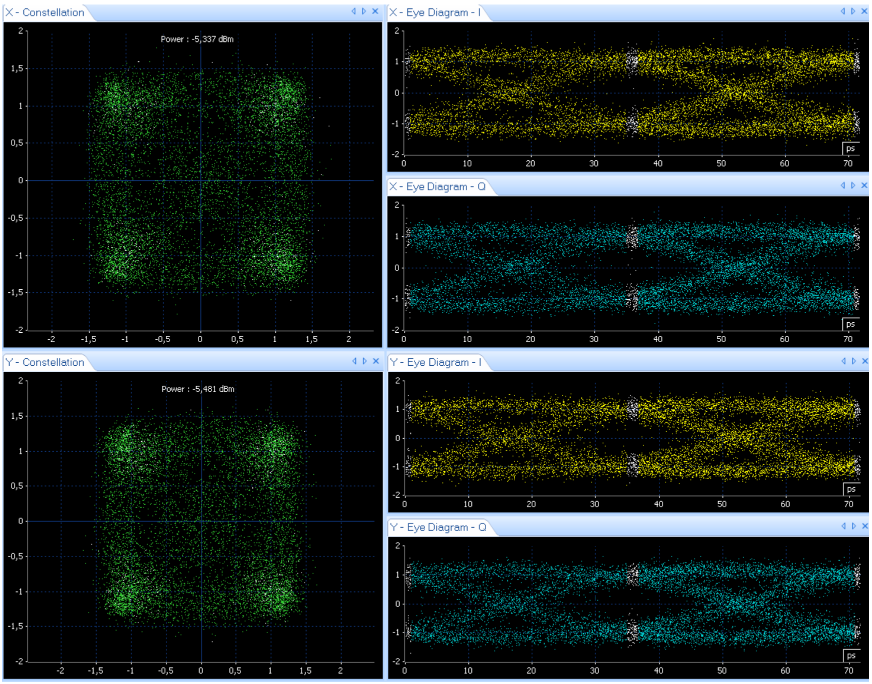


Figure 2.41: Constellation diagram of 100G DP-QPSK modulation after 100 km of fibre with precise dispersion compensation

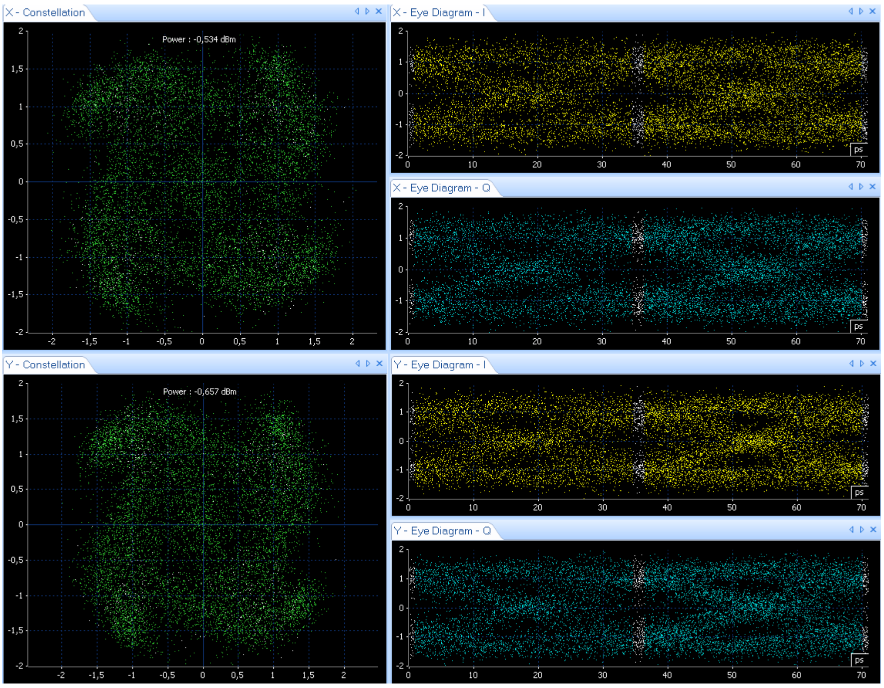


Figure 2.42: Constellation diagram of 100G DP-QPSK modulation after 100 km of fibre with 170 ps uncompensated dispersion

The constellation diagrams above show the need for testing equipment with integrated signal processing if the aim is to be able to verify signal quality directly on the line on DWDM systems utilising coherent modulation formats. With the rapid development of different modulation formats and proprietary FEC algorithms, however, the authors believe that such testing equipment will be extremely difficult to produce, and that users of future DWDM systems will be forced to utilise the performance counters that are built into the transponders,

2.4.4 Field Tests in CESNET2 Live Network

After extensive testing in the laboratory, several scenarios in the live CESNET2 network were prepared to verify interoperability of a coherent 100G DP-QPSK system with standard 10G Non-Return-to-Zero (NRZ) systems and special photonic services. Figure 2.43 shows the CESNET2 network with Cisco DWDM and Open DWDM network equipment highlighted.

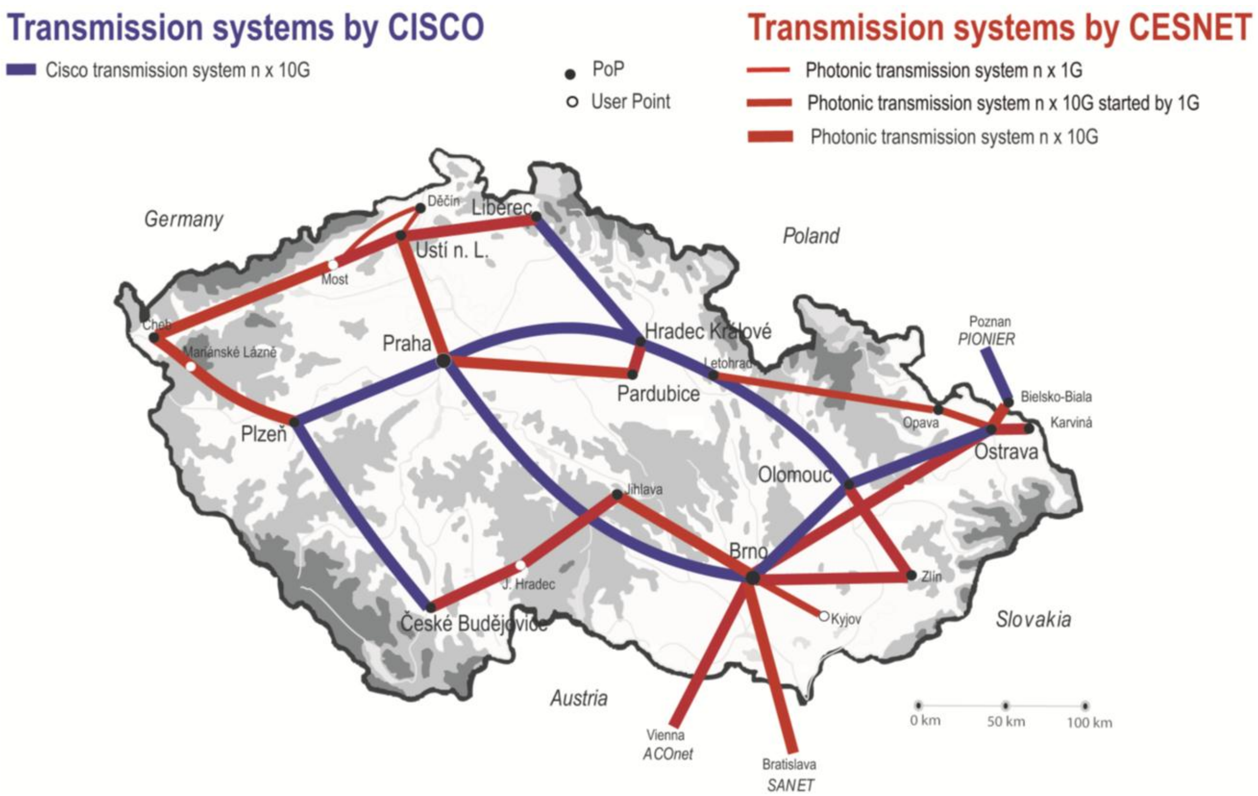


Figure 2.43: Map of CESNET2 network with Cisco lines marked in blue and lines lit by open systems in red

First, a loop of 1063 km total length was established over production lines equipped with Cisco ONS 15454 MSTP by connecting Praha–Hradec Králové–Olomouc–Ostrava–Olomouc–Hradec Králové–Praha. The total attenuation overcome was 276 dB with two spans of 22 dB attenuation. Overall performance of the 100G system was measured by embedded AFEC performance and a BER tester running on one of the multiplexed 10G channels. The 100G system ran satisfactorily, with 33e+9 corrected and no uncorrected errors in AFEC every 15 minutes.

The second field test reduced the total test distance to 778 km, but the 100G signal was sent over the same line as a photonic service of precise atomic clock comparison (the 100G signal and the photonic service were transmitted in the same fibre). The ring Praha–Hradec Králové–Olomouc–Brno–Praha (see Figure 2.43) had 208 dB of attenuation and also included three spans with attenuation of 22 dB. The 100G system ran satisfactorily with just 4e+9 corrected and no uncorrected errors in AFEC every 15 minutes. During the test the photonic service was in operation on the line Praha–Brno, with no evidence of mutual influence in the electrical domain, i.e. no degradation of the photonic service (used for synchronising atomic clocks) was seen when the 100G was lit.

The third test was conducted over a combination of Cisco and open transmission systems on the line Praha–Brno–Vienna–Brno–Praha, with concurrent transmission of a photonic service of atomic clock comparison. The open transmission system is a multi-vendor DWDM system based on optical network devices from the CzechLight family. (Details can be found at [CzechLight].) The total length of line was 1056 km with 285 dB of attenuation and 4 spans of 22 dB plus another four critical spans of 30 dB, 31 dB, 32 dB and 34 dB. AFEC reported 303e+9 corrected errors and BERT measured an uncorrected bit error rate of 25e+3. The main reason for this effect is believed to be the reduction of OSNR at the four critically long spans.

The fourth test was conducted over single-fibre bi-directional transmission lines. The ring Praha–Plzeň–Cheb–Most–Ústí nad Labem–Praha includes part Cisco and part open transmission systems, with a total length of 655 km and 180 dB of attenuation. The ring had three critical spans of 35.5 dB, 34 dB and 35.5 dB. AFEC corrected 118e+9 errors with no uncorrected errors over 15 minutes.

2.4.5 Conclusions

A 100G coherent transmission system is resilient to many network impairments such as optical line impairments, filtration and inter-channel interference (although some interference effects were counterintuitive and require further investigation). Coherent systems can work over compensated networks with no known influence from the type of dispersion compensation. In a comparison of DCF, DCM and uncompensated scenarios, no impact from the type of dispersion compensator was observed; however, more attenuation was observed as DCF length increased. FBG should be preferred for chromatic dispersion compensation due to its lower insertion loss, fewer non-linear effects and lower latency. New coherent systems can therefore be deployed within operational 10G NRZ transmission systems provided that the network remains dispersion compensated.

The tests verified that the ALU 100G Photonic Service Switch platform works with Cisco and CzechLight transmission systems in a multi-vendor environment. They also proved that the ALU 100G can work over single-fibre bi-directional transmission lines and in parallel with photonic services such as atomic clock scale comparison.

2.5 Conclusions

The tests presented in this chapter reflect the current status of many NRENs with regard to their optical infrastructure. They have a large installed base of DWDM equipment designed and optimised for 10G transmission, and are faced with the question of whether the networks are capable of supporting higher transmission speeds and newer modulation formats. The introduction of 40G into the optical core failed to have the impact expected, mainly due to confusion about preferred modulation formats, which resulted in higher costs. It is therefore logical to investigate and adopt 100G as the direct successor to 10G transmission.

In the field tests, the 100G signal was fed into systems that were designed for 10G transmission and had the required dispersion compensation fibres or modules. In all cases the 100G was able to traverse the compensated spans and the client traffic was delivered error free on the client side, proving that the coherent modulation format of the 100G can coexist with 10G NRZ signals. Although the tests featured various fibre types, lengths and guard bands, they do not offer definitive proof that 100G will always work in a 10G legacy network: there is still some uncertainty about non-linear effects between 10G and 100G, the difference between 652 and 655 fibre use, etc. In two of the cases, the 100G was operated as an alien wavelength, which highlighted cross-vendor design issues. In that respect, the introduction of 100G in legacy networks faces the same problem as optical design of alien wavelengths, where many factors, usually unknown to the end user, have to be validated in order to guarantee the performance of the network. Sections 2.4.1 to 2.4.3 indicate a small part of what is necessary to perform such a validation. The need for an optical design tool to guarantee the performance of the entire network is evident. Because such tools are often vendor specific, the tests carried out by the participating NRENs and described in this chapter can serve as important guidelines for future multi-vendor tests.

3 GMPLS in the Optical Domain

3.1 Introduction

Generalised Multi-Protocol Label Switching (GMPLS) is seen as one of the ways to achieve fully automated restoration and provisioning in the network, and is implemented by several Dense Wavelength-Division Multiplexing (DWDM) vendors. The NRENs' interest in advanced control planes is closely related to the wish for Bandwidth on Demand solutions, which could enable more timely and efficient use of the resources within the community, and to the general need for better control of complex networks, e.g. for virtualised network resources.

This chapter describes the service restoration tests conducted by PSNC on the production ADVA Optical Networking DWDM transmission system of the PIONIER network; services were restored in the optical domain using a modified version of GMPLS. The chapter describes the testbed environment and the goals of the tests, and discusses the signal flow configuration and requirements. The results cover service restoration times for: different types of faults, different numbers of switching services, switching with or without wavelength change, and switching with different path lengths.

3.2 Background

3.2.1 Testbed Environment

All tests were conducted on the production ADVA DWDM transmission system of the PIONIER network (i.e. not in a laboratory). The total PIONIER DWDM network extends across 6,000 km, but the test environment consisted of a 1,000 km ring with 6 add/drop points, as shown in Figure 3.1 below.

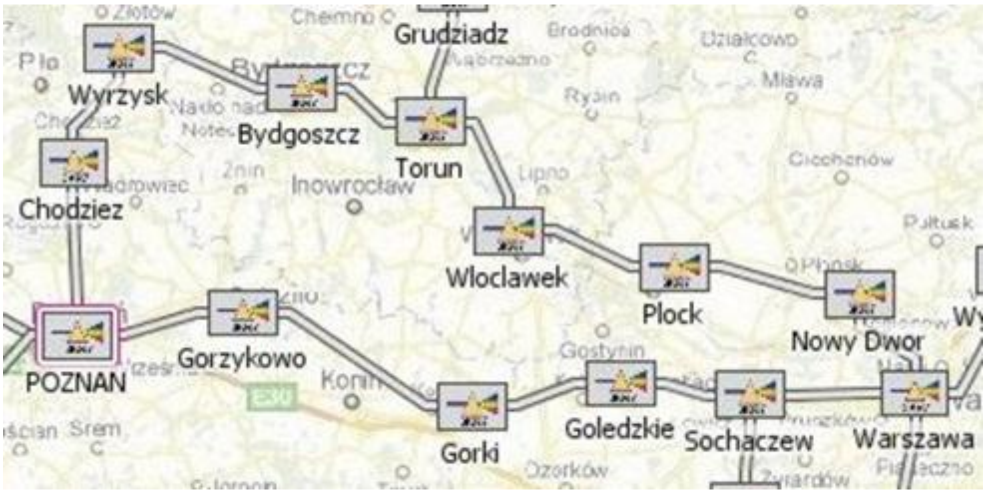


Figure 3.1: PIONIER DWDM test environment

The PIONIER DWDM network has implemented colourless and directionless functionalities. This means that any service can use any wavelength and connect in any direction.

The testbed was based on the ADVA Fibre Service Platform (FSP) 3000 R7 Rel.10.2.3 DWDM, and services were created using FSP Network Manager 6.5.1. ADVA Network Manager allows services to be created automatically between client ports of transponders. It is also able to create services through a command line interface (CLI) (Craft Terminal), but this solution only makes it possible to create connections between network ports. This means that client ports of transponders need to be configured separately.

In the tests described below, services were restored in the optical domain using the ADVA INTERNAL protocol (modified Generalised Multi-Protocol Label Switching (GMPLS)).

For greater data reliability, service availability was measured by Internet Control Message Protocol (ICMP) echo response, generated from servers connected to transponders.

3.2.2 Test Goals

In order to determine the suitability of the restoration function, the tests aimed to establish the difference in restoration time for the following scenarios:

- A selection of fault types (e.g. amplifier laser off, fibre cut).
- Different numbers of switched services.
- Switching with or without wavelength change.
- Switching with different path lengths (calculated as a distance or number of reconfigurable elements).

3.2.3 Signal Flow

Figure 3.2 below shows a typical colourless and directionless node configuration using an example configuration used in the testbed environment.

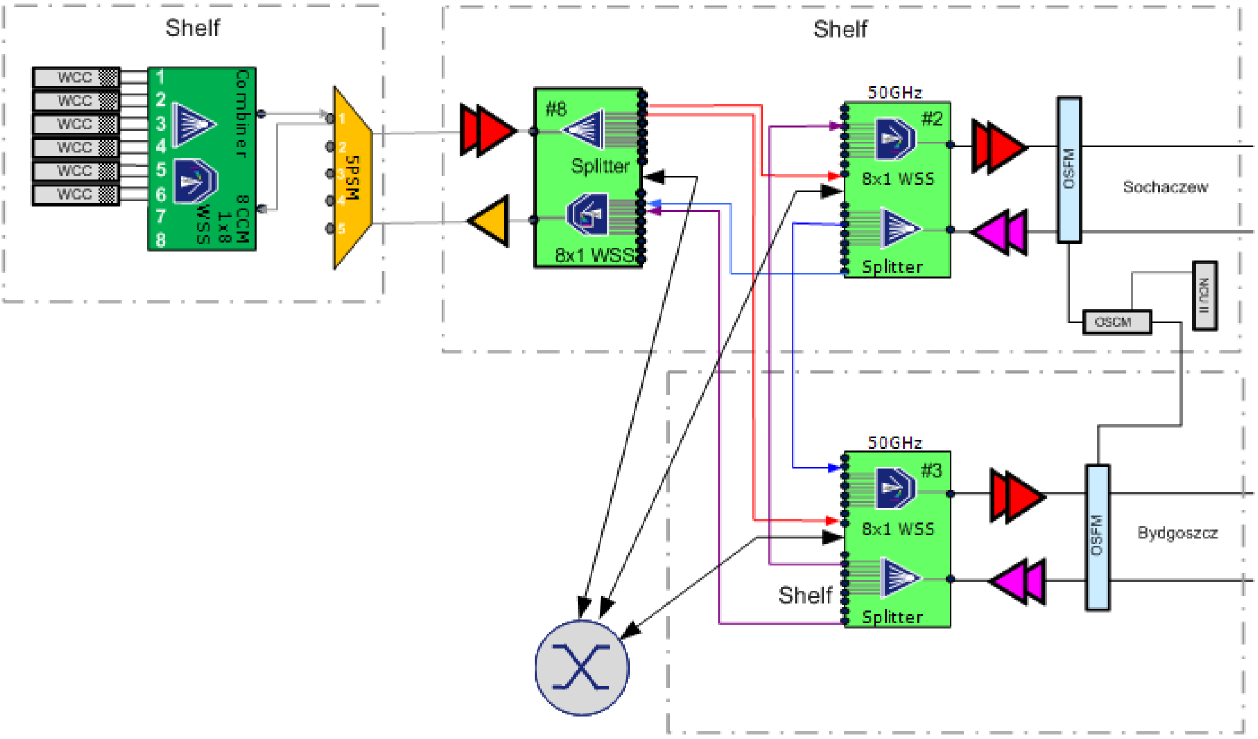


Figure 3.2: Typical colourless and directionless node configuration

As shown in the block diagram in Figure 3.2, the signal comes from the transponder (WCC card) network port followed by a reconfigurable filter (in this case an 8CCM card – the dark-green WSS component in the top left corner of the figure), which is responsible for multiplexing signals from transponders and, in the opposite direction, for splitting the proper wavelength to each transponder. Next, signals from the 8CCM modules are combined into one (in this case by a 5PSM card) and send to a cascade of ROADMs structure. These ROADMs are responsible for sending a proper service signal in the proper direction (output) or dropping it. The most important aspect of this configuration is that all modules containing a Wavelength Selective Switch (WSS) element need to equalise the signal. It should be stressed that all the elements presented in Figure 3.2 have a WSS switch in one direction. This means that not all of the elements achieve signal equalisation in all cases, or signal direction flow.

The following elements need to be equalised and wavelength-tuned:

- ROADM.
- 8CCM (reconfigurable filters).
- Reconfigurable transponders (laser tuning).

In the testbed presented here, equalisation and tuning of those elements is required at the following points:

- At the Add point: laser tuning in transponder and equalisation of one ROADM.
- At the Pass Thru point: equalisation of one ROADM.
- At the Drop point: equalisation of one ROADM and 8CCM module.

3.3 Service Restoration Results

This section presents the results of the service restoration tests, to meet the goals stated in Section 3.2.2.

3.3.1 Restoration Time for Different Types of Faults

3.3.1.1 *EDFA Turned Off*

On the link between Warszawa–Poznan, the Erbium Doped Fibre Amplifier (EDFA) element in the In-Line Amplifier (ILA) node at Gorzykowo was turned off. Turning off an EDFA results in unidirectional loss of signal (as opposed to the complete signal loss resulting from a fibre cut), which is why internal control mechanisms are responsible for the fault communication to the upstream node. The aim of this test was to verify that GMPLS operates correctly under these circumstances. A schematic of the topology of the optical circuit is shown in Figure 3.3.

In this scenario, the optical path Poznan–Sochaczew–Warszawa was switched to the path Warszawa–Toruń–Bydgoszcz–Poznań. One service was switched.

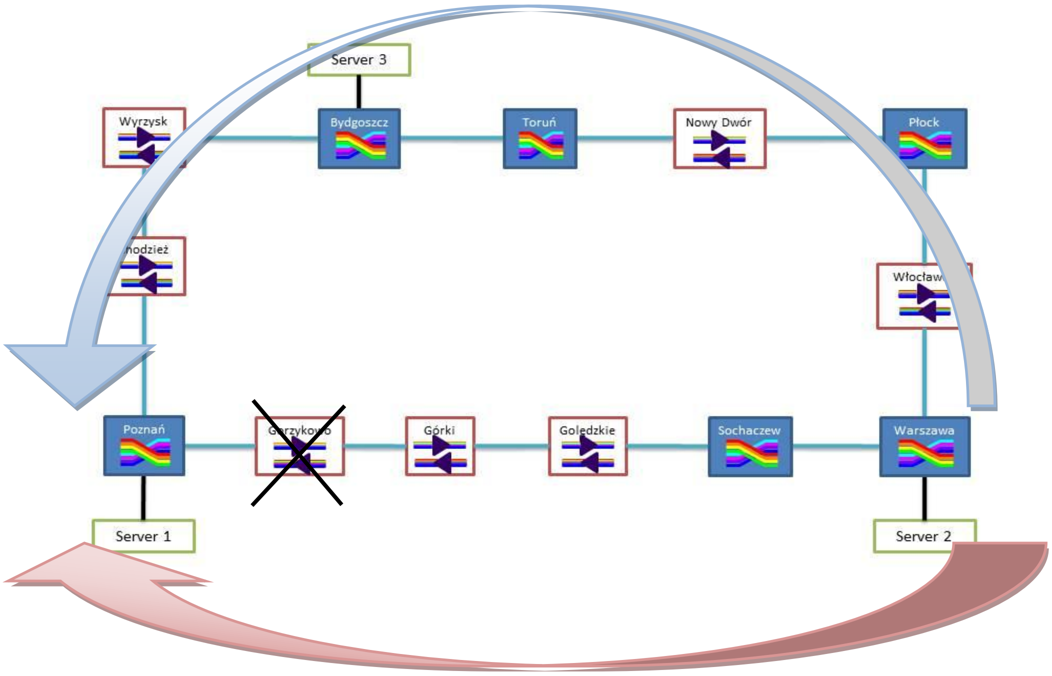


Figure 3.3: Schematic of the optical circuit topology – EDFA turned off

The restoration time observed was 3 min 46 sec.

3.3.1.2 *Fibre Cut*

On the link between Warszawa–Poznan, the fibre was "damaged" (the fibre patch cord was unplugged). A schematic of the optical circuit topology is shown in Figure 3.4. In this scenario, the optical path Warszawa–Sochaczew–Poznan was switched to Warszawa–Toruń–Poznan. One service was switched.

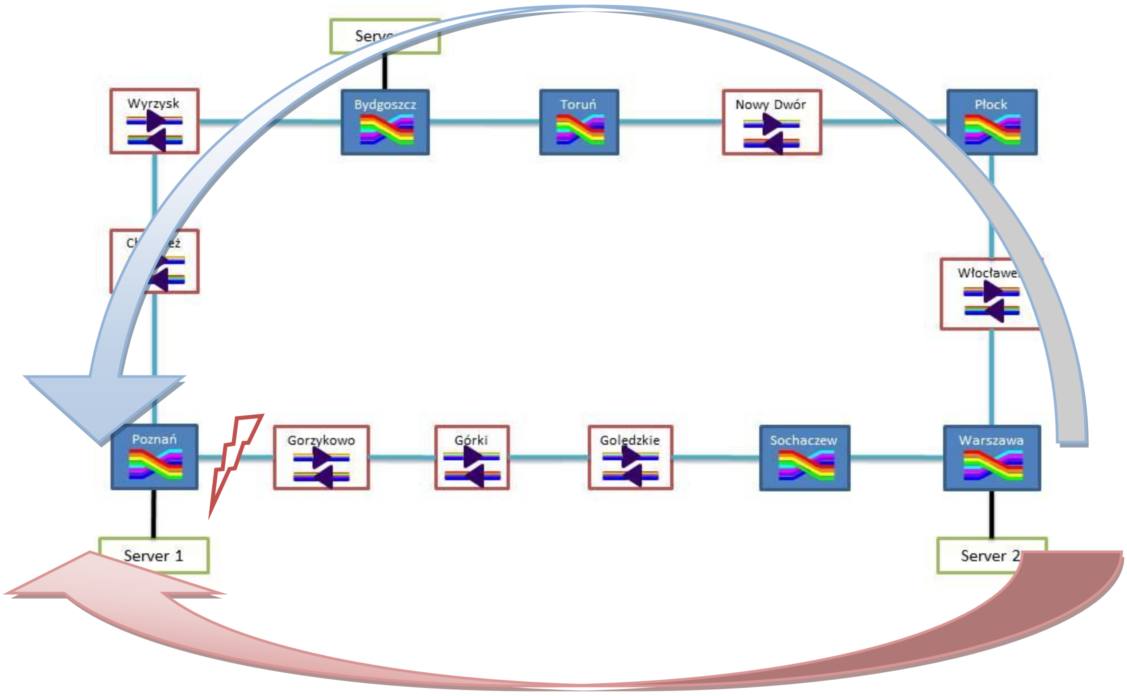


Figure 3.4: Schematic of the optical circuit topology – fibre cut

The restoration time observed was 3 min 47 sec. This was similar to the time in the EDFA turn-off test, from which it may be concluded that fault types do not have an impact on restoration time.

3.3.2 Restoration Time for Different Numbers of Switched Services

This test measured the restoration time of switching of one, two and three services. The services were switched while the EDFA was turned off in the ILA node (between Poznan and Warsaw).

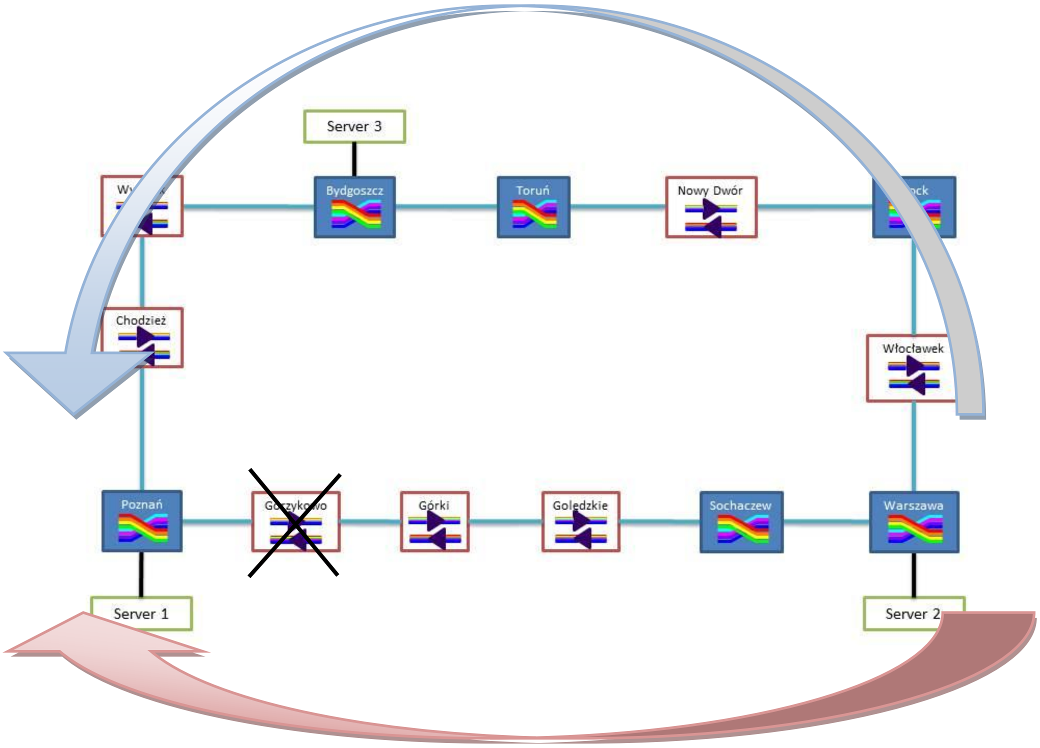


Figure 3.5: Schematic of the optical circuit topology – service switching

The outcome of this test was as follows:

- Switching of one service – 3 min 46 sec.
- Switching of two services – 3 min 50 sec.
- Switching of three services – 3 min 49 sec.

No difference in restoration time was observed with regard to the number of switched services. The restoration times for switching one, two and three services are similar, and are comparable to the restoration times for different fault types seen in Section 3.3.1.

3.3.3 Restoration Time for Switching with or without Wavelength Change

In this scenario, switching was performed with a wavelength change from 1561.42 nm to 1553.33 nm and next without a wavelength change. The change to the optical path was forced by turning off the EDFA in the ILA node (between Poznan and Warsaw).

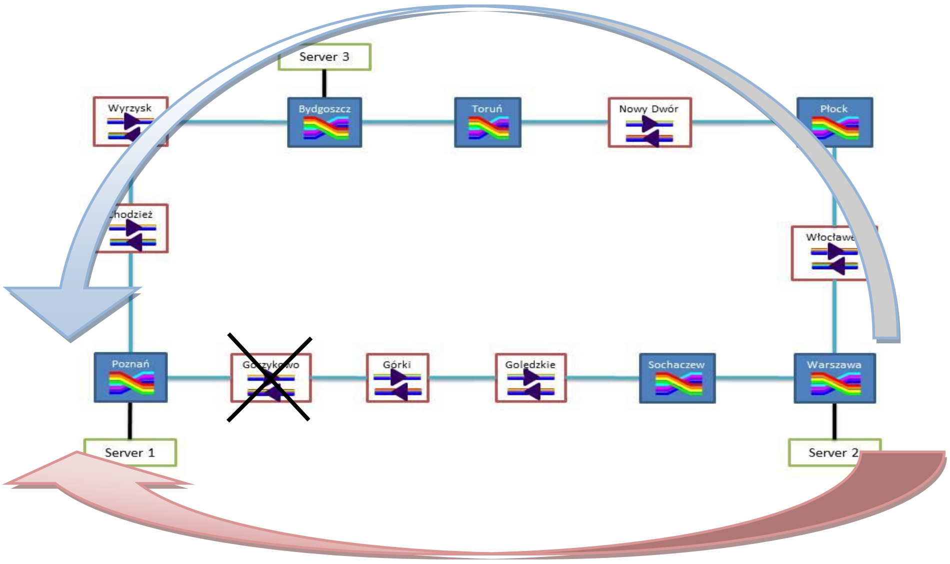


Figure 3.6: Schematic of the optical circuit topology – service switching by turning off the EDFA in the ILA node

The following restoration times were observed:

- With wavelength change: 3 min 47 sec.
- Without wavelength change: 3 min 46 sec.

No difference in restoration time was observed with regard to switching with or without wavelength change. The reason for this is that laser tuning time is included in the preparation time. The laser is "forced on" and then there is a delay until it becomes stable; this time is less than the time taken for the restoration path to be established.

3.3.4 Restoration Time for Switching with Different Path Lengths

This series of tests observed the restoration time for switching taking into account the number of ROADMs and length of the fibre path.

The optical paths were established between nodes with distances from 239 km to 767 km. The shortest link included two ROADMs and the longest six.

Figure 3.7, Figure 3.8 and Figure 3.9 below show different switching scenarios between the main nodes (Poznan, Bydgoszcz and Warszawa).

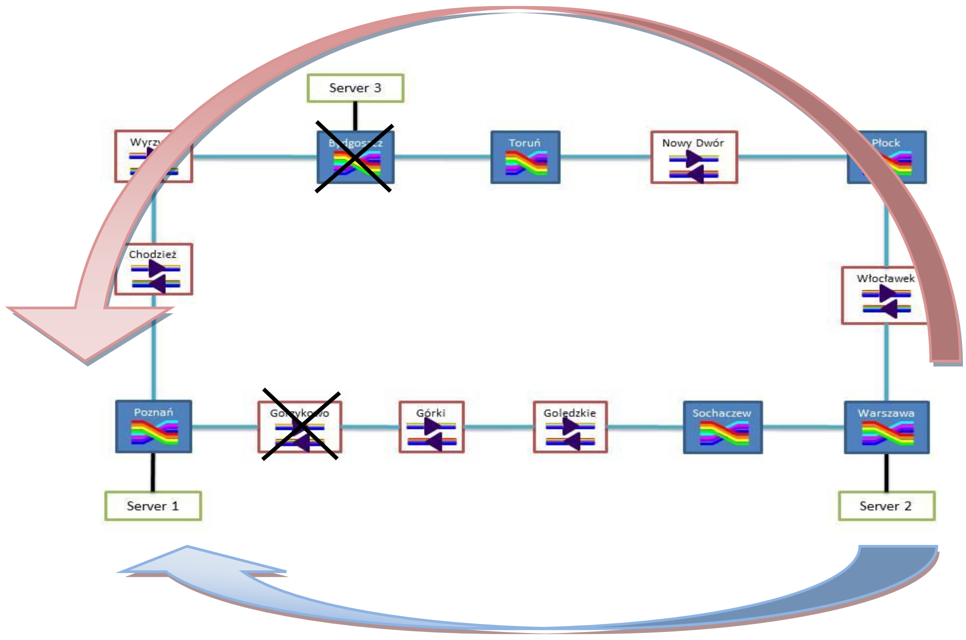


Figure 3.7: Switching scenario between Poznan and Warsaw nodes

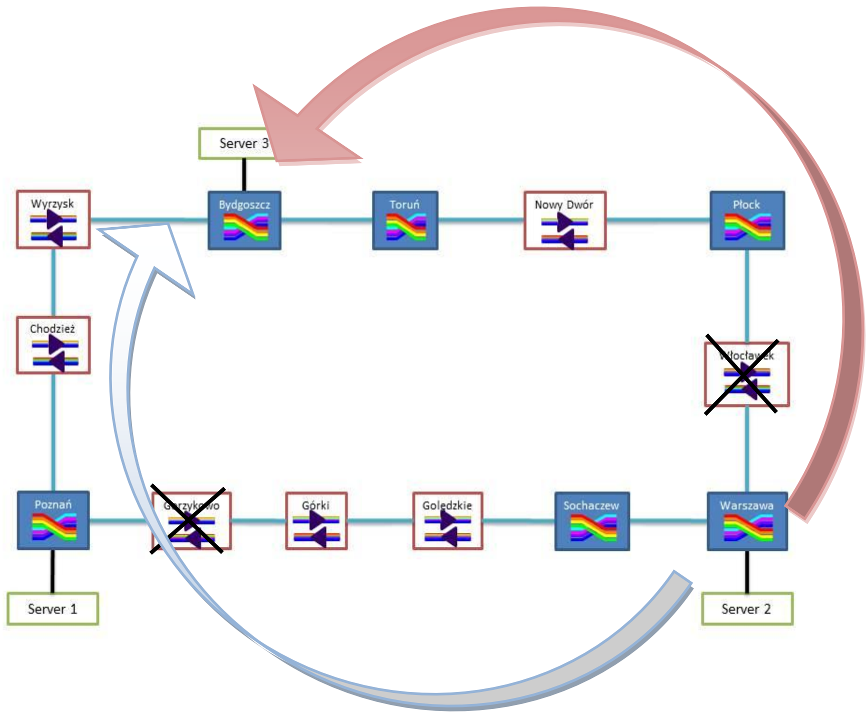


Figure 3.8: Switching scenario between Bydgoszcz and Warsaw nodes

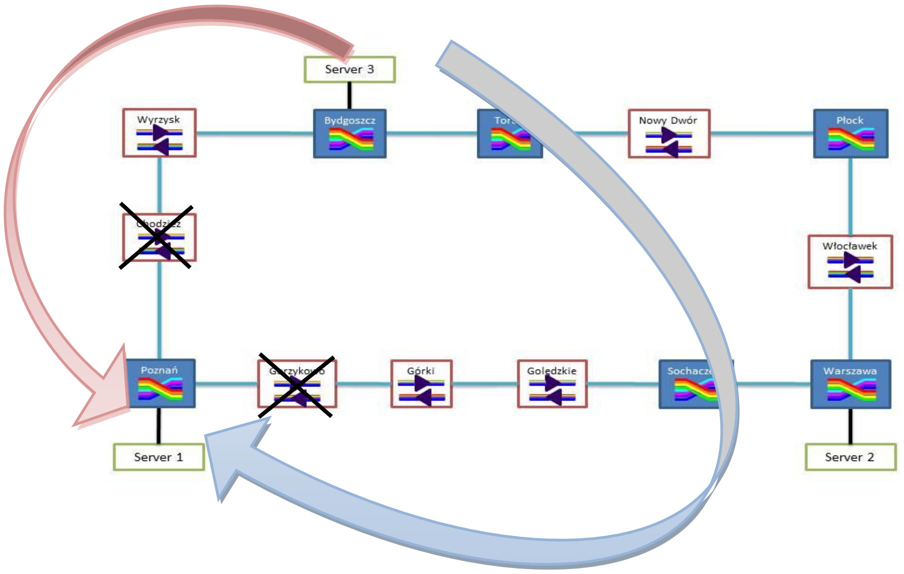


Figure 3.9: Switching scenario between Poznan and Bydgoszcz nodes

The details of the scenarios, and the results, are summarised in Table 3.1 below.

Service Routing	Path Length (km)	Number of ROADMs	Time of Service Restoration
Poznań-Bydgoszcz	239	2	2 min 17 sec
Warszawa-Sochaczew-Poznań	385	3	2 min 50 sec
Warszawa-Poznań-Bydgoszcz	624	4	3 min 9 sec
Warszawa-Toruń-Bydgoszcz	382	4	3 min 29 sec
Warszawa-Bydgoszcz-Poznań	620	5	3 min 50 sec
Poznań-Warszawa-Bydgoszcz	767	6	4 min 2 sec

Table 3.1: Restoration times for switching with respect to number of ROADMs and length of fibre path

Restoration times are in general not specifically quantifiable, although the times contributed by the various stages of restoration can be described. The table below shows the different stages and the times observed during the tests.

No.	Stage	Comment	Observed Time
1	Initial fault identification and localisation	30 seconds or more can be added to fault indications, in order to ensure proper de-bouncing and jitter removal from IP message delivery.	Stages 1 to 3 take between 1 min and 1 min 30 sec.
2	Determining an alternative path via computation	Normally happens quite rapidly, in the order of sub-second, for average-sized networks. Networks with large numbers of elements and/or links may experience longer computation times.	
3	Signalling the new path in the network	It is highly dependent on path length and element complexity, taking potentially tens of seconds per node to configure.	
4	Subsequent optical power equalisation in both directions	–	About 30 sec per ROADM. Thus the addition of ROADMs on the path causes an increase in restoration time of 30 seconds per ROADM. (ROADMs need to be sequence equalised.)
5	Removal of the old/failed path	No impact on transmissions.	Not measured during the tests.

Table 3.2: Restoration stages and observed times

The difference in fibre length was not observed to cause changes in the restoration time. The two cases with 4 ROADMs actually showed a shorter restoration time for the longest path, which can only be attributed to differences in stage 2, 3 or 4 for this specific case.

3.4 Conclusions

The tests show that service restoration within an ADVA transmission system is possible, with restoration taking approximately a few minutes. To summarise, the restoration time is heavily dependent on the number of components that need tuning and equalising. Adding ROADMs on the path causes an increase in restoration time of 30 seconds per ROADM, but not all ROADMs need to be equalised (see Section 3.2.3 above). In addition, the ADVA system requires from 1 to 1.5 minutes for:

- Service fault detection (e.g. Loss of Signal (LOS)).
- New path recalculation.
- Transponder laser tuning (< 45 sec according to the specification).
- Tunable filter equalisation (e.g. 8CCM).

- Switching client ports to InService mode.

A small difference in restoration time can be caused by communication between network elements. Moreover, it should be noted that restoration time needs to be calculated for the protection path (the path that needs to be established).

Although the restoration time varies with the number of ROADMs involved and would be difficult to predict in a large meshed network, the GMPLS-controlled restoration mechanism is a robust and efficient way to restore traffic in the event of fibre cuts, where restoration time at best is several hours. For critical services, the restoration capabilities must be combined with protection functionality, which in general is performed in the electrical layer to obtain sub-second protection. In other, non-critical cases, the restored path may have an increased delay, which makes it unsuited for specific services.

In respect of path length, no differences in restoration time caused by the physical fibre length between service termination points were observed. In addition, during the tests no major differences in switching time caused by different fault types (laser off, fibre cut) were observed, nor was there a difference in switching time between one and multiple services.

During the tests it was observed that the service does not automatically switch back to the primary path after the primary path has been restored. This means that the service is still on the backup path. The next ADVA software release is due to have a new feature that will allow switching of services to be manually forced.

In order to prevent flapping of services, ADVA devices are preconfigured in such a way that restoration from backup to primary path can take place only after 2 hours. A user of the system is not able to change this parameter.

4 Alien Wavelength

4.1 Introduction

The ongoing adoption of hybrid networking sparked the demand for cross-border fibre (CBF) Dense Wavelength-Division Multiplexed (DWDM) links between NRENs. In this context, the use of alien (or foreign) wavelengths via DWDM systems from different vendors is an appealing concept. An alien wavelength is a DWDM wavelength that is established between a transmitter and a receiver and then transported over the DWDM system of another vendor. In the case of a multi-domain alien wavelength, the alien wavelength is transported over multiple DWDM systems from different vendors, where no optical-to-electrical-to-optical (OEO) regeneration is used at the boundary between the two DWDM systems. This approach reduces the cost per wavelength by approximately 50% compared to a 40 Gbit/s connection with regeneration. Furthermore, this approach offers a “greener” solution since the required power consumption of the alien wavelength is about 50% less than a comparable solution using regeneration. In terms of operation, it greatly simplifies the design of the intermediate Point of Presence (PoP) where the two DWDM systems interconnect, resulting in CAPEX and OPEX savings.

The use of alien wavelengths has four main attractions:

1. Direct connection of customer equipment to third-party DWDM equipment and elimination of expensive transponders at the transition between two DWDM systems.
2. Reduced power dissipation due to elimination of regeneration.
3. Faster time to service.
4. Extended network lifetime owing to support of different modulation formats.

However, there are a variety of challenges that complicate the application of alien wavelengths within multi-domain DWDM networks. The main challenges are:

- System performance validation.
- Operation, Administration, Maintenance and Provisioning (OAM&P).

Alien wavelength implementations, both experimental and fully operational instances, have been documented on multiple occasions during the last couple of years both by commercial operators and by the NREN community (including RENATER, as described in Chapter 2 on page 7). The majority of these have been implemented within a single-domain, single-vendor environment, with the result that the complex task of predicting the performance and feasibility of the alien wavelength can be performed by a vendor-provided optical simulation tool. As mentioned above, stitching an alien wavelength within a multi-domain, multi-vendor environment poses numerous challenges (e.g. mixed dispersion maps, different noise figures, variation in fibre types and alternating power control mechanisms). The general acceptance that coherent modulation schemes are the near-future de facto standard for DWDM transmission has diminished the very challenging task of matching the dispersion maps. Combined with the growing use of CBF, operational alien wavelength deployments between NRENs are imminent. While the dispersion issues are solved by coherent modulation, the NREN community still lacks optical simulation tools that can account for the non-linear effects occurring in the DWDM systems that limit the alien wavelength's performance.

The following sections describe the work carried out to establish an alien wavelength between Amsterdam (SURFnet) and Copenhagen (DTU and NORDUnet), from the very first step of verifying optical line of sight to the complex task of validation and predicting the performance utilising an advanced optical model for simulation of alien wavelength within multi-domain DWDM scenarios.

4.2 First Setup

In order to explore the use of 40Gbit/s alien wavelengths within multi-domain NREN networks, SURFnet and NORDUnet first conducted a joint alien wavelength experiment on the CBF connection between Amsterdam and Copenhagen. The Polarisation Multiplexed-Quadrature Phase Shift Keying (PM-QPSK) modulation scheme was used for the 40 Gbit/s alien wavelength. In this experiment, the single 40 Gbit/s bi-directional wavelength traversed a Nortel Common Photonic Layer (CPL) DWDM system between Amsterdam and Hamburg and an Alcatel-Lucent DWDM system between Hamburg and Copenhagen without regeneration.

Figure 4.1 below shows the system configuration of the 40 Gbit/s alien wavelength experiment. The transmission fibre was TrueWave Reduced Slope (TWRS) fibre and the total transmission distance was equal to 1056 km. The DWDM system between Amsterdam and Hamburg did not use dispersion compensators. In the DWDM system between Amsterdam and Hamburg, the 40 Gbit/s wavelength was spaced at 100 GHz from a 40 Gbit/s wavelength and at 900 GHz from five 10 Gbit/s channels with 50 GHz spacing, all carrying live traffic. In the DWDM system between Hamburg and Copenhagen, the alien 40 Gbit/s wavelength signal was spaced 350 GHz from five 10 Gbit/s channels spaced at 100 GHz (the other 40 Gbit/s data was routed through a geographically separate Alcatel-Lucent transmission system). The large guard band of 350 GHz between the 40 Gbit/s alien wavelength and the other live traffic was believed to be necessary to ensure minimal interaction between the alien wavelength and other traffic (i.e. 40 Gbit/s PM-QPSK and 10 Gbit/s On-Off Keying (OOK) channels).

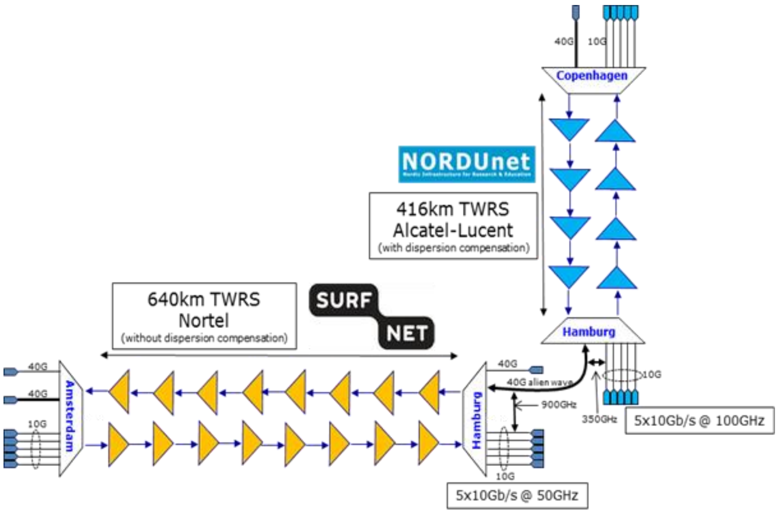


Figure 4.1: First 40 Gbit/s alien wavelength transmission system setup – with guard bands

4.2.1 SC2009

The initial test results, which were presented at the SC2009 conference, proved the feasibility of the setup. Using a large guard band of 350 GHz to live traffic, the alien wavelength was injected into the Alcatel-Lucent system with estimated power levels calculated by the simulation tool provided by Ciena. While this approach was sufficient to demonstrate "optical line of site", large variations were observed between the monitored and calculated values, highlighting the difference in the power-equalising philosophies used by the Alcatel-Lucent and Ciena systems. The built-in pre-Forward Error Correction (FEC) counters in the Ciena transponders was the only means to monitor the setup, as the built-in Optical Spectrum Analyser (OSA) in the ALU equipment was not fully operational in 2009.

A 1056 km error-free transmission was demonstrated for 23 hours (i.e. Bit Error Rate (BER) <10-15).

4.3 Second Setup

After the first experiment, described in Section 4.2, more traffic was deployed on this CBF system. In order to utilise the available system capacity efficiently, simulations and experiments without large guard bands were necessary. These were intended to help develop engineering rules for use of alien wavelengths in systems while efficiently using the available bandwidth.

This section investigates the effects of the adjacent 10 Gbit/s channels on the performance of the 40 Gbit/s alien wavelength, both theoretically, by numerical simulations of the pre-FEC BER, and experimentally, by measuring the pre-FEC BER rates of the 40 Gbit/s alien wavelength for different power levels of the adjacent 10 Gbit/s channels.

Figure 4.2 shows the system configuration of the CBF transmission system used for the 40 Gbit/s alien wavelength experiment without guard bands. The transmission fibre and DWDM system were the same as in the first experiment described in Section 4.2, i.e. the transmission fibre was TWRS fibre and the total transmission distance was equal to 1056 km. The DWDM system between Amsterdam and Hamburg was equipped with four 40 Gbit/s channels, at the wavelengths of 1546.52 nm, 1546.92 nm, 1547.32 nm and 1548.11 nm.

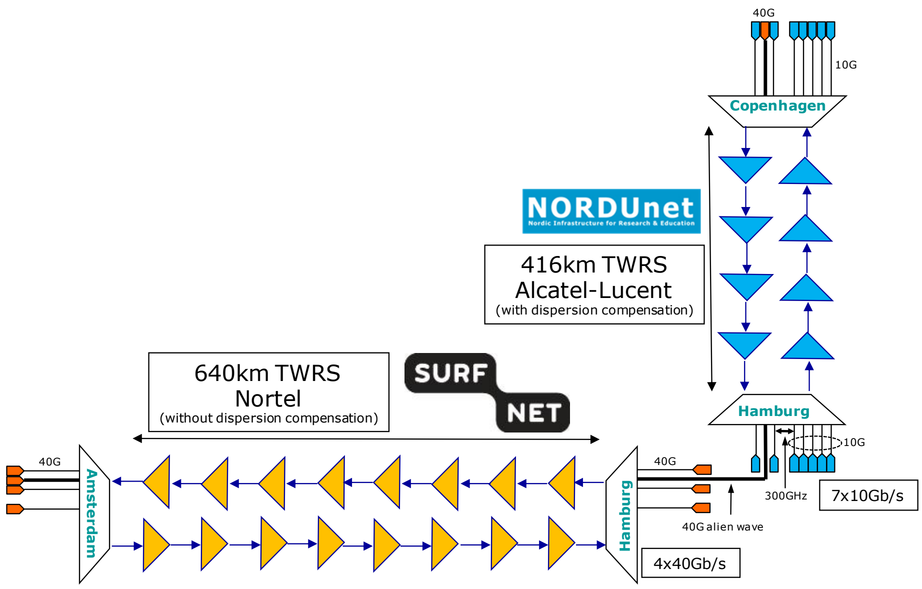


Figure 4.2: Second 40Gb/s alien wavelength transmission system setup – without guard bands

The four 40 Gbit/s channels used PM-QPSK transmitters and coherent receivers capable of electronically compensating more than 40,000 ps/nm of chromatic dispersion. For this reason, this section of the link was not equipped with optical in-line dispersion compensators. In Hamburg, the 40 Gbit/s wavelength of 1546.92 nm was all-optically connected to the DWDM system between Hamburg and Copenhagen. Two 10 Gbit/s OOK test wavelengths (one on each side) were injected in Hamburg and the spacing varied from 50 GHz to 150 GHz in order to evaluate the guard band size versus system performance. The traffic in the other three live 40 Gbit/s wavelengths was routed through a geographically separate Alcatel-Lucent transmission system towards Copenhagen, utilising traditional regeneration.

The following sections discuss the simulations followed by the field tests.

4.3.1 Simulations

This section covers the following aspects of the simulations:

- The model.
- Simulation results:
    - Limiting factors.

- Effect of 10G neighbours' power on 40G BER performance.

4.3.1.1 *The Model*

VPIphotonics' simulation tool VPItransmissionMaker (VPI) was used in this project. VPI was chosen because it supports end-to-end photonic design automation and fully configurable optical equipment modules. Using VPI provides the option to fully verify link designs at a sampled-signal level to identify system shortcomings, investigate possible improvements, or test special scenarios.

VPI is widely used within both scientific research and applied R&D contexts to evaluate commercial subsystem designs and optimise systems technologies. VPI handles various coding schema, modulation formats, monitoring tools, dispersion compensation techniques, regeneration and amplification for access, core and long-haul applications.

In the present case, VPI was used to investigate limiting effects in the Amsterdam–Hamburg–Copenhagen test link. Of particular interest was the effect of mixing channels with different modulation formats and bit rates. Previous experience and theory predicted that non-linear factors such as self-phase-modulation (SPM), cross-phase-modulation (XPM) and possibly polarisation mode dispersion (PMD) can have unexpected effects on alien wavelengths in long-haul systems. VPI offers the option to disable and separate various non-linear effects to allow further investigation and pinpoint the causes of limitations.

The following sections consider the schematics on which the VPI model design is based; the Monte Carlo method for calculating symbol error rate and the importance of efficient time usage; and the digital signal processing settings.

Schematics

The model design in VPI is based on schematics that are built from modules. Each module has a number of parameters that can be adjusted as needed. Most physical parameters are represented in the models, thus for an amplifier module, for example, it is possible to specify parameters such as noise, max gain, gain tilt, gain shape, max output power, amplifier type and so forth. Figure 4.3 below shows an example of an amplifier parameter set in VPI, which in this case is based on a simple transmission link with Non-Return-to-Zero (NRZ) transmitter, fibres, amplifiers and receiver. The parameter editor visible in the right-hand panel shows some of the parameters that can be specified for the Erbium Doped Fibre Amplifier (EDFA). In this way a full system can be constructed, consisting of transmitters, multiplexers, filters, amplifiers, fibres and transceivers; even advanced digital signal processing (DSP) is possible. DSP becomes necessary when considering coherent signals as in the present case, where 40 Gbit/s polarisation multiplexing (PolMux) QPSK is used.

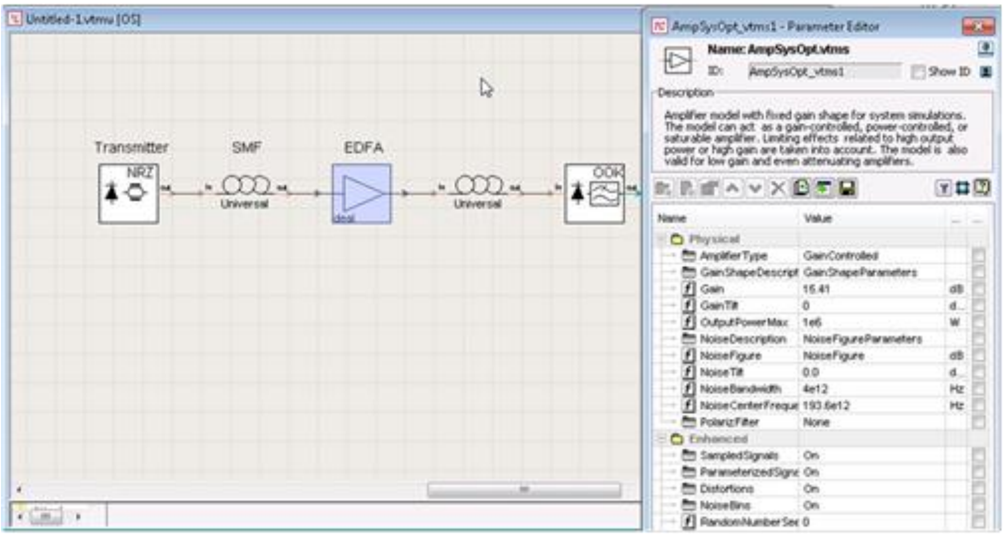


Figure 4.3: Example of a VPI schematic.

Based on these principles it is therefore theoretically possible to model an existing physical system in VPI, adding all modules and adjusting the parameters accordingly. In practice, however, it is difficult or even impossible to identify every parameter for the fibres, amplifiers, etc. within a system. This can be due to non-disclosed features in equipment, or unknown fibre properties. (Non-linearity parameters are often only guaranteed but not actually specified and disclosed for fibre spans.) Furthermore, it might not always be advantageous to model each and every aspect of a system. This is partly because it will require significant time and effort to gather this information, but also because much of the information will not have any practical effect on the results.

For the Amsterdam–Hamburg–Copenhagen link, as much information about the physical system parameters was gathered as possible, i.e. parameters such as transmitter frequencies, fibre span lengths, fibre dispersion, PMD, amplifier noise figure, Optical Signal-to-Noise Ratio (OSNR) at reception, optical filter bandwidth, etc. These were inserted into the first schematic, which can be seen in Figure 4.4 below.

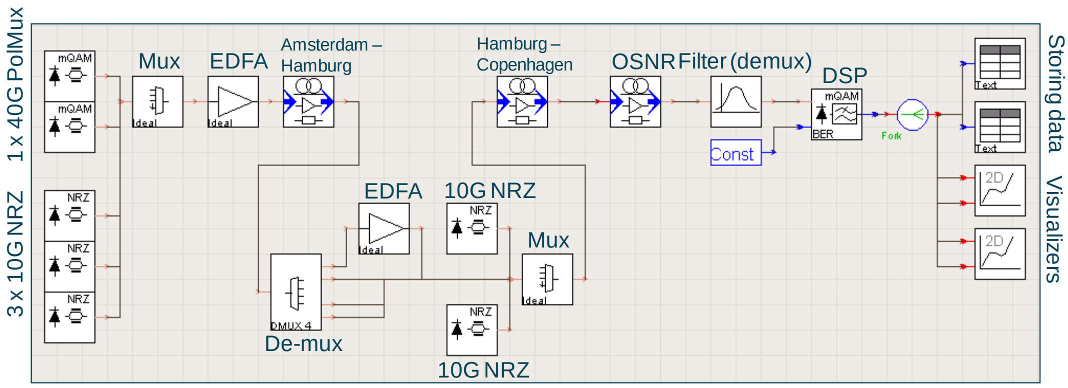


Figure 4.4: Schematic of initial setup

The schematic represents a 40 Gbit/s Pol-Mux transmitted with 10 Gbit/s NRZ neighbours to Hamburg and onwards to Copenhagen. This initial setup was later developed to include more details and channels. The Hamburg–Amsterdam modules were sub-modules, illustrated in Figure 4.5 below.

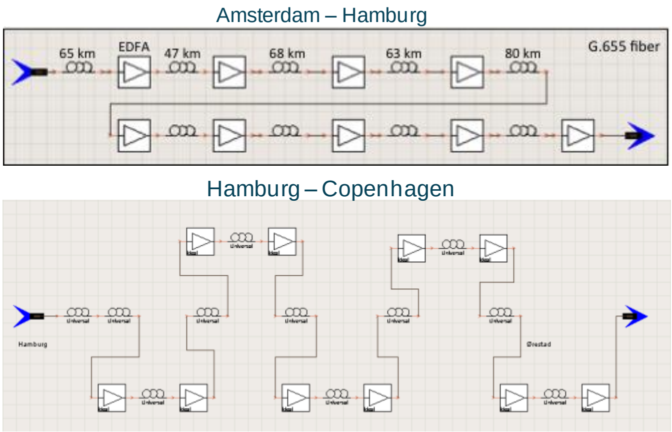


Figure 4.5: Sub-modules used in main schematic

Each sub-module consists of fibre, dispersion compensating fibre (if applicable) and amplifiers. These sub-modules represent the actual links between the nodes Amsterdam, Hamburg and Copenhagen.

Using this schematic it was possible to transmit the signals and achieve a simulated performance similar to actual field tests. With further analysis and data gathering on physical parameters, a more accurate and final schematic was created. This is shown in Figure 4.6 below.

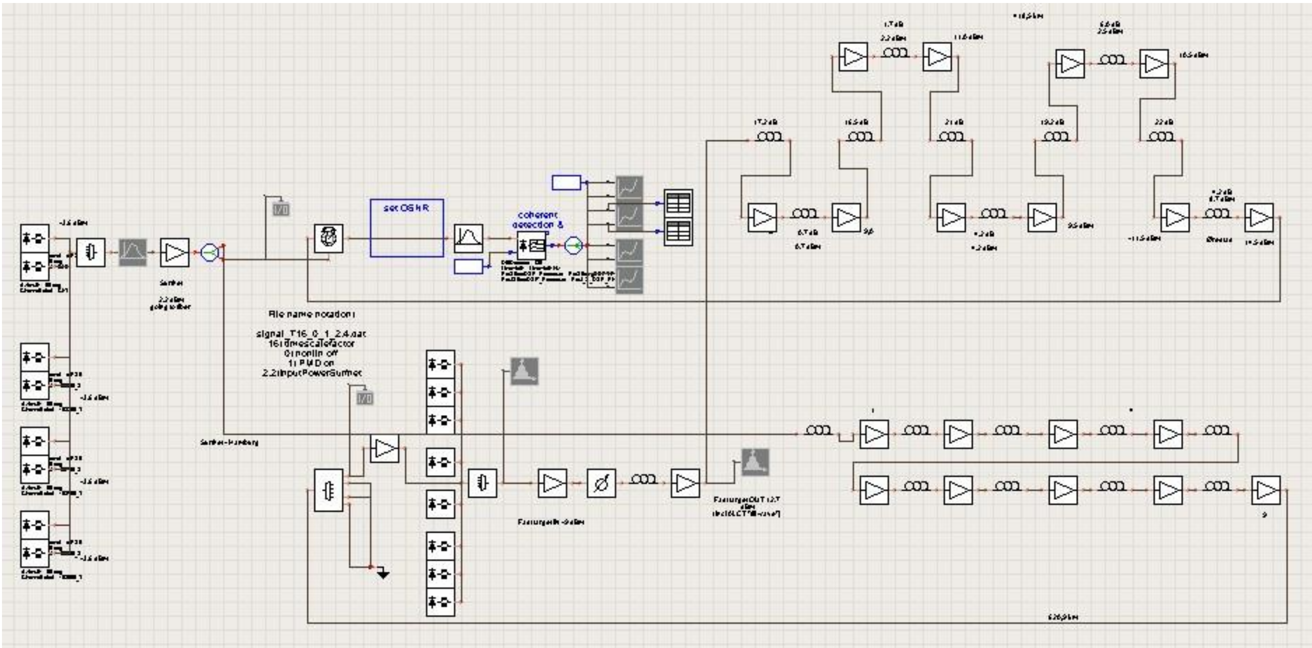


Figure 4.6: Full schematic of VPI model representing all vital modules in the actual Amsterdam–Hamburg–Copenhagen link

Monte Carlo Method and Efficient Time Usage

Collecting data points when modelling is often a time-critical factor and that was the case in these simulations. Modelling components with non-linearities (e.g. transmission and dispersion fibres) at high optical powers is one of the most time-consuming operations in optical modelling. Furthermore, in these simulations it proved impossible to use symbol error rate (SER) calculations based on the Gaussian assumption. The Gaussian SER is calculated on the assumption that the signal's probability density function (PDF) is Gaussian, with mean and variance equal to the mean and variance of the signal samples. In the present case, however, the constellation diagrams clearly demonstrated that the PDF was not Gaussian, consequently this somewhat faster method for SER estimation could not be used. Figure 4.7 below shows an example of a constellation diagram from a simulation that illustrates how the PDF does not follow a Gaussian distribution satisfactorily.

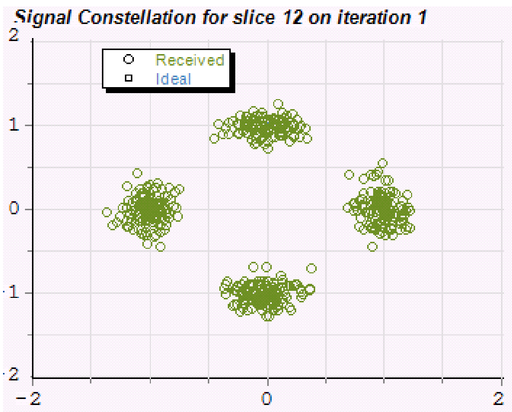


Figure 4.7: A constellation diagram showing a PDF that does not have a Gaussian distribution

Instead it was necessary to implement the more accurate Monte Carlo method, where the SER is estimated by direct error counting. This has the advantage that it is very accurate and does not require any special PDF assumptions; on the other hand it is a very time-consuming simulation. For example, assuming that 100 errors are required to assure a good statistical basis, 100,000 bits must be simulated to measure a SER of 10e-3 (100,000 bits * 0.0001 errors/bits = 100 errors). This in turn imposes a requirement on the time window of the simulation (specified using the TimeWindow parameter in VPI): a TimeWindow value of 3 ms, corresponding to the time window of 100,000 bits, yields a simulation that can take as long as 15 or 20 hours to complete in VPI.

Therefore it is vital to minimse any unnecessary effects by, for example, identifying beforehand the potential limiting effects within the system. For example, it may transpire that PMD is not a limiting or contributing factor, in which case simulation time can be reduced by removing the effects of PMD from the schematic. Efficiency can also be increased by splitting up the schematic into several schematics and then saving their respective transmission signal In/Out (I/O) modules (visible in Figure 4.4) for subsequent re-use.

DSP Settings

Parameter settings in the digital signal processing unit can have a significant influence on the results. The main parameters are listed and described in Table 4.1 below:

Parameter	Description
k-value	k is the number of symbols used in the phase averaging process in the DSP. More symbols give better phase estimation and fewer errors. Computational complexity increases linearly with k. k ~ 5 is referenced to be “enough to obtain most of the sensitivity enhancement” and is also a computationally reasonable value in practical DSPs.
NTaps	Related to chromatic dispersion (CD) compensation. As a rule of thumb, 200 km needs 9 taps, 2000 km needs 19 taps, 4000 km needs 39 taps. One cannot have too many taps but in practice it does not make sense to use more than needed.
Span length	The span length is a mandatory parameter in the DSP, required for the electrical dispersion compensation to function properly. It need not be 100% accurate but within 10–20 km is best, seen in relation to the 1040 km transmission span.

Table 4.1: Key DSP parameters

A note about SER vs. BER: In an additive white Gaussian noise channel with grey-coded QPSK, BER=SER/2 (i.e. one symbol error results in at most 1 bit error). As error monitors often give the error rate in counted errors (i.e. BER), this provides a simple way to convert between the two.

Full Schematic Parameters

The full parameter set currently consists of 11118 lines and is provided in [Parameters].

4.3.1.2 *Simulation Results*

Limiting Factors

After creating the schematics and making sure that everything was working correctly, the first task was to identify the limiting factors in the system. The factors investigated were mainly PMD, noise, non-linearities and degradations from spectral crosstalk between closely spaced channels.

It quickly became evident that parameters such as the noise figure (NF) and the general noise level (OSNR) were not the main limiting factors. Figure 4.8 below shows the result of two simulations where PMD was turned ON and OFF. Figure 4.8A shows the case of no PMD, while in Figure 4.8B the PMD in the transmission fibre was set to 0.1 ps/√km. This value was estimated, as actual PMD data was not available for the transmission fibres in question. Despite the PMD, which shows a relatively high value considering the age of the fibres in question, the constellation diagram displays only little signal degradation.

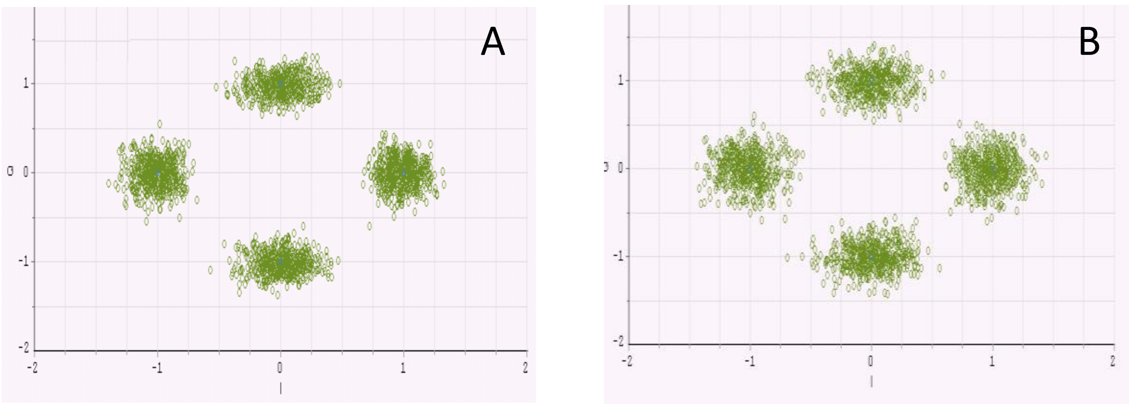


Figure 4.8: Constellation diagrams showing the difference between no PMD (A) and a PMD of 0.1 ps/√km (B)

In a similar manner simulations were carried out to establish whether the noise generated in the amplifiers constituted a limiting factor in the transmission link. The parameter noise figure (NF) characterises the amount of noise an amplifier adds to a signal under certain conditions. In the case of the Amsterdam–Hamburg–Copenhagen link, several types of amplifiers from different vendors were used. For this reason, and because the NF parameters were not disclosed by the manufacturers, it was decided to settle on a common noise figure of 5, which is a realistic parameter for modern amplifiers.

Figure 4.9 below shows two constellation diagrams from two simulation runs: case A with NF = 0 (no noise) and case B with NF = 5 in all amplifiers. When comparing the two it is clear that the noise from the amplifiers is not a limiting factor in this transmission link. This would be expected, as system links are often designed with a safe margin in terms of amplifiers and noise.

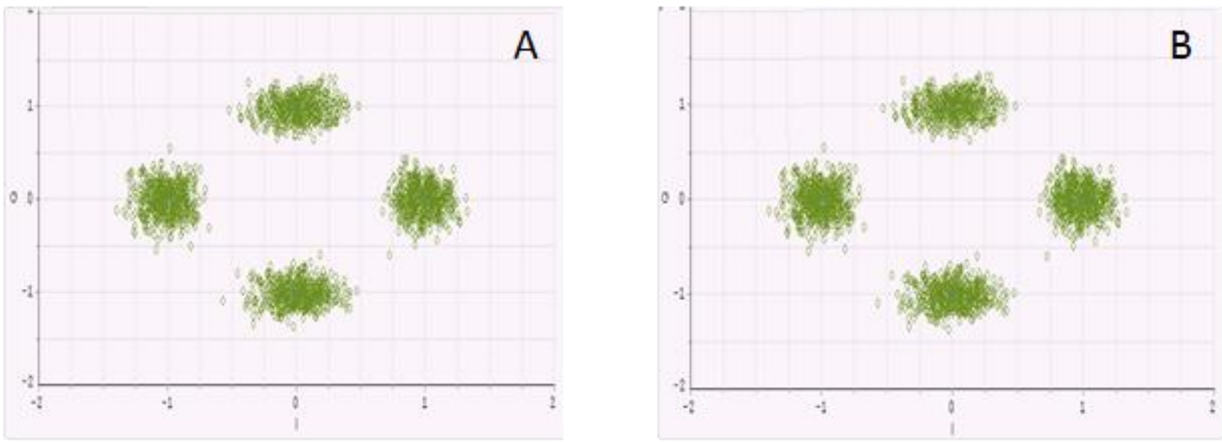


Figure 4.9: Constellation diagrams showing the difference between no NF (A) and an NF of 5 in all amplifiers (B)

While PMD and noise did not seem to constitute limiting factors in the link, further investigations using the VPI simulation tool revealed that non-linearities are a significant limiting factor in the transmission link. An example of such an investigation is shown below in Figure 4.10. The non-linearity parameter n2 has been artificially increased to see the effect.

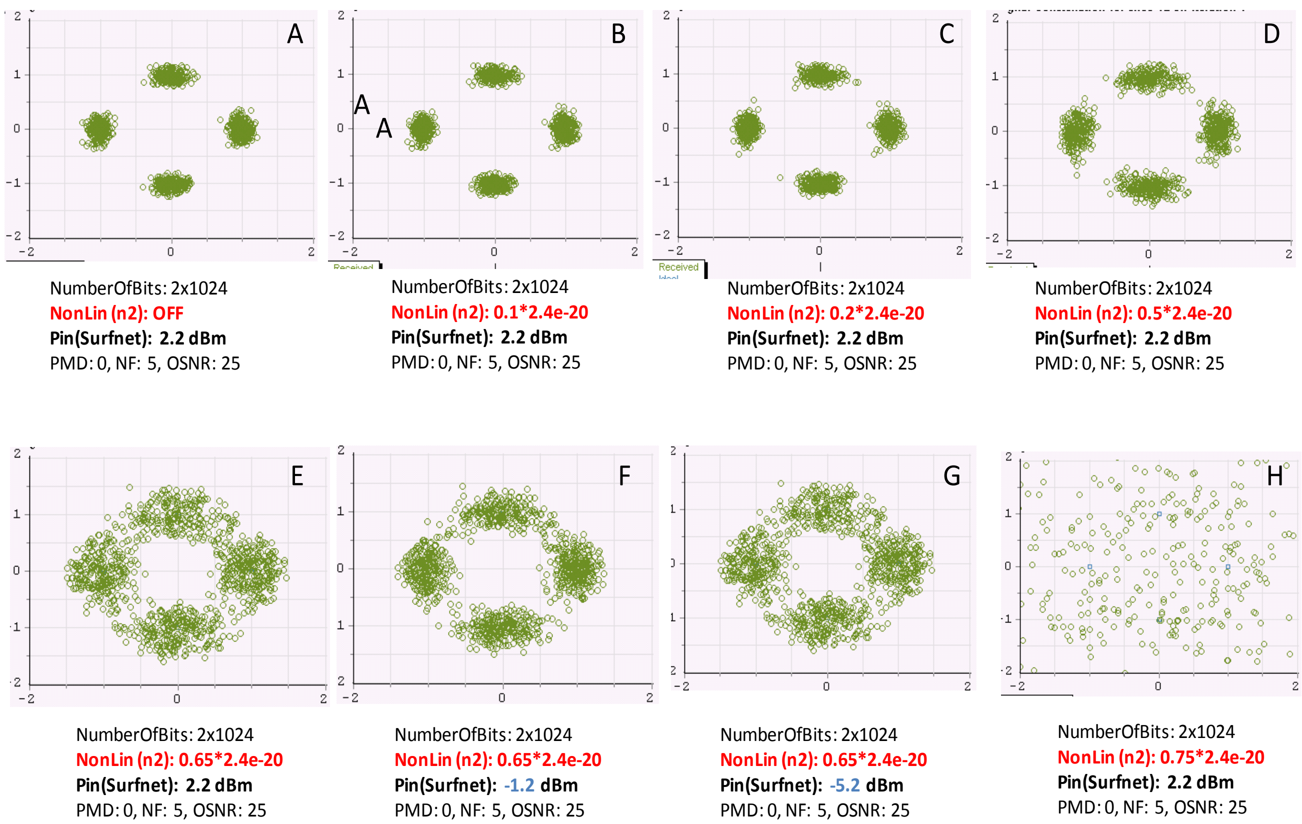


Figure 4.10: Constellation diagrams from simulations with varying fibre non-linearity parameters

Figure 4.10 illustrates the difficulties of even getting the signal through using the power levels measured in the field trials. In the first four constellation diagrams (A–D) it can be seen how increasing the non-linearity influence from 0% to 10% to 20% to 50% slowly deteriorates the signal. Finally, at 65% (E), the signal is virtually destroyed, and at 100% (H) the signal is completely unrecognisable.

The solution to getting the signal through at 100% non-linearity was to make small power adjustments in the amplifiers in the Hamburg–Copenhagen span. The power levels were measured using 20dB tap-offs and local photo diodes. Both devices can have a margin of error associated with them; assuming just 1–2 dB inaccuracy in a few of the measurement points can yield a very different situation.

Rather than varying the non-linearity parameter one can instead vary the optical power, which will have the same effect on the level of non-linearities in the system. In the constellation diagrams E, F and G in Figure 4.10 the non-linearity parameter influence was kept constant at 65% and instead the optical input power in Hamburg was varied. The power was only varied in a single point, in this case Hamburg, and it seems that in this case it does not have a significant influence. This kind of launch power variation was performed in several points across the network in an attempt to identify points within the network that might be responsible for the signal degradation. A single amplifier set at an unnecessarily high power level can result in a totally destroyed signal. Therefore, in links limited by non-linearities, it is important to keep optical power levels to a minimum but obviously at a level that is sufficiently high to avoid noise.

Effect on 40G BER Performance of 10G Neighbours' Power

A principal goal of these investigations was to explore the influence of the 10 Gbit/s NRZ neighbouring channels on the 40 Gbit/s PolMux QPSK alien channel. Factors such as channel spacing and the channel power of both the 10G and 40G channels influence the signal quality of the 40G channel. As a first step, the investigations focused on the signal quality of the 40G channel.

Figure 4.11 below shows an example of a simulation where the power of the neighbouring 10G channels was varied while maintaining the level of the 40G channel power. The power levels shown in this figure are relative power levels. The insert on the right-hand side indicates that it is the central 40G channel that is being investigated for various optical input power levels.

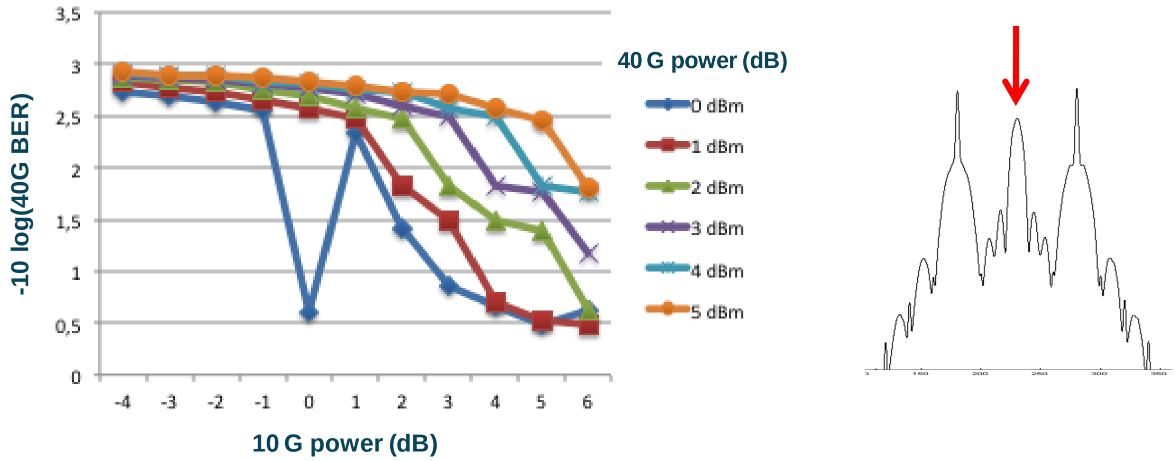


Figure 4.11: Effect on 40 Gbit/s PolMux QPSK BER performance of 10 Gbit/s NRZ neighbouring channels' power

Overall the results show a drop in 40G BER when the 10G neighbouring channel power is increased. This is generally a sign of cross-phase modulation (XPM), which is possible with the 100 GHz channel spacing used in this simulation run. It can also be observed that the 40G pre-FEC BER increases with increased 40G power if a certain 10G power point is kept constant. For example, if the 10G power is fixed at 5 dB, the 40G BER increases from 0.5 up to 2.5. In this case the 40G BER increases as the 40G channel becomes stronger and therefore the XPM influence from the 10G channels is relatively less influential. The increasing BER with increasing 40G power also shows that the alien wavelength is not suffering from self-phase modulation (SPM); potentially, therefore, increasing the 40G alien wavelength power would assure its quality. One could argue, though, that this would have a drastic influence on the 10G neighbours, which would eventually suffer from XPM caused by the 40G channel. The 40G channel, however, is a phase-modulated signal and therefore does not cause XPM as an intensity-modulated signal would. These limits and influences remain to be investigated.

The 40G channel's performance without 10G neighbours was also simulated, to learn more about regular limitations that are not related to closely spaced 10G channels.

Figure 4.12 shows a simulation run from the case where the 10G neighbours are off, as indicated in the right-hand insert. Whereas Figure 4.11 above did not reveal any SPM limitations for the 40G channel, the situation has now changed. The BER seems to reach an optimum at 3 dB power, after which it drops. This decline must be attributed to SPM as there are no neighbouring channels to cause problems. The BER drop at lower 40G launch powers is caused by the increased noise additions in the amplifiers when a lower power 40G signal is amplified. This behaviour, where the signal is partly noise limited and partly SPM limited, is a classic transmission system case.

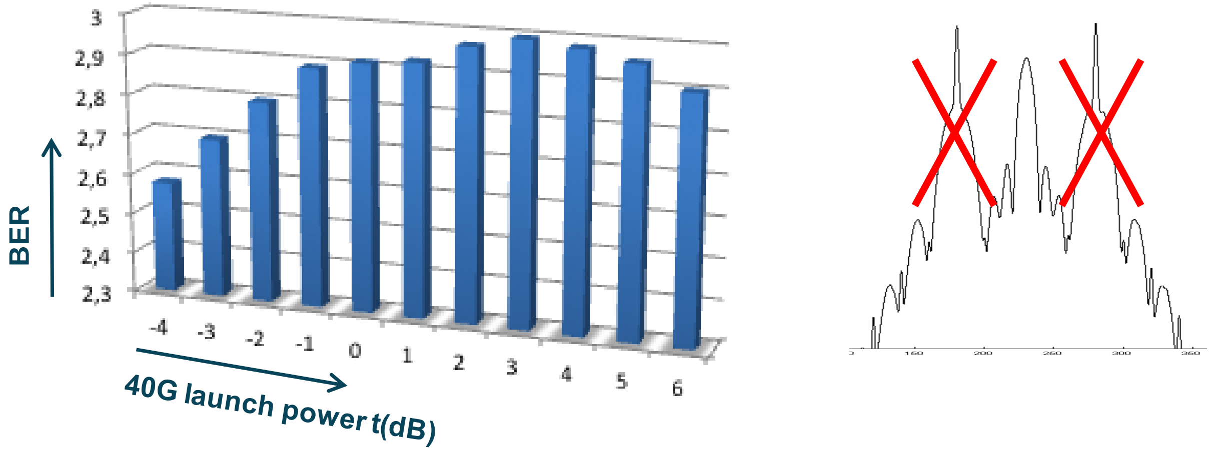


Figure 4.12: 40 Gbit/s PolMux QPSK BER performance without neighboring channels

Figure 4.13 below shows a simulation where the 40G power was varied and plotted against 40G pre-FEC BER. This was performed for three cases of 10G neighbour power: 0 dBm, 3 dBm and 6 dBm relative to the 40G power. The two 10G neighbours were spaced 100 GHz on either side of the 40G alien wavelength.

The same effects as were observed before are also evident in Figure 4.13. With increasing 10G power, the XPM level increases and affects the BER of the 40G signal. Also, there seems to be a strong drop in 40G signal quality, i.e. -log(BER) drops when the 40G signal power reaches around 6–7 dBm. This is attributed to SPM in the 40G alien wavelength signal. The drop in signal quality at lower 40G powers is more likely to be due to an increasing XPM influence from the 10G channels than to be a noise issue. The argument for arriving at this explanation is that the 40G signal quality has already dropped at 3 dBm with 10G power at 6 dBm compared to the case of 10G power at 0 dBm where the 40G signal quality remains high down to 1 dBm. If noise limitation were the cause, the drop in 40G signal quality would have happened in parallel in all three cases.

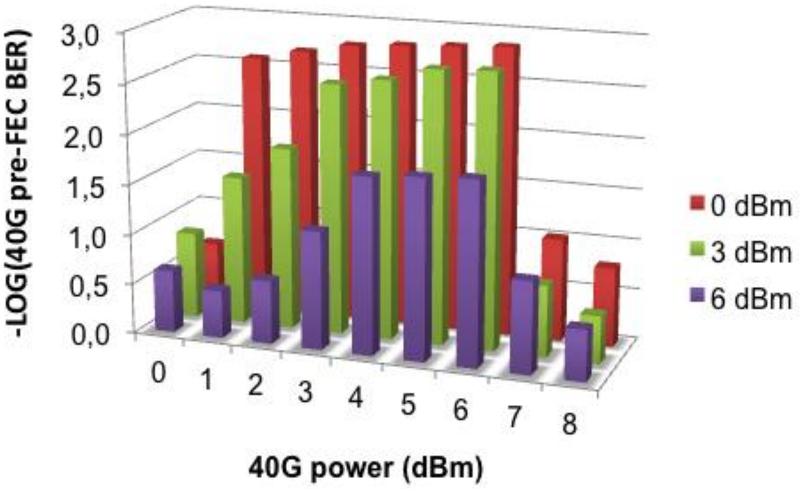


Figure 4.13: 40 Gbit/s PolMux QPSK pre-FEC BER performance with varying 40G power and 10G power levels of 0 dBm, 3 dBm and 6 dBm relative to 40G power

4.3.2 Field Tests

This section presents results from field investigations similar to the VPI simulations described above. It covers:

- Setup.
- Method used.
- Results.

4.3.2.1 *Setup*

This section presents the setup of the experimental tests on the alien wavelength running between Amsterdam and Copenhagen. More than 200 measurement points were recorded in order to have sufficient data to validate the simulation results and verify/test previous assumptions about strong interworking between PM-QPSK and NRZ-OOK modulation formats. Of particular interest was the influence of the guard band size, which is one of the key limiting factors in the potential application of alien wavelengths (not only as a way of simplifying the handover between two domains, but also as a way of introducing new modulation schemes into legacy networks).

In order to determine the impact of the guard band on the performance of the alien wavelength, the pre-FEC BER of the alien 40 Gbit/s PM-QPSK wavelength that was operated end-to-end across the 1050 km system between Amsterdam and Copenhagen was measured. In the SURFnet system between Amsterdam and Hamburg, the 40 Gbit/s PM-QPSK wavelength co-propagated with two live-traffic 40 Gbit/s PM-QPSK channels at +50 GHz and -50 GHz spacing. In the NORDUnet system between Hamburg and Copenhagen, the 40 Gbit/s PM-QPSK wavelength co-propagated with two 10 Gbit/s OOK signals. The pre-FEC BER of the alien 40 Gbit/s wavelength was measured for different guard bands of 50 GHz, 100 GHz and 150 GHz between the 40 Gbit/s alien wavelength and the two 10 Gbit/s OOK channels. The pre-FEC BER measurements of the 40 Gbit/s PM-QPSK channel were performed in the Amsterdam to Copenhagen direction.

4.3.2.2 *Method Used*

All experimental testing was performed on live systems utilising the built-in monitoring and adjustment capabilities of the Ciena and Alcatel-Lucent DWDM equipment. While this approach is less precise compared to a laboratory setup and dedicated advanced test equipment, it resembles more closely the optical network environment in which most NRENs operate. Few NRENs have access to laboratories where experiments similar to these can be executed, and if alien wavelengths are to have any significant value, it must be possible to implement and operate them without access to specialised test equipment.

The performance of the alien wavelength was measured by retrieving the pre-FEC counters of the Ciena transponders. The range of these counters is effectively 0 – ±10-4. Above ±10-4 the incoming signal cannot be recognised and the FEC is not able to clean up the signal. With regard to the adjustment and calibration of the optical spectrum and power levels in general, the Ciena systems from Amsterdam to Hamburg followed the Ciena engineering guidelines and no special changes were applied to the alien wavelength.

The task of controlling and adjusting the optical spectrum was performed in the Alcatel-Lucent system. The alien wavelength entered the ALU system through a passive coupler, which in turn was connected to a Wavelength Selective Switch (WSS). It was through the features of the WSS that admission control and power adjustments were exercised. The WSS component is able to operate in two dimensions: admission, where the beam of light is granted or not granted admission to the optical spectrum, and attenuation, where “misadjustment” of the focal point towards the output port creates the required attenuation. The precision of the attenuation was estimated to be at least ±0.5 dB, and the minimum controlled/detected power inside the WSS component was -23.5 dBm. To limit the effect of any misalignment in the mechanics of the Micro Electro-Mechanical Systems (MEMS), calibration of the power levels was always performed from high to low power levels.

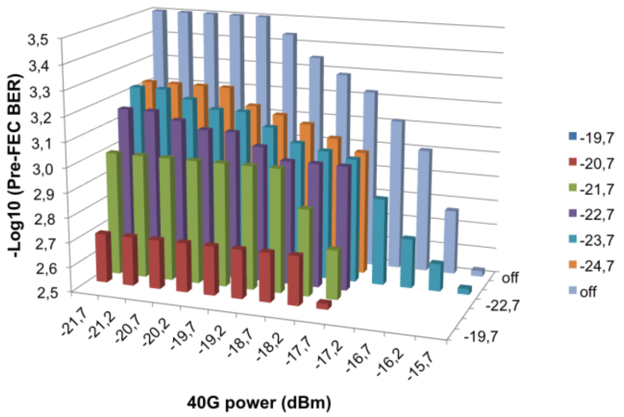
The adjacent 10 Gbit/s test channels were added to the spectrum in the same way as the alien wavelength. As the output wavelengths of the ALU transponders are variable through the whole C band, the variation of the spacing between the alien and the test wavelengths could easily be obtained by simply adjusting the output wavelength.

On the drop side of the ALU system, both alien and test wavelengths were passed through a colourless DWDM complex, consisting of post-amplifier, passive splitter and wavelength selective filter. The colourless capabilities made it possible to monitor the test wavelengths remotely even though the wavelength (and thereby the guard band) was changed. At all times throughout the experiment the performance of the 10 Gbit/s test wavelengths was monitored through observation of Bit Errors Corrected (BEC) counters showing the number of bits corrected by the FEC scheme in the ALU transponders. Apart from changing the wavelength on the wavelength selective filter to accommodate changes in guard band, no special configuration was applied to the drop side of the system. Both alien and test wavelengths were dropped according to standard ALU procedures, the test wavelengths to their matching ALU transponders, and the alien wavelength to the Ciena transponder.

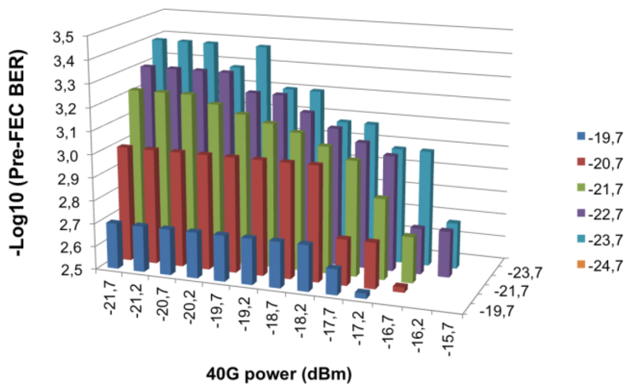
4.3.2.3 *Results*

This section presents the highlights of the results obtained from the experimental tests on the alien wavelength running between Amsterdam and Copenhagen.

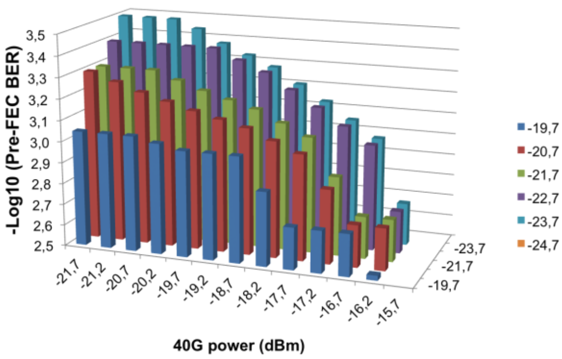
Figure 4.14 (a)–(c) below show the measured pre-FEC BER of the 40 Gbit/s channel as a function of the power per channel of the 10 Gbit/s channels, and for the case without 10 Gbit/s channels, for nine different values of the 40G channel power in steps of 0.5 dB, and for three different guard bands of 50 GHz (a), 100 GHz (b) and 150 GHz (c). The measurements show that for a given 10G power level of -24.7 dBm, the pre-FEC BER remains nearly constant with changing 40G power level in a 4dB range, from -21.7 dBm to -17.7 dBm, i.e. 7 dB stronger than the 10G channels. This suggests a small susceptibility of the 40G channel to SPM.



(a)



(b)



(c)

Figure 4.14: Performance of alien wavelength with 50 GHz (a), 100 GHz (b) and 150 GHz (c) guard band and variation of both 40G and 10G power

Comparing these experimental results with the simulations described in Section 4.3.1 above, it is clear to see that increasing the 10 Gbit/s channel power has the same effect in all three cases. In Figure 4.14 (a) it can be seen that the BER keeps almost constant but then drops rapidly as the 10 Gbit/s signal power increases beyond -22 dBm. Again the conclusion is that this should be attributed to XPM.

To summarise these experimental and numerical trials, it has been seen how XPM plays a major role in this type of transmission system, where a 40 Gbit/s PM-QPSK alien wavelength is inserted into a 50 GHz slot in an operational 10 Gbit/s NRZ system. To avoid severe signal degradation on the 40 Gbit/s PM-QPSK signal it is necessary to optimise the power of the surrounding channels, particularly if these are amplitude-modulated signals such as NRZ or RZ. On the other hand, PMD and SPM were both confirmed to play a smaller role in this system.

Figure 4.15 below shows the performance of the alien wavelength for variable alien wavelength power levels and variable guard bands. The horizontal axis is the alien power level, the vertical is –Log10 to the pre-FEC value, and the depth axis is the variable guard band size. The 10G power level is -20,7 dBm. The data shows that the BER reduces as the size of the guard band between the alien wavelength and the 10Gbit/s channels increases.

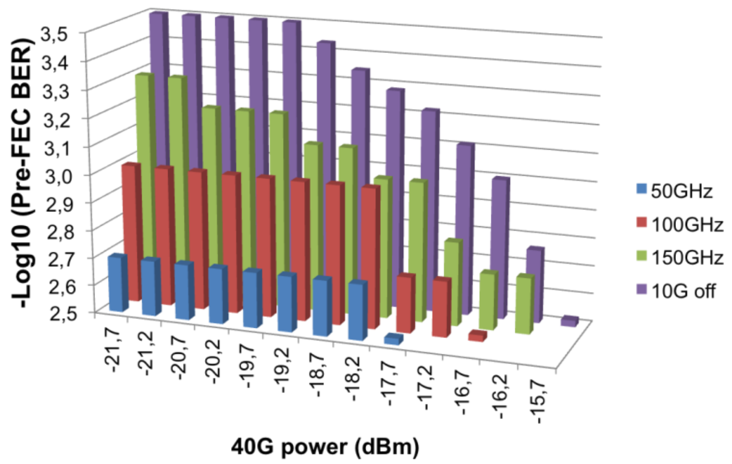


Figure 4.15: Performance of alien wavelength with variable guard bands and variation of 40G power

4.4 Operational Aspects

Transparent OAM&P of alien wavelengths within multi-domain networks is essential for successful deployment. However, a lack of standardisation prevents the exchanging of OAM&P information between DWDM systems from different vendors. This section provides an overview of:

- Standardisation efforts for alien wavelengths at the ITU-T and state of the art.
- Operational issues with introducing alien wavelengths.
- OAM&P solution.
- CAPEX and OPEX of alien wavelengths.

4.4.1 Standardisation Efforts and State of the Art

The only work within the standardisation sector of the international telecommunication union, ITU-T, related to alien wavelength support can be found in recommendations G.698.1 and G.698.2 [G.698.1, G.698.2], which specify operational ranges for interoperability of transponders for 2.5G/10G NRZ signals for different applications. Multi-vendor interoperability is guaranteed only if the same application codes (the same type of signals) are connected on a link. A mix of signals needs to be jointly “engineered”. The standards specify a generic definition of an alien wavelength: it is called a “single-channel interface” under a “black-link” approach. Under this specification, the native transponders at the entry of a standard DWDM system architecture are removed. The standard does not differentiate between User Network Interface (UNI) and External Network-to-Network Interface (E-NNI), i.e., the proposed architecture is generic.

Considering the state of the art, though, there are two views of the alien wavelength concept. The authors of [Gerstel, Melle, Ventorini, Slavicek] see it as a wavelength generated by an IP router (or an Ethernet switch) integrated with a DWDM transponder (i.e., at the UNI interface of a network between the digital and the optical layers), whereas the authors of [Nuijts, Smith, Chen] see it in a more generic way as a wavelength generated by a component that is from a different vendor than the considered DWDM system (i.e., it could be applied at the E-NNI interface as in [Nuijts]). According to this interpretation, an alien wavelength can potentially have an unsupported modulation format, framing and bit rate. Since direct control (at the digital level) by the transport network provider is impeded, providing guaranteed performance for the wavelength is difficult to achieve. Accordingly, different field trials have been documented, illustrating the technical feasibility of both alien wavelength concepts [Nuijts, Ventorini, Slavicek].

Furthermore, many vendors and providers have reported studies focused on CAPEX/OPEX savings due to electronic-bypass and alien wavelength support. Some support the CAPEX-/OPEX-saving hypothesis [Lord, Melle2] while others conclude that such savings are marginal and are not worth the increased complexity (in terms of lack of manageability and problematic provisioning and troubleshooting [Melle]).

4.4.2 Operational Issues with Introducing Alien Wavelengths

Regardless of the differences in these concepts, several main challenges related to operating alien wavelengths have been outlined among interested vendors and operators [Gerstel, Smith, Melle]. These can be classified in several groups as follows:

- Optical transmission performance: it is possible that the performance of the system will be reduced since larger operating margins need to be considered in order to mitigate any possible performance degradations incurred by introducing the alien wavelength alongside existing legacy services. However, since the different equipment vendors often use transponders produced in accordance with Multi-Source Agreements (MSAs) and supplied by a variety of transponder suppliers, the optical transmission performance of the alien wavelength can be the same as that of a native wavelength.

- Reduced diagnostic and troubleshooting ability, limited performance monitoring and fault isolation.

- Lack of direct control over the alien wavelength, which might lead to serious service disruptions for legacy services;

- FEC interoperability: in the event that an alien wavelength needs to be regenerated mid-way on an Ultra-Long Haul (ULH) system. If the third-party DWDM system does not support the client FEC, then it will be impossible to regenerate the signal.

- Service provisioning issues: lack of interoperability between the client and the server data/control plane systems makes automatic deployment impossible. Lack of knowledge about the exact performance of each system element in a scenario where an arbitrary mix of signals with diverse modulation formats, framings and bit rates is deployed makes engineering alien wavelengths a very complex task.

- Lack of robustness and increased complexity: may turn CAPEX/OPEX costs up, not down [Melle].

4.4.3 OAM&P Solution

There are several solutions for some of the OAM&P issues outlined above. Cisco [Gerstel] suggest the so-called virtual transponder solution, but it is a transponder that is between the client router and the network element, i.e., it cannot be applied at the E-NNI interface between two optical carriers. Their proposal is to have an XML session between the client and the WDM NE [Gerstel] for OAM&P support. Such a solution, though, is not universal since it requires the specific network elements present in the Cisco trial setup. A universal solution should be built on either a standardised control plane (such as GMPLS) or a standard information exchange model.

A third solution is to utilise an intelligent demarcation card, which is able to add an optical tag to the alien wavelength. With the addition of the tag it is then possible to trace, monitor and adjust the power levels of the alien wave throughout the network (Alcatel-Lucent 1830 PSS SVAG card).

With respect to monitoring, Cisco [Gerstel] suggest using a test access point of the ROADM, where a copy of the alien wavelength is sent to an integrated monitoring device; in this way, the integrity of the signal can be monitored without needing access to the client transponder. However, this solution can only offer very crude monitoring – power levels, presence of signal, and OSNR. With more sophisticated monitoring devices, chromatic dispersion and polarisation mode dispersion can also be monitored [Roberts]. In order to provide a truly guaranteed transmission performance, the network operator needs digital access to the alien wavelength. Under the general definition of an alien wavelength this is not possible. One option is to have direct communication between the management planes of the different vendors via a custom-made proxy or to design a standard for information exchange. Such options have not been addressed in the standardisation bodies since the management plane implementation is a strictly proprietary matter.

The OAM&P environment for the present experiment is best explained and discussed by describing the add and drop paths of the alien wavelength. The left- and right-hand sides of Figure 4.16 below show the add and drop paths respectively.

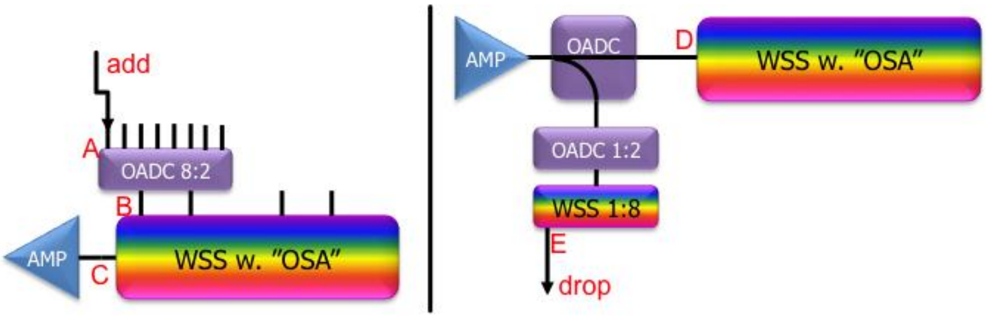


Figure 4.16: Add/drop paths of alien system, identifying key components and monitoring/adjustment points for wavelength control

The add/drop paths consist of the following components:

Ref.	Component	Description
A	OADC 8:2	Double 4:1 optical add/drop coupler with power monitoring
B, C, D	WSS w. OSA	Wavelength selective switch with ability to shut input ports (B) and measure and adjust power (C, D)
	AMP	Two-stage EDFA amplifier
	OADC	Passive optical add/drop coupler
E	WSS 1:8	Tunable filter with ability to measure and adjust power

Table 4.2: Add/drop path components

The environment shown in Figure 4.16 allows excellent control of the resulting optical spectrum at C as the WSS is able to adjust the alien and native wavelengths very precisely according to predefined values. These values are most often calculated by vendor-specific and proprietary simulation tools, which is why several problems can occur when used in combination with alien waves. In the present case, 40G PM-QPSK is not a modulation format utilised by Alcatel-Lucent, thus no predefined settings for the spectrum at C were present. The optimum spectrum at C was initially found by a “trial and error” method, and subsequently guided by the simulations.

While effective control of the spectrum is possible, point A still remains a source of concern with regard to controlling admission to the spectrum. In the native configuration, several element-control mechanisms prevent misconfiguration of native transponders, which is why wavelength doubling at OADC8:2 is not possible. These mechanisms are disabled when alien waves are installed, and only power monitoring is possible at point A, which is why injection of the wrong wavelength at A can jeopardise existing traffic. The only option for wavelength doubling is to shut the input port at point B, which could cause loss of service for the two additional wavelengths.

The drop path does not have any severe drawbacks. The received spectrum can be measured at D, and the channel is dropped at E through the tunable filter, where power can also be adjusted.

The environment described above was found to be sufficiently secure for the test, where the setup was strictly controlled, but the lack of admission control at point A presents an obstacle to secure, high-volume implementations. Furthermore, it could be argued that not only wavelength admission control but also modulation format control should be exercised at point A, in order fully to control possible disruptive non-linear effects.

Monitoring the alien wavelength was done with Element Manager (EM). As points A, C and E were monitored per wavelength, most fault scenarios on EM were similar to native waves. An important exception was LOS in point A, which can cover line LOS (Optical Transport Section / Optical Multiplex Section OTS/OMS)) as well as transponder failures in the remote system.

The figures below show the most common alarm scenarios in the “native system”. All the alarms relate to analogue measurements, as there is no access to the digital overhead of the carried signals, and in a more open definition of alien wavelengths there might not even be an overhead to monitor as the signal could be a photonic service. The alarms are from the Alcatel-Lucent Element Manager.

WARNING	R5NU-ORE-LM-01/r01sr1/board#14	Performance Degraded	channel 193800

Figure 4.17: Alarm view of power fluctuation of alien wavelength below/above predefined value (point C)

As explained in Section 4.3.2.1, the WSS component is able to operate in two dimensions: admission and attenuation. In attenuation mode, a target value can be set for the power of the alien wavelength, and the WSS will, through an integrated OSA control loop, maintain the specified value. If for any reason the specified value cannot be maintained, the WSS will raise an alarm. The alarm threshold value can be varied according to how strictly the operator wants to control the optical spectrum; furthermore, it is possible to change the severity of the alarm. Figure 4.17 above is an example of the scenario mentioned above, where one of the test wavelengths has dropped below the specified level; Figure 4.18 below shows the other test wave in the situation where the wavelength power is too low to be detected as valid signal power. It should be noted that, due to different design rules of DWDM systems, “valid signal power” is an ambiguous term, and careful cross-engineering between the DWDM systems used must be carried out to ensure that wrong alarms are not raised.

MAJOR	R5NU-ORE-LM-01/r02sr1/board#14	Input Power Loss	channel 193900

Figure 4.18: Alarm view of alien wavelength lost at transit node (point D)

An important place to have knowledge of the state of the alien wavelength is at the demarcation points between alien and native DWDM transmission systems. Figure 4.19 and Figure 4.20 below show the respective cases where the wavelength is lost on its way through the native system and when the wavelength fails to enter the native system at all.

MAJOR	R5NU-HMB2-LM-01/r02sr2/board#14	Output Power Loss	8th channel output

Figure 4.19: Alarm view of alien wavelength lost at the drop (point E)

MAJOR	R5NU-HMB2-LM-01/r02sr2/board#02	Input Power Loss	Input Port #5

Figure 4.20: Alarm view of alien wavelength LOS entering the “native system” (point A)

As can be seen from the examples above, all the scenarios contain alarms with unique identifiers that make it possible for the operator to create email trigger scripts that will alert the Network Operations Centres (NOCs) of the DWDM systems involved. That approach is possible on most Element Managers, and has been deployed in NORDUnet for internal alien wavelength tests.

Although the trigger option is usually extremely easy to implement, the major drawbacks are the lack of integration with the Operations Support Systems (OSSs) used in the native NOC, and that the alien NOC is not (and should not be) aware of the alarm structure of the native system. (The trigger option is based on element alarms and is not correlated to a single service, thus the alien NOC could receive many alarm emails from the native system without being able to action them. The alien NOC should know only whether the service is up or down.) Therefore a better approach is to forward the alarms of both the involved NOCs to a common surveillance solution, e.g. the End-to-End Monitoring System (E2EMon). The integration of E2EMon has not yet been concluded, but is expected to be delivered in Year 4 of the GN3 project.

4.4.4 CAPEX and OPEX of Alien Wavelengths

This section compares the capital expenditure (CAPEX) and operating expenditure (OPEX) of the alien wavelength and native wavelength approaches, and attempts to analyse and quantify (in terms of expenditure) the benefits of using alien wavelengths and their contribution to the reduction of expenditure.

In order to investigate the CAPEX and OPEX of DWDM systems with alien wavelengths, the cost was calculated of transponders, energy, installation and configuration for the implementation of a 200 Gbit/s link (with 20 x 10 Gbit/s at each client side) between Amsterdam and Copenhagen for the system shown in Figure 4.1 on page 68, for two cases: using alien wavelengths and using regeneration in Hamburg. The following assumptions were made:

- Installation (all including fibre setup):
  - 6 minutes per XFP installation.
  - 12 minutes per muxponder card.
  - 30 minutes per DWDM card.
- Configuration:
  - 15 minutes per wavelength.
- Travel:
  - 20 hours for the alien wavelength case.
  - 30 hours for the case with regeneration.

Note that this analysis does not include the cost for the DWDM layer. Since all amplification sites need to be visited for the rollout of a DWDM system, the installation costs (including travel and lodging) make up a much larger part of the total cost of the system – about 10%~20% of the DWDM equipment cost. However, since the cost of the DWDM system is the same in both cases (i.e. alien wavelength and regeneration), it is not included in the analysis.

Figure 4.21 below shows the normalised cost (on a logarithmic scale) for the alien wavelength case. The cost is broken down into the cost of the equipment/transceiver (TRV-cost), the energy per year (Power/yr), the installation (Labour) and the configuration (Config) for three different bit rates per wavelength of 10 Gbit/s, 40 Gbit/s and 100 Gbit/s. It is important to note that the second- and third-largest costs, the cost of energy per year and the cost of labour for installation, are two and nearly three orders of magnitude smaller than the cost of the transponders (respectively). Thus in the most beneficial scenario with a 100 Gbit/s alien wavelength, equipment represents more than 98% of cost for an alien wavelength connection, with power accounting for 0.8% and labour 0.6%. In the case with regeneration, costs nearly double. Cost per bit is lowest for the 100 Gbit/s solution.

In conclusion, the use of alien wavelengths is clearly more cost efficient if compared to the case of two cascaded native wavelengths. Furthermore CAPEX constitutes the vast majority of the investment.

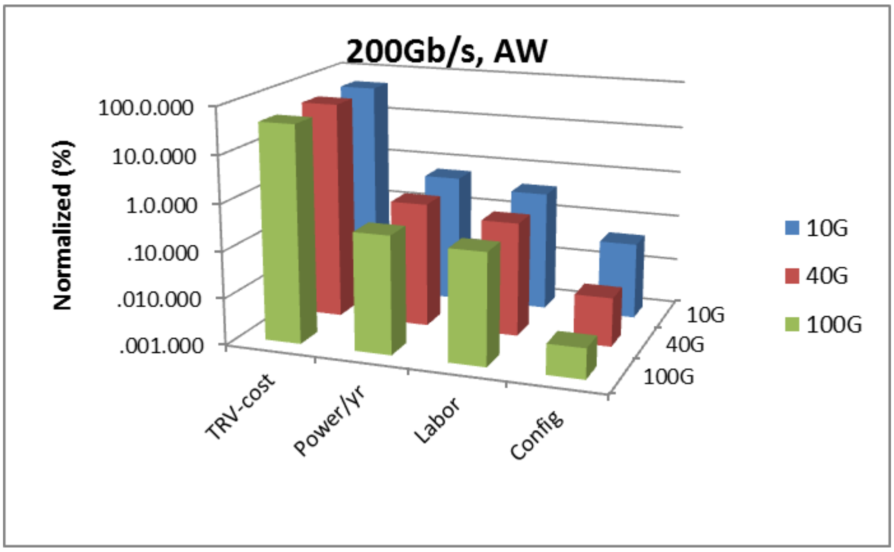


Figure 4.21: Normalised cost for a 200 Gbit/s alien wavelength connection between Amsterdam and Copenhagen

4.5 Conclusions

This set of tests investigated, by simulation and field experiment, the performance of a 40 Gbit/s PM-QPSK alien wavelength in a multi-domain CBF DWDM transmission system between Amsterdam and Copenhagen. The DWDM system between Amsterdam and Hamburg comprised a Ciena DWDM system on 620 km of TWRS fibre without any dispersion compensation. Two 40 Gbit/s PM-QPSK wavelengths with live traffic spaced at 50 GHz from the alien wavelength co-propagated with the alien wavelength. Between Hamburg and Copenhagen an Alcatel-Lucent DWDM system was used over 430 km of TWRS fibre with dispersion compensation. In this section, two 10 Gbit/s OOK wavelengths co-propagated with the alien wavelength with varying guard bandwidths.

The performance was investigated in terms of pre-FEC BER for different values of the guard band between the 10 Gbit/s OOK wavelengths and the alien wavelength. The main result is that a near-optimum guard band of 150 GHz was found (i.e. a wider guard band did not seem to improve the BER performance significantly). The test results also determined a range of power for the 40 Gbit/s alien wavelength with negligible susceptibility to SPM and acceptable BER performance (i.e. error-free after correction).

The simulation studies revealed that it is vital to use pre-studies to reduce computation time that can otherwise increase to days. In this case it was found that PMD and noise were not of major importance in the scenarios tested. It was found, however, that non-linearities were the main limiting factor in the Amsterdam–Hamburg–Copenhagen link. The simulations also showed that incorrectly setting a single amplifier with only 2 dB higher output power can effectively distort the signal beyond recovery. Work continues to optimise the VPI schematic and its level of detail to predict and optimise the live system link more accurately, primarily in terms of launch power, channel spacing and the importance of the modulation format of neighbouring channels.

Supervision was achieved by configuring the trigger solution as mentioned in Section 4.4.3, but the native NOC found it insufficient as the script reacted to element alarms and did not correlate these to the offered service. It was difficult to incorporate the received emails into the existing OSS and the alarms were sometimes “forgotten” in the mailbox. It is therefore important that future alien wavelength implementations focus on the OSS integration, to offer the same operational environment currently offered to other services.

The CAPEX and OPEX of transmission systems with native (i.e. regenerated) and alien wavelengths were compared, using the example of a 200 Gbit/s link (with 10 Gbit/s interfaces at the client side). The main conclusion was that equipment cost dominates the cost of the transmission system at 98% of the cost, with the second- and third-largest costs (energy and labour respectively) more than an order of magnitude less. These CAPEX and OPEX results, in combination with the performance results summarised in the previous paragraph, are important steps in the future of international networking across geographical, technical and administrative borders.

5 Power Consumption

5.1 Introduction

The evolution of the Internet has, over time, increased the bandwidth available to deliver broadband applications to network end users, e.g. Internet Protocol television (IPTV) or Voice over IP (VoIP). In addition, new real-time applications have emerged with improvements in Internet capacity [CESNETPR1April2010]. The power consumption of network devices has increased steadily with the growth in Internet traffic and is approximately doubling every year [Neilson]. Today, the Internet consumes about 0.4% of total electricity in broadband-enabled countries [Tucker] and up to 8% in the USA [Bathula]. Such rapid growth of electricity consumption by large-scale distributed systems is becoming an issue. A network dedicated to the Internet can be divided into access and edge network, core network routers and core transport network. The power consumption of each part is dependent on the access speed required by end users and is summarised in Table 5.1. The numbers represent ISP networks in around 2009.

End-user Access Rate	Access and Edge Network	Core Network Routers	Core Transport Network
1 Mbit/s	90%	9%	1%
100 Mbit/s	65%	30.5%	4.5%

Table 5.1: Internet power consumption [Tucker]

The majority of consumed power is in the access and edge parts of the network. The main impact of fibre optics is in the core network (routers and transport), where about 90% of power is consumed in routers, 7% in transponders, and 3% in the rest of the network equipment (e.g. Erbium Doped Fibre Amplifiers EDFAs) [Shen]. Energy saving for the core network can be improved by introducing the sleep mode for nodes (routers) and core transport links [Bathula, Yamanaka], changing the network architecture [Stavdas] and allowing the optical bypass that can lower the core node consumption by 25–45% [Tucker, Shen]. Another option is to change the network concept from optical circuit switching (OCS) to optical packet switching (OPS), which improves the overall network utilisation. However, OPS is not mature enough to compete with current technology, mainly due to the absence of optical memory and problems with optical buffering [Tucker, Aleksic]. Although the power consumption of core network transmission equipment is about 10% of total network consumption, the core network operation cost over five years can reach more than 11% of core network capital expenditure [Palkopoulou], when annual increase of electricity cost is considered. This fact gave rise to the need to create an indicator of consumption for the core transport network. This chapter introduces the consumption indicator for a core transport link from node A to node B based on basic link parameters. It also shows the computation of the indicator for real examples of core transport links and assesses the indicator's usefulness in comparing links.

5.2 Consumption Indicator Estimation

The consumption indicator (CI) is derived from the annualised consumption of the whole DWDM transmission link and takes into account the length of the core transport link. CI is based on good knowledge of three basic transmission parameters:

1. Consumption of transmission components (e.g. transceivers and amplifiers).
2. Length of core transport link.
3. Number of transmitted channels (lambdas).

The indicator can be easily estimated by completing Table 5.2.

Core Link Design ID	Line Length (km)	No. 10G Channels	No. of Spans	Transport Link Consumption (W)	Link CI (W/m/y)	Channel CI (W/m/y/ch)	Costs CI (E/km/y)

Table 5.2: Consumption indicator estimation

The first four columns of Table 5.2 describe basic information about the core transport link. The "Transport Link Consumption" column represents the total average consumption in Watts per hour of all the transmission equipment that makes up the core transport link (i.e. the transceivers and everything between them). The last three columns of Table 5.2 show power consumption indicators related to the length of the core transport link and per year, assuming 24 hours a day and 365 days a year. The annual link consumption indicators are related to the length of the link in the sixth column (Link CI) and also to one optical channel in the seventh column (Channel CI). Finally, the local electricity cost is needed to estimate the power consumption indicator in Euros per kilometre of the link and year of service (Costs CI). These calculations are reasonable for core transport links that have a similar transmission rate, otherwise the comparison would not be that essential. On the other hand, this is usually the case during core transport link procurement, which generally includes several transport solutions from different vendors to achieve the desired core transport link parameters. The consumption indicator gives an insight into the energy efficiency of transport solutions offered by different vendors, although a comparison of consumption indicators can be relevant only when the compared systems have similar services and features (electric power management, optical power management, lambda management, out-of-band management channels, etc.).

5.3 CI Estimation of Open DWDM System

The CI estimation approach described above was applied to the real multi-vendor OpenDWDM – 01 core transport link in the Czech Republic between Prague and Ústí nad Labem, which is 150 km long. The distance of 150 km is overcome in one span thanks to CzechLight amplifiers CLA PB01F and Fibre Bragg Gratings (FBG)-based chromatic dispersion compensators. The core transport link employs Cisco XENPAKs, passive multiplexers, demultiplexers and dispersion compensation units (DCUs). The link can be easily upgraded to 32 transmitted optical channels by installing additional transponders. The current setup of the core transport link is for three transmitted lambdas in C band and 10 Gbit/s transmission rate. The nominal consumption of the link components is shown in Table 5.3 below.

Node Equipment ID	Node Equipment Description	No.	Consumption of One Device (W)	Total Consumption (W)
Prague				
CLA-PB01F	CL Amplifier – Preamp/Booster	1	80	80
XENPAK-DWDM	10GBASE-DWDM XENPAK (100 GHz ITU grid)	3	9	27
15454E-CTP-MIC48V	ONS15454SDH Craft,Timing,-48V PwrMgmt IF Conn	1	0.38	0.38
15454E-AP-MIC48V	ONS15454SDH Alarm,-48V PwrMgmt IF Conn	1	0.13	0.13
15454E-FTA-48V	ONS 15454 SDH 48V Fan Tray with filter for ETSI Chassis	1	55	55
Ústí nad Labem				
CLA-PB01F	CL Amplifier – Preamp/Booster	1	80	80
XENPAK-DWDM	10GBASE-DWDM XENPAK (100 GHz ITU grid)	3	9	27
15454E-CTP-MIC48V	ONS15454SDH Craft,Timing,-48V PwrMgmt IF Conn	1	0.38	0.38
15454E-AP-MIC48V	ONS15454SDH Alarm,-48V PwrMgmt IF Conn	1	0.13	0.13
15454E-FTA-48V	ONS 15454 SDH 48V Fan Tray with filter for ETSI Chassis	1	55	55
			Total (W)	**325.02**

Table 5.3: Nominal consumption of link components – Open DWDM system

The total consumption is not dependent on the number of transmitted bits, because transceivers generate data patterns even while idle, but rather on the transmission rate, which increases the demand on the transceivers.

5.4 CI Estimation of a Ciena System

The same approach was applied to another vendor Ciena – 03 core transport link in RoEduNet between Bucharest and Brasov. The distance of 179 km is overcome in two spans. The intermediary node Ploiesti and the Bucharest PoP act as 4-direction ROADM nodes in the RoEduNet2 network. In these circumstances, more equipment (at the photonic layer) is installed in the PoPs than is necessary for this link, but these nodes serve many other links with the same equipment and provide the required services and functionalities to manage the links.

Node Equipment ID	Node Equipment Description	No.	Consumption of One Device (W)	Total Consumption (W)
Bucharest				
Common Photonic Layer (CPL) – 4-direction ROADM				
NTT838AA	50GHz 4 Port Optical Power Monitor	2	11	22
NTT830BA	CPL EDFA Module 2 (MLA)	4	40	160
NTT837DA	100GHz 5 Port Wavelength Selective Switch	4	12	48
NTT839BA	Uni OSC 1510nm	4	40	160
NTT862AA	44 Ch Mux/Demux (CMD44) C-Band 100GHz	4	0	0
NTT830AA	CPL EDFA Module 1 (SLA-Pre)	1	35	35
OME6500				
NTK503AD	19in. Optical Shelf Assembly (Converged)	1	0	0
NTK507LD	Fan Front Exhaust High Flow Cooling	3	20	60
NTK530AB	NGM WT 1x10GE LAN 1x11.1G DWDM	1	75	75
NTK555CA	SP-2	1	40	40
NTK505FB	MIC (Maintenance Interface Card)	1	1.2	1.2
NTK505CA	Power Card 60A breakered	2	2	4
Ploiesti (Intermediary Node)				
Common Photonic Layer (CPL) – 4-direction ROADM				
NTT838AA	50GHz 4 Port Optical Power Monitor	2	11	22

Node Equipment ID	Node Equipment Description	No.	Consumption of One Device (W)	Total Consumption (W)
NTT830BA	CPL EDFA Module 2 (MLA)	4	40	160
NTT837DA	100GHz 5 Port Wavelength Selective Switch	4	12	48
NTT839BA	Uni OSC 1510nm	4	40	160
NTT862AA	44 Ch Mux/Demux (CMD44) C-Band 100GHz	4	0	0
NTT830AA	CPL EDFA Module 1 (SLA-Pre)	1	35	35
Brasov				
Common Photonic Layer (CPL)				
NTT830FA	CPL EDFA Module 6 (MLA2)	2	40	80
NTT839BA	Uni OSC 1510nm	2	40	80
NTT810CF	SCMD4 Gr6 w/ingress VOAs C-band	2	7.5	15
OME6500				
NTK503AD	19in. Optical Shelf Assembly (Converged)	1	0	0
NTK507LD	Fan Front Exhaust High Flow Cooling	3	20	60
NTK530AB	NGM WT 1x10GE LAN 1x11.1G DWDM	1	75	75
NTK555AB	Processor SP with I2C support	1	25	25
NTK505FB	MIC (Maintenance Interface Card)	1	1.2	1.2
NTK505CA	Power Card 60A breakered	2	2	4
			Total (W)	**732.9**

Table 5.4: Nominal consumption of a Ciena link

The total consumption is not dependent on the number of other lambda circuits that are passing through Bucharest and Ploiesti PoPs.

5.5 CI Estimations of Existing DWDM NREN Links

Similar data to that shown above for the CESNET and RoEduNet networks was collected from other production DWDM links. The consumption indicator, the cost of the operation in EUR, can be estimated from the consumption by introducing the local electricity price, which is currently 179 EUR/MWh in the Czech Republic. This value has been used for all links for consistency, independent of the link country localisation. The CIs calculated for different DWDM links are summarised in Table 5.5. CI is non-linear with respect to the number of spans used on the link, but yet reflects the differences in the vendors' approaches. For example, if the number of channels increases, the Link CI slowly increases, and the Channel CI and Costs CI slowly decrease, but not in a directly proportional way. This trend can be explained by the presence of common equipment in the PoP for all channels, such as optic boosters, monitoring and management devices, etc. In the same way, Costs CI as defined above are relevant only for link connection, and not for link functionality since different vendors have different technological approaches and solutions, and different related features/services.

Core Link Design ID	Line Length (km)	No. 10G Channels	No. of Spans	Transport Link Consumption (W)	CI (W/m/y)	CI (W/m/y/ch)	CI (E/km/y)
OpenDWDM – 01	150	3	1	325	18.98	6.33	**3.40**
OpenDWDM – 02	224	1	1	561	21.94	21.94	**3,93**
Cisco – 01	178.3	3	2	997	48.97	16.32	**8.78**
Alcatel-Lucent – 01	160	3	2	724	39.66	13.22	**7.11**
Alcatel-Lucent – 02	150	3	1	604	35.25	11.75	**6.32**
Ciena – 01	86	1	1	555	56.56	56.56	**10.13**
Ciena – 02	75	1	1	552	64.46	64.46	**11.55**
Ciena – 03	179	1	2	733	35.87	35.87	**6.43**
Ciena – 04	236	1	2	671	24.90	24.90	**4.46**

Table 5.5: Consumption indicator examples

The impact of CI is twofold. First, it helps to compare the different approaches of various vendors – or even the different approaches of one vendor. For example, the core links Alcatel-Lucent – 02 and OpenDWDM – 01 are designed for the same distance in a "hut-skipping" design without inline amplification sites. OpenDWDM – 01 allows a saving of about 50% of operating expenditure according to the CI. The core links Alcatel-Lucent – 01 and Alcatel-Lucent – 02 reflect a difference in technology approach, where Alcatel-Lucent – 01 uses inline amplification sites and Alcatel-Lucent – 02 utilises Raman amplification. Second, CI can help to calculate average savings in operating expenditure related to power consumption for multiple offers during the procurement evaluation process. Although operational savings can be minor for a single transmission link, the amount can become considerable for large-scale European NRENs.

5.6 Conclusions

This chapter has shown that core transport links can be compared in terms of energy efficiency and has introduced the consumption indicator. The indicator is given in the local currency (Euro in these examples) per kilometre of link and year of service. The difference in power consumption of transport solutions from various vendors is best seen when all solutions have the same transmission rate and number of optical channels and are of similar length. This is usually the case during the transport solution procurement. Although the difference in cost consumption indicator of different solutions may be small, the cooling cost must also be taken into account. The overall saving in operational cost is significant for large-scale networks, especially when considered over a five-year lease period with steadily increasing electricity costs.

Aside from the cost considerations there is also the political agenda and wider concern for the constant increase of power consumption by society as a whole. Seen in that light the CI value can be used to benchmark and evaluate the greenest DWDM transport solutions.

The consumption indicator estimates shown are based on available data for links in European NRENs. It is worth noting that although collection of data has been made with best effort, the estimates do not reflect the latest technology and may not be completely precise. Therefore no conclusions or recommendations have been drawn from them. Nevertheless, the consumption indicator is seen as a valuable tool for evaluating energy consumption as part of the transmission link procurement process.

6 NGN Solution Based on ALU 1830 PSS Platform

6.1 Introduction

This chapter describes PSNC's investigation of a next-generation network (NGN) solution to the delivery of photonic services based on the Alcatel-Lucent 1830 Photonic Service Switch (PSS) platform (the only platform available). It provides an overview of the 1830 PSS series, discusses the different requirements for 40G and 100G solutions, and considers in detail the aspects of the 1830 PSS platform that make it an NGN architecture, particularly its colourless and directionless functionalities and dynamic reaction to network faults. It then describes the laboratory test environment and the following functional tests and results: measurement of channel spacing; chromatic dispersion resistance for coherent and incoherent transmission; and optical signal switching times.

A next-generation network is a packet-based network able to provide Telecommunication Services to users and able to make use of multiple broadband, QoS-enabled transport technologies and in which service-related functions are independent of the underlying transport-related technologies [NGN-Ddef].

The primary goal of NGN in the optical domain is to create an environment based exclusively on switching in the optical domain. The ideal solution would be the creation of a transparent optical network or even the guarantee of being able to do full optical switching at the second layer of the ISO/OSI model.

Optical NGN network features allow the following functionalities to be achieved:

- Resistance to certain network section faults – possibility of dynamic network reconfiguration without limitation of throughput for end users on primary paths, backup paths and the possibility of supporting multiple successive or parallel link failures in the network topology.
- Flexibility – possibility of dynamic or programmed network configuration or topology changes depending on current needs.
- Priorities assignment – possibility of channel priority assignment, capable of preempting channels with lower priority by channels with higher priority in the event of a network fault.
- Simplicity of alien wavelength implementation – possibility of resource (channel) assignment.

6.2 ALU 1830 PSS Overview

The family of Dense Wavelength Division Multiplexing (DWDM) equipment in the Alcatel-Lucent (ALU) 1830 Photonic Service Switch (PSS) series embraces five different sizes of devices:

- Edge devices (a set of specialised 1830 PSS-1 1RU boxes, and the 1830 PSS-4, a 2RU generic shelf), which typically adapt or mux low bit rate client services into 2.5G/10G uplinks.
- Metro to long-haul design for medium-density central offices (1830 PSS-16), which typically adapts or muxes client services to 10G uplink.
- Regional to long-haul design for high-density central offices (1830 PSS-32), which typically adapts or muxes client services to 10G/40G/100G uplinks.
- Converged Optical Transport Network (OTN) and Wavelength Division Multiplexing (WDM) product, which supports Optical Channel Data Unit k (ODUk) grooming from low bit rate clients adapted to 10G/40G/100G uplinks (1830 PSS-36).

The 1830 PSS is a multi-reach DWDM platform for metro, regional and national core and metro/access backhauling. In the present set of tests, the platform was run using a 50 GHz ITU grid in the C band (giving 88 channels in the DWDM system). The platform allows the creation of a meshed network topology using the multi-degree Reconfigurable Optical Add-Drop Multiplexers (ROADMs) (2–8 degree, based on Wavelength Selective Switch (WSS) architecture, to ensure node connectivity as needed) with directionless add/drop functionality. The 1830 PSS platform includes a wide range of interfaces for port aggregation on the local side with Universal Client Interface Cards (10 x any muxponder, 11G any rate transponder). Transponders and muxponders – on the line side – have colourless functionality (i.e. are full C-band tunable). The1830 PSS has deployed transponders operating with 2.5G, 10G, 40G and 100G technologies. In addition, the 1830 PSS platform supports protection and restoration mechanisms. A unique and extremely useful feature is the Wavelength Tracker, which provides optical channel monitoring, enabling the tracking of the selected service for the entire length of the optical path, whether for native 1830 wavelengths or for third-party system alien wavelengths. This mechanism is described further in Section 6.4.5 below.

6.3 40G & 100G Solution

The initial proposal was to implement the 40G transmission using “standard” coding and decoding, i.e. non coherent.

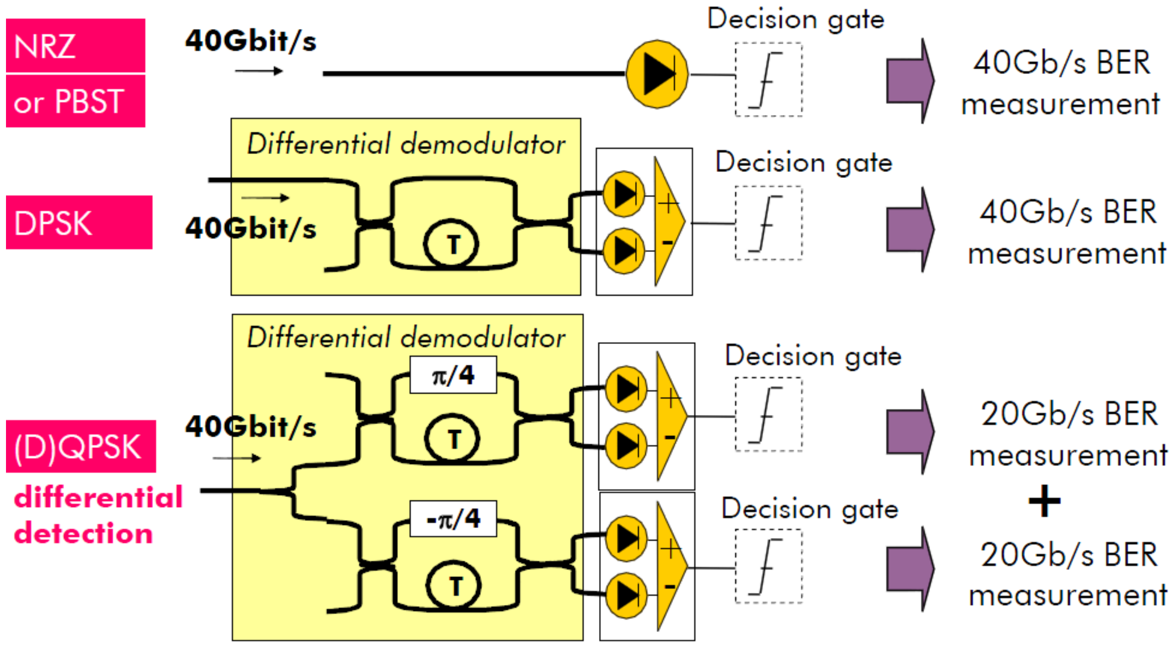


Figure 6.1: Today's possible (non-coherent) receiver schemes at 40 Gbit/s [ALU materials]

However, during the 100G technology research stage, it emerged that it is impossible to deploy incoherent signal coding with respect to fibre propagation effects (chromatic dispersion (CD), polarisation mode dispersion (PMD), single-channel non-linearities). It also emerged that a reduction of baud rate is required. The consequence of these issues was the need to use more complex modulation formats, with coherent transmission/detection, to significantly reduce the impact of line effects and to simplify the line design itself.

In brief, the coherent transmission used in the 1830 PSS at 100 Gbit/s is a combination of two parameters:

- Polarisation-Division Multiplexing (PDM) also known as Dual Polarisation (DP).
- Quadrature Phase-Shift Keying (QPSK) (4 phase states).

In addition, it uses only one optical frequency carrier and one pixel in the 50 GHz grid.

The combination of these features allows the baud rate to be decreased by a factor of four (from 100G to 25G baud – each symbol transports 4 bits). To date ALU's 1830 PSS is unique on the market in offering this powerful capability for 100 Gbit/s.

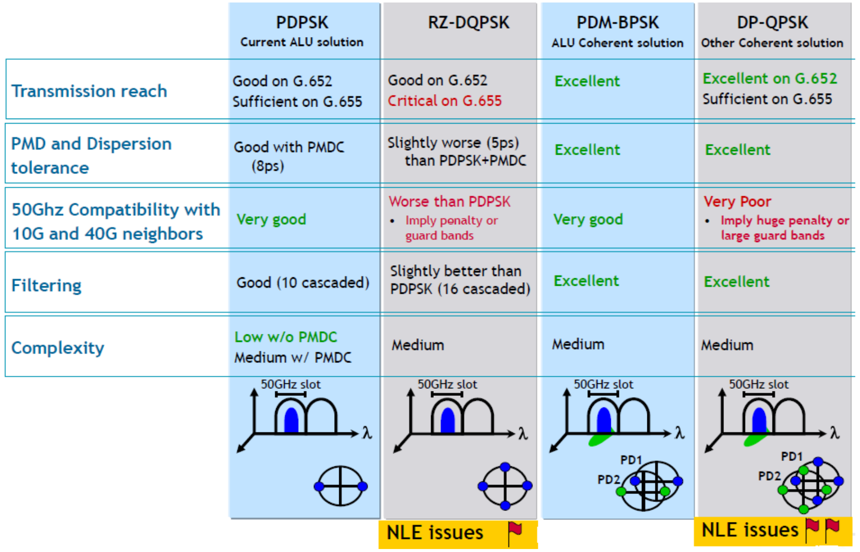
The principal advantage of coherent detection with digital post-processing is the compensation of linear impairments (PMD, CD). ALU's coherent transponders (40 Gbit/s, 100 Gbit/s) and muxponders (4 x 10 = 40 Gbit/s, 10 x 10 = 100 Gbit/s) have PMD tolerance extended up to 28 ps and CD tolerance up to 40000 ps/nm at 100 Gbit/s (60000 ps/nm at 40 Gbit/s), while preserving a 50 GHz spacing ITU grid whatever the bit rate carried on each spectrum frequency.

Figure 6.2: PDM-BPSK with coherent detection at 40G [ALU materials]

Figure 6.3: PDM-QPSK with coherent detection at 100G [ALU materials]

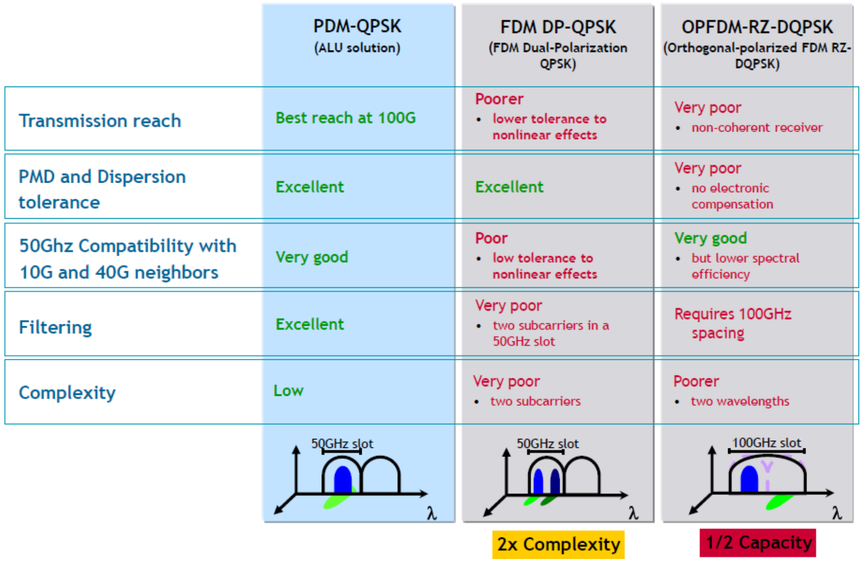
below shows a comparison of the different modulation methods offered by ALU for 40 Gbit/s transmission, including the non-coherent method, called “Current ALU solution” in the figure, and coherent PDM-BPSK, called “ALU Coherent solution” in the figure. ALU advocates this modulation format as a superior option (in their opinion) to DP-QPSK solutions for 40 Gbit/s systems.

Figure 6.3 below shows a comparison made by ALU of the different modulation methods offered by ALU for 100 Gbit/s transmission. The comparison indicates that the ideal format for 100 Gbit/s is PDM-QPSK, even though it was not ideal for 40 Gbit/s. As mentioned above, it optimises spectrum occupancy, and provides longer system and spectrum lifetime with up to 88 x 100 Gbit/s in a single fibre.



	PDPSK Current ALU solution	RZ-DQPSK	PDM-BPSK ALU Coherent solution	DP-QPSK Other Coherent solution
Transmission reach	Good on G.652 Sufficient on G.655	Good on G.652 Critical on G.655	Excellent	Excellent on G.652 Sufficient on G.655
PMD and Dispersion tolerance	Good with PMDC (8ps)	Slightly worse (5ps) than PDPSK+PMDC	Excellent	Excellent
50Ghz Compatibility with 10G and 40G neighbors	Very good	Worse than PDPSK • Imply penalty or guard bands	Very good	Very Poor • Imply huge penalty or large guard bands
Filtering	Good (10 cascaded)	Slightly better than PDPSK (16 cascaded)	Excellent	Excellent
Complexity	Low w/o PMDC Medium w/ PMDC	Medium	Medium	Medium
		NLE issues		NLE issues

Figure 6.2: PDM-BPSK with coherent detection at 40G [ALU materials]



	PDM-QPSK (ALU solution)	FDM DP-QPSK (FDM Dual-Polarization QPSK)	OPFDM-RZ-DQPSK (Orthogonal-polarized FDM RZ-DQPSK)
Transmission reach	Best reach at 100G	Poorer • lower tolerance to nonlinear effects	Very poor • non-coherent receiver
PMD and Dispersion tolerance	Excellent	Excellent	Very poor • no electronic compensation
50Ghz Compatibility with 10G and 40G neighbors	Very good	Poor • low tolerance to nonlinear effects	Very good • but lower spectral efficiency
Filtering	Excellent	Very poor • two subcarriers in a 50GHz slot	Requires 100GHz spacing
Complexity	Low	Very poor • two subcarriers	Poorer • two wavelengths
		2x Complexity	1/2 Capacity

Figure 6.3: PDM-QPSK with coherent detection at 100G [ALU materials]

6.4 1830 PSS Node Architecture

The 1830 PSS platform allows the implementation of all of the features needed to achieve a Next-Generation Network (NGN) architecture, particularly colourless and directionless functionalities and dynamic reaction to network faults (e.g. topology changes and failures).

The sections below present a selection of those solutions, including the cards needed to achieve a “flexible” network, namely:

- Universal service cards.
- ROADM.
- 1830 PSS optical protection options.
- Optical restoration – GMPLS.
- Wavelength Tracker.
- Additional features.

6.4.1 Universal Service Cards

The 1830 PSS allows many types of universal transponders to be applied, which offer support as follows:

- Single 10G (OTU-2) transponder supporting all types of 10G services – STM-64/OC-192, 10GE WAN, 10GE LAN, 10G FC, OTU-2, OTU-2e, CBR10G, etc. – and quadruple transponder board for cost-effective and compact 10G transport (including 8G FC support).
- As above for 40G (STM-256/OC-768, 40GE, OTU-3) and 100G (100GE, OTU-4).
- Tunable for single code, or unique host board to plug in any pluggable optics (SFP, XFP, including tunable XFP).
- Line- or client-pluggable optics.

ALU offers a wide range of transponders with flexible aggregation on client side (“muxponders”):

- n x any into OTU-2 for any low-rate service mix (FE, GE, STM-1/4/16, FC-1/2/4G, SDI, HD-SDI, etc.)
- 12 x GbE into OTU-2 for GbE client services.
- 4 x any into OTU-1 for metro access and aggregation of lower rate signals (down to E1).
- 4/10 x 10G into OTU-3/4 supporting all 10G service inputs for transport at 40 Gbit/s or 100 Gbit/s.
- ITU-T standards-based mappings (OTN).

In addition, it is possible to use a wide range of universal, tunable muxes and demuxes with single code over the full WDM spectrum in the 1830 PSS system.

6.4.2 ROADM

A very important feature of NGNs is an element that allows flexible and dynamic switching of any lambda (colour) in any direction. To achieve this functionality, ALU hardware allows, on appropriate connections, ROADM cards built upon WSS optical switch technology. The WSS ports are shared between the transponders and the multi-degree connections. An example ROADM architecture is shown in Figure 6.4 below.

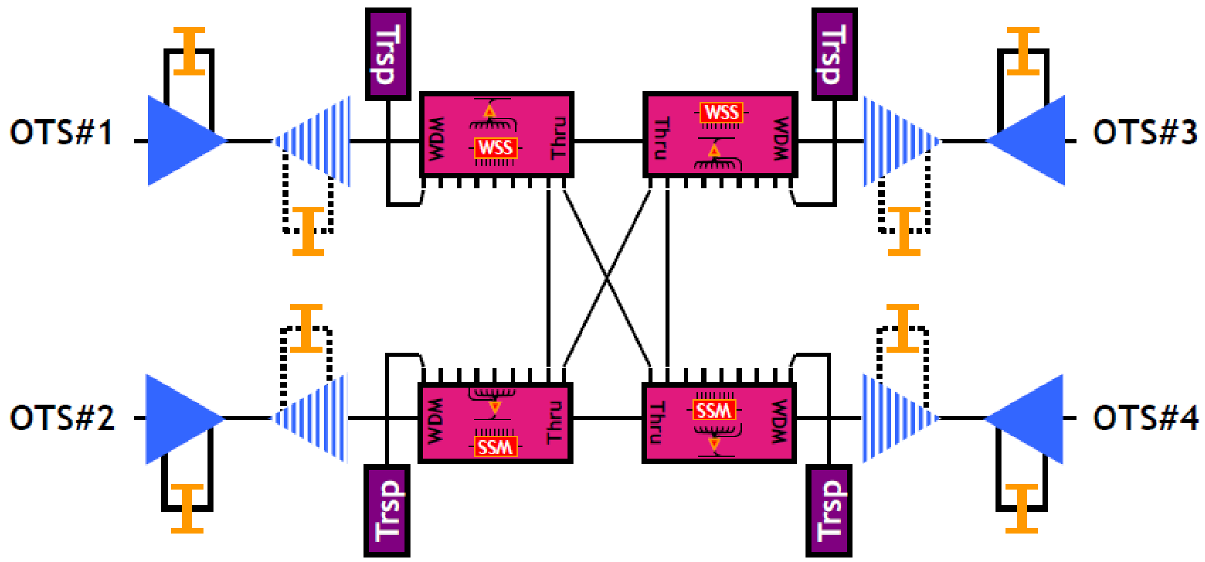


Figure 6.4: Example of colorless ROADM architecture [ALU materials]

An example of an ALU implementation of colourless and directionless ROADM is shown in Figure 6.5 and Figure 6.6 below, where WSS technology is implemented in the “CWR8” and “WR8” building blocks.

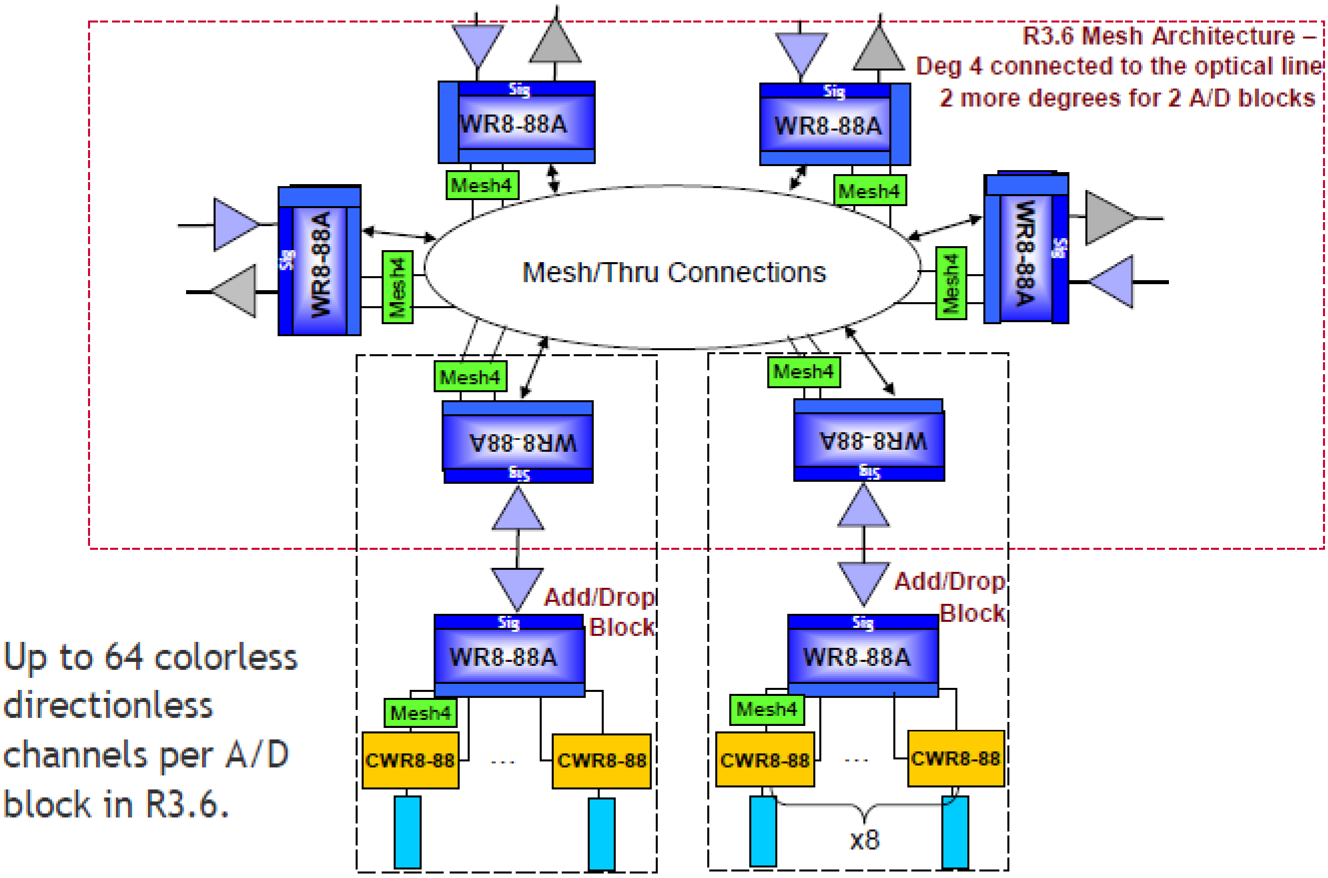


Figure 6.5: Multi-directional A/D degree-4 example with R3.6 packs [ALU materials]

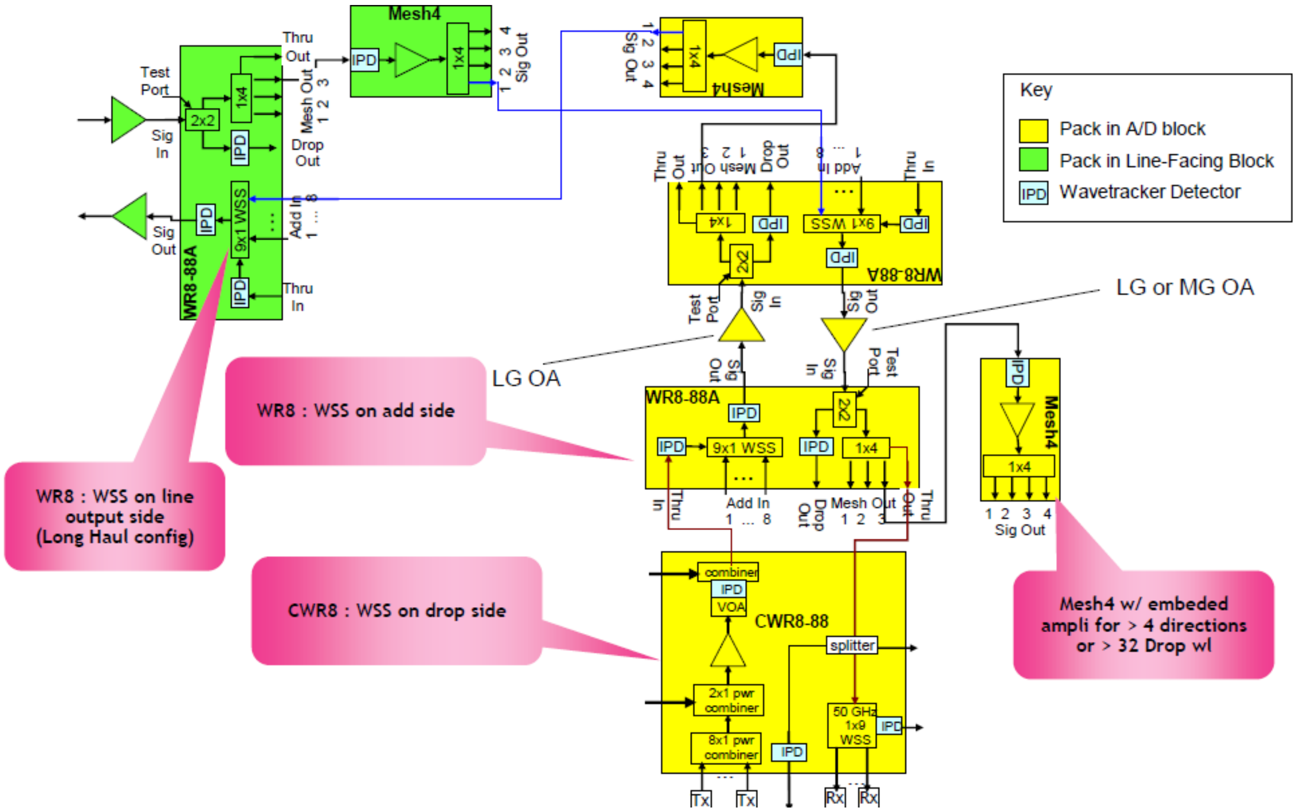


Figure 6.6: Detailed view: 1 A/D block + 1 part of line-facing block [ALU materials]

6.4.3 1830 PSS Optical Protection Options

The ALU 1830 PSS offers the following protection options:

- 1+1 optical channel protection (based on OPS switch card):
  - Against fibre, amplifier and ROADM outage.
  - Applicable to tunable and pluggable transponders and muxponders.

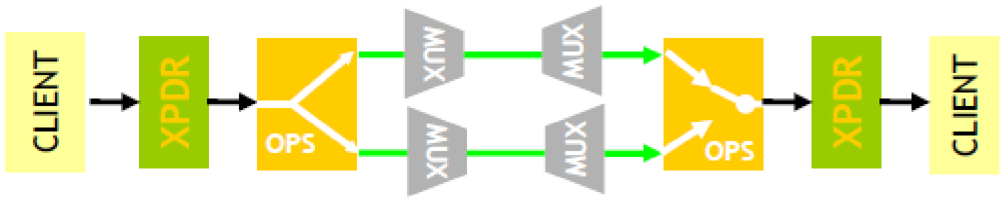


Figure 6.7: 1+1 optical channel protection based on OPS switch card

- 1+1 electrical sub-network connection protection:
  - Against fibre, amplifier and ROADM outage.

- Applicable to pluggable transponders/muxponders with two line interfaces on the board itself.

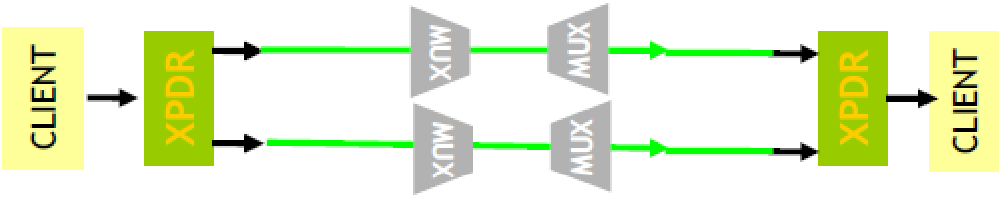


Figure 6.8: 1+1 electrical sub-network connection protection

- 1+1 optical sub-network connection protection:
  - Against fibre, amplifier, ROADM and transponder outage.
  - Applicable to tunable and pluggable transponders/muxponders.

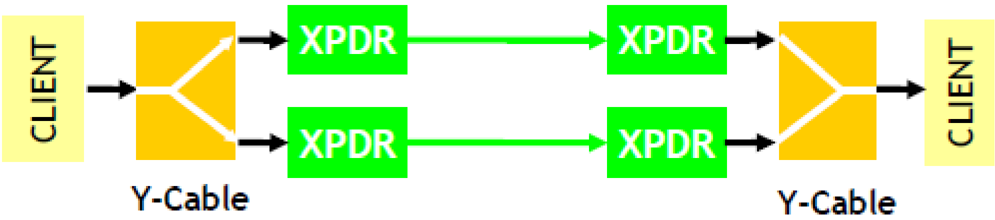


Figure 6.9: 1+1 optical sub-network connection protection

6.4.4 Optical Restoration – GMPLS

During testing, Generalised Multi-Protocol Label Switching (GMPLS) was not available on the 1830 PSS platform. However, it has been implemented at the time of writing. GMPLS is available from the R3.6 software version, providing protection against multiple successive or parallel link failures. It is applicable to directionless and colourless ROADMs and tunable transponders/muxponders.

Because there is a considerable amount of information about the GMPLS mechanism, it will be covered in separate document (not yet available at the time of writing).

6.4.5 Wavelength Tracker

Wavelength Tracker is a unique and very useful feature of the 1830 PSS platform which allows individual services (channels) in the network to be monitored with full efficiency, reliability and at low cost, everywhere in the network. Among other functionality, this feature shows the signal level at individual components of the optical system for a given path as well as acceptable/desirable levels/ranges of signals.

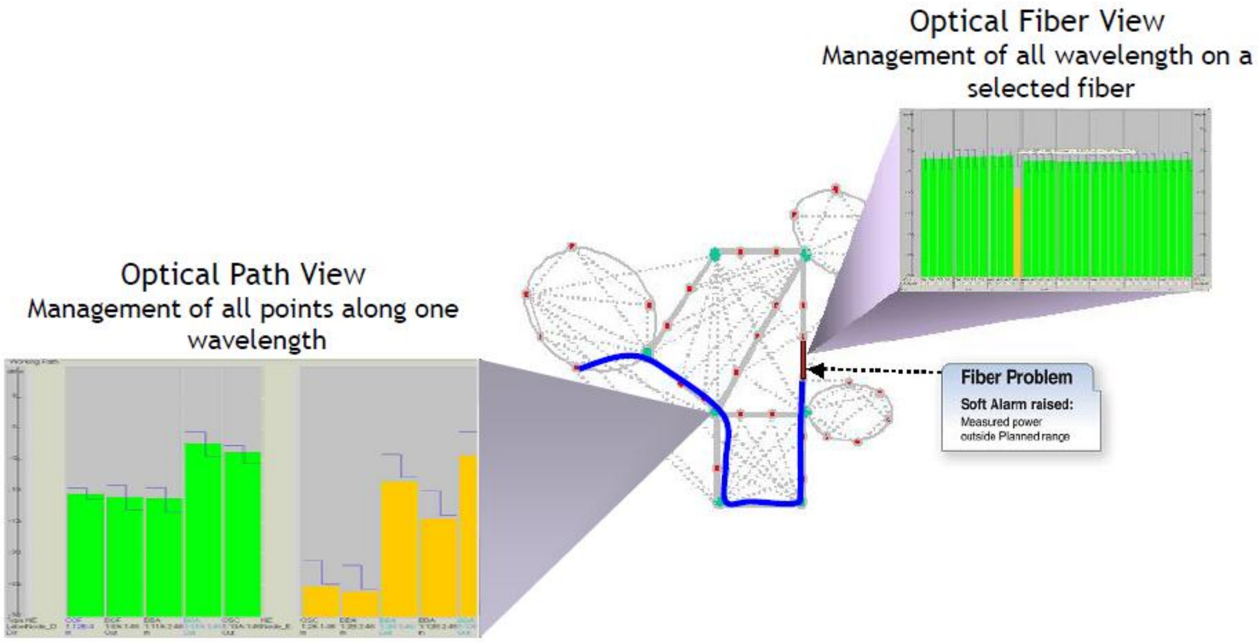


Figure 6.10: Sample Wavelength Tracker view [ALU materials]

From a technical point of view, “marking” a lambda involves adding unique small amplitude modulation to the data signal. The slowly changing modulation signal is a combination of two unique keys. The “marking point” of a signal is the point where the data signal enters the DWDM optical system. The assignment of “wavetracker keys” can be managed by network elements (NEs) or the Network Management System (NMS). The keys are printed on each wavelength either by the transponders and muxponders, or via a gateway function (SVAC/MVAC) in the case of third-party alien wavelengths. The marking is done fully in the optical domain and represents the possibility of controlling and monitoring alien wavelengths without disturbing the signal.

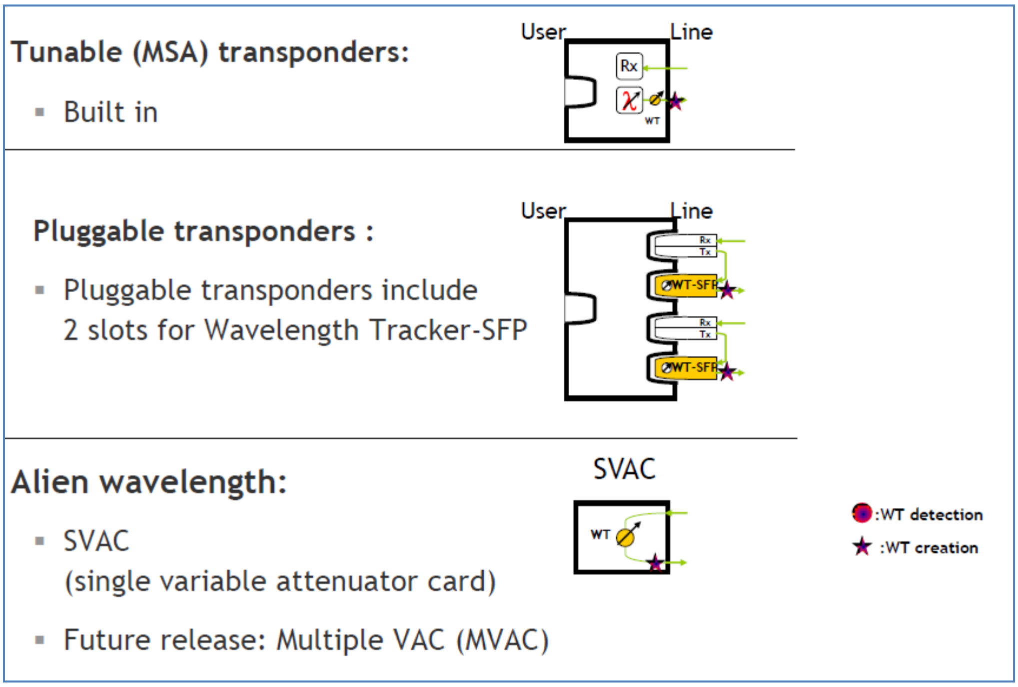


Figure 6.11: Points of Wavelength Tracker implementation [ALU materials]

The primary advantage of the Wavelength Tracker solution is the ability to monitor the service without current knowledge about the physical routes of the optical path. This feature is particularly vital for systems with GMPLS technology implemented where the routes of the physical optical path can change dynamically over time.

6.4.6 Additional Features

Other features and functions of the ALU 1830 PSS are as follows:

- “All optical” wavelength path trace.
- Fault sectionalisation and isolation.
- Remote optical power control.
- Threshold alarming.
- Automated fault correlation.
- Multiple detection per NE.
- Automatic service provisioning enabling.
- Distributed path tracing.
- Service collision detection.
- Associated faults detection.
- G.709 client monitoring.

6.5 Functional Testing of ALU 1830 PSS Platform

This section describes the laboratory test environment and the following functional tests and results:

- Measurement of channel spacing.
- CD resistance for coherent and incoherent transmission.
- Optical signal switching times.

6.5.1 Test Environment

The tests described below were conducted in the ALU laboratory in Villarceaux, France between 14th September and 15th September 2011. A diagram of the test environment is presented in Figure 6.12. The test laboratory was equipped with the following elements:

- 5 x 1830 PSS-32.
- 100G card with coherent transmission.
- 40G cards with incoherent transmission.
- 10G cards.
- Optical protection switches.
- ALU Network Management System.

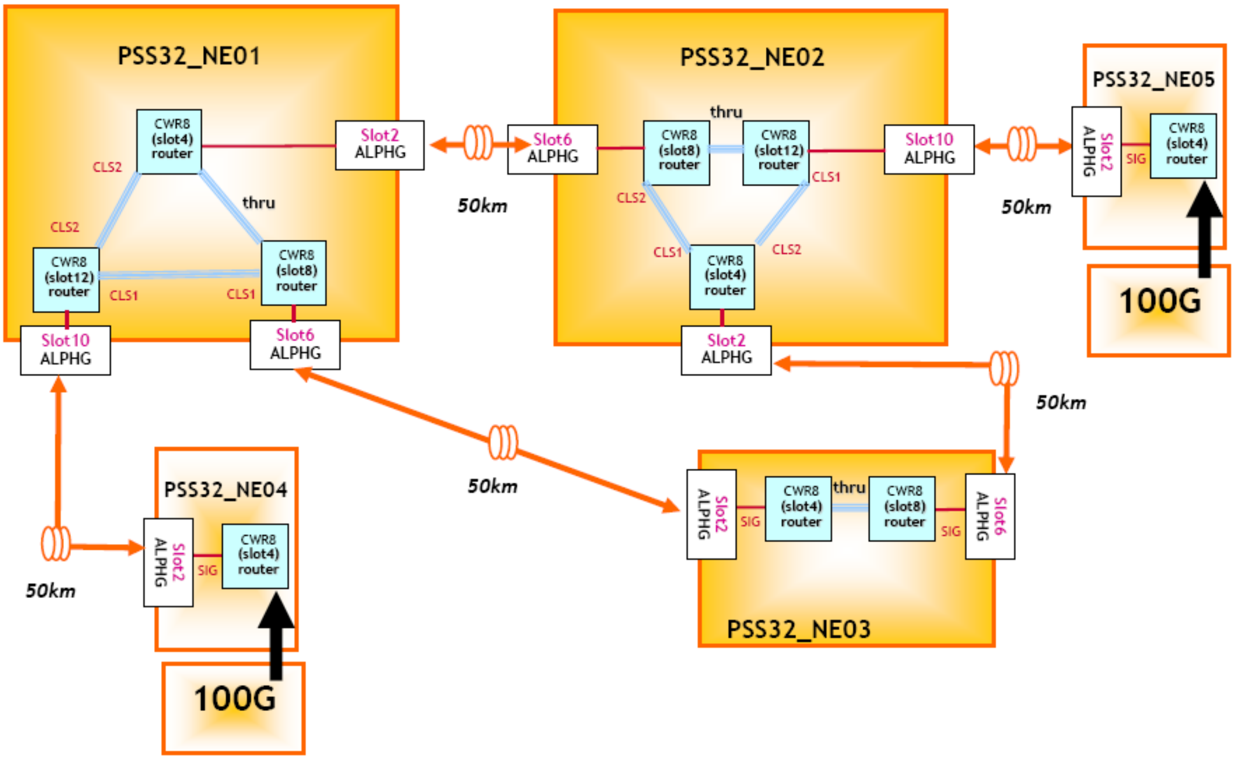


Figure 6.12: Diagram of laboratory test environment

6.5.2 Measurement of Channel Spacing

During the tests, the channel spacing for 10G, 40G and 100G transmission was measured. The measurements for all three channels used in the laboratory are shown in Figure 6.13 below.

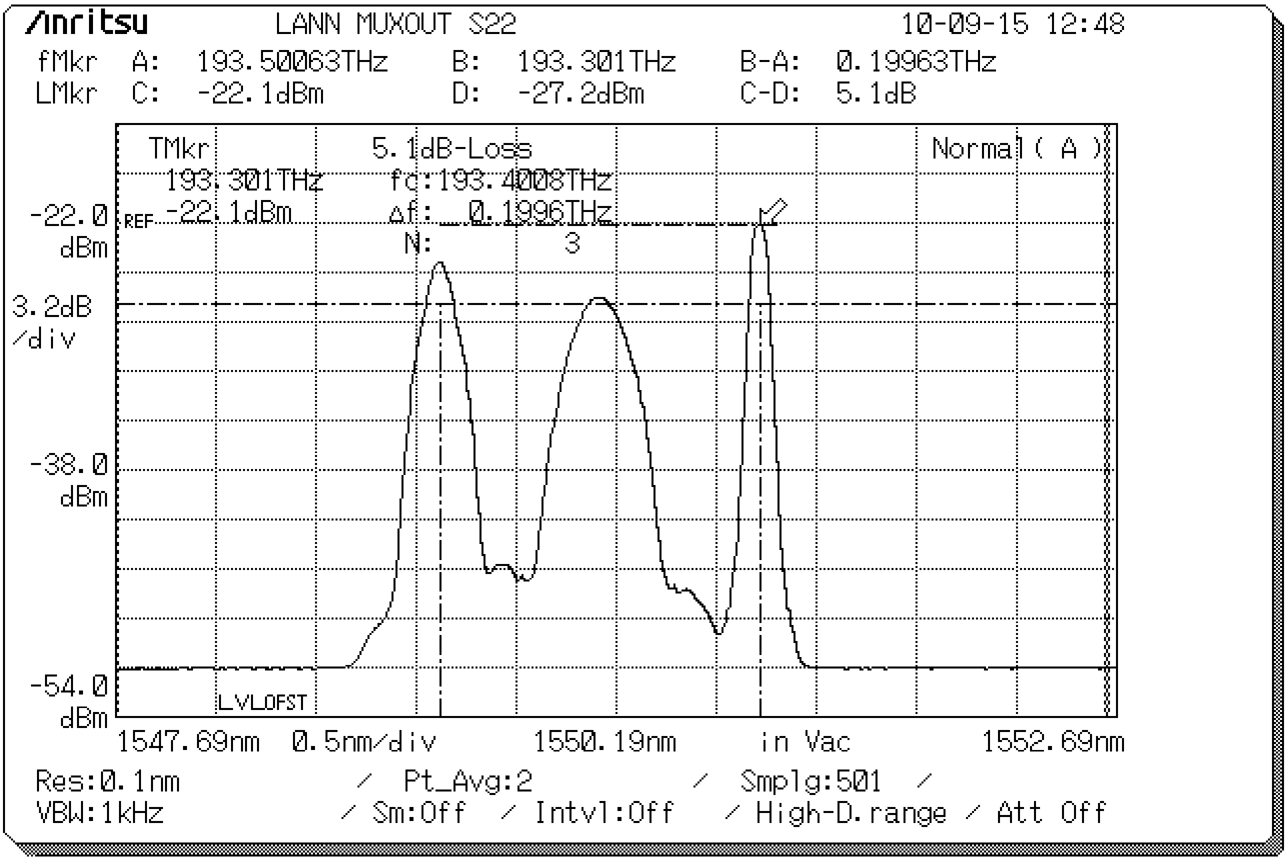


Figure 6.13: Spectrum view of three channels (from left: 100G, 40G and 10G transmission)

As can be seen in Figure 6.13, the widest channel is at the 40G transmission. This is because of the high baud rate of 40G PD-PSK modulation and the lack of a coherent modulation scheme. On the other hand, 100G cards had coherent transmission implemented with decreased baud rate and spectral width (it is lower when 40G).

The results of the measurements for different transmission interfaces are shown in Figure 6.14 to Figure 6.16 below.

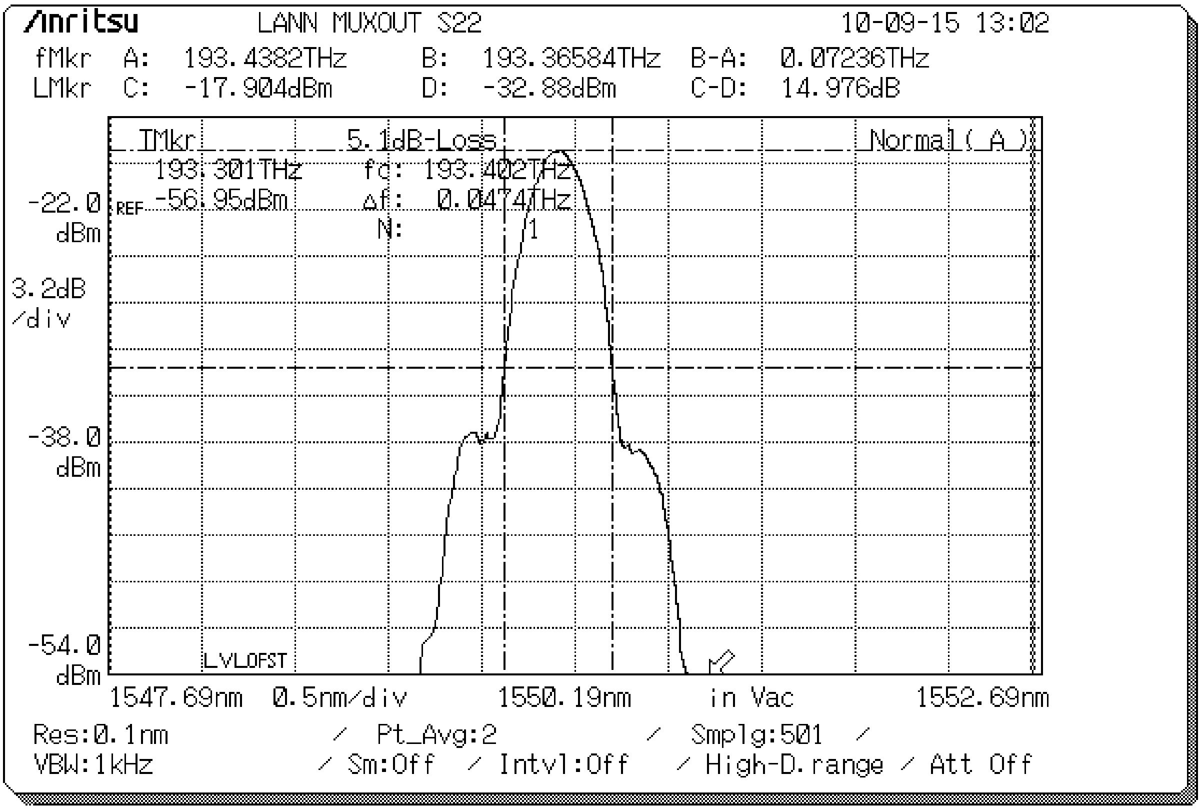


Figure 6.14: Spectrum view of 40G PD-PSK transmission channel

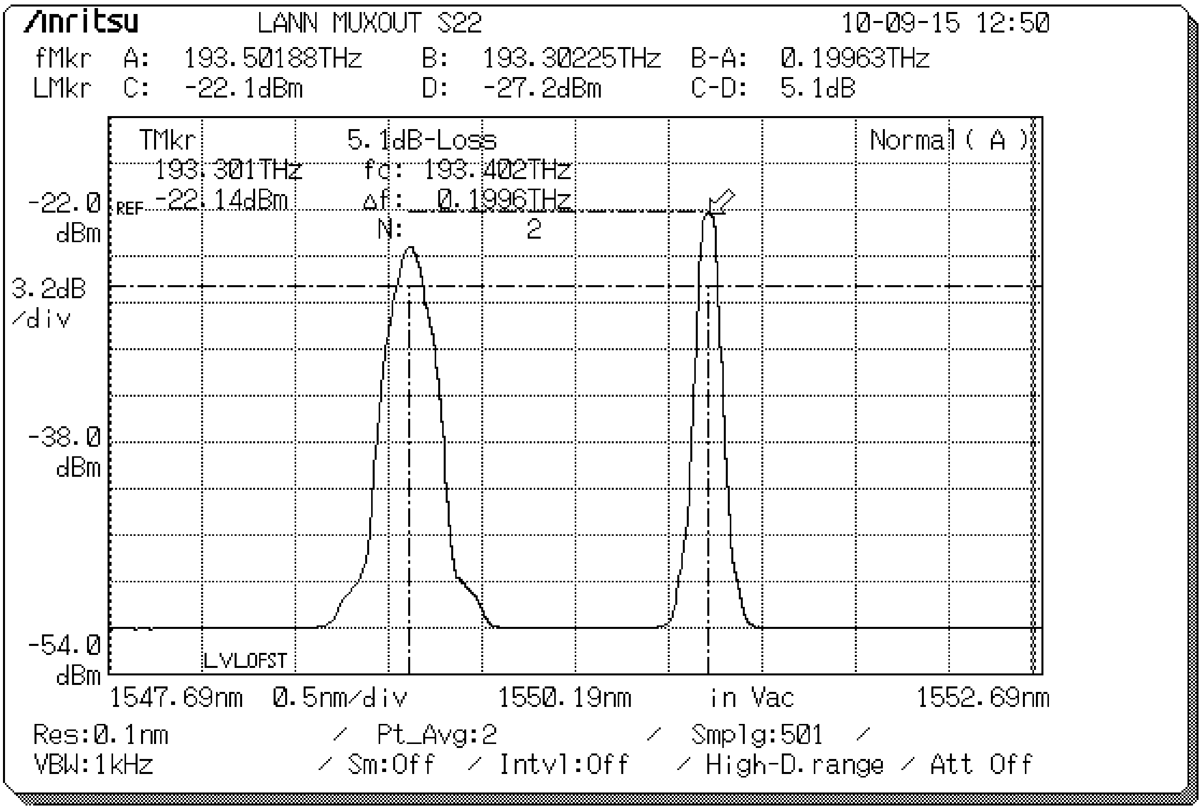


Figure 6.15: Spectrum view of two channels (from left: 100G and 10G transmission)

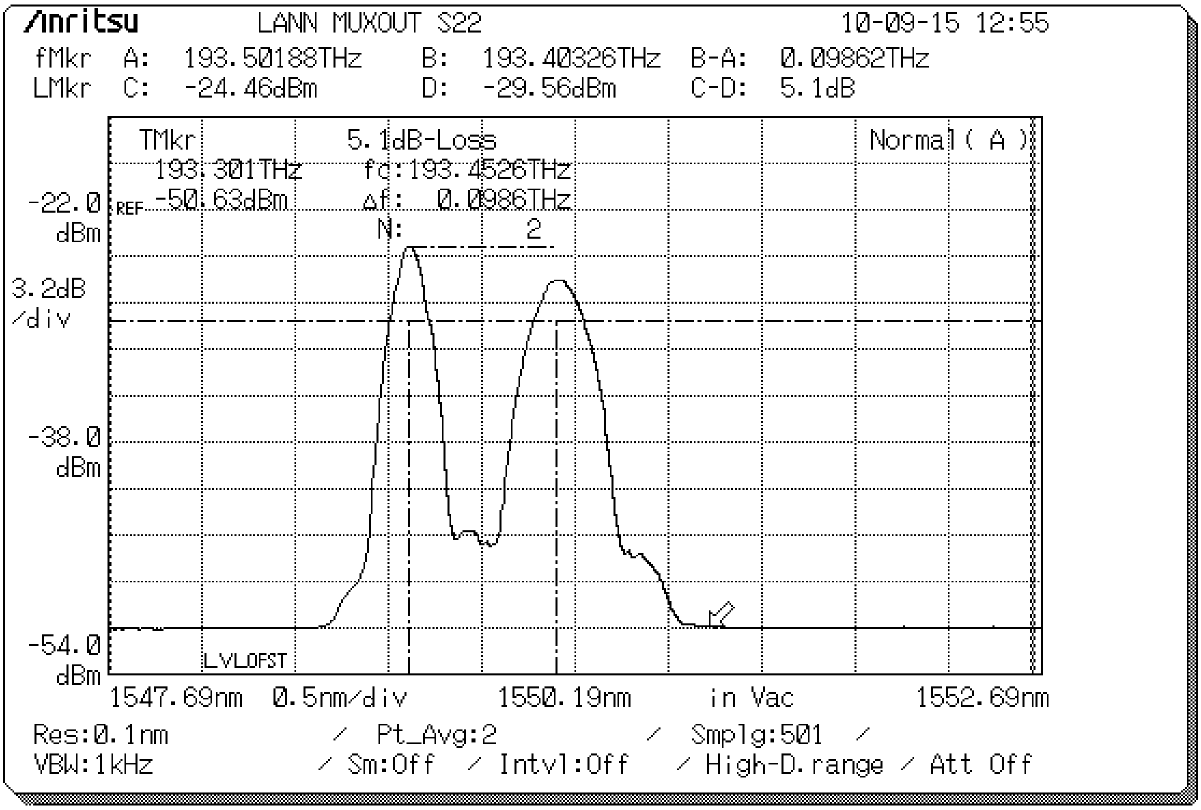


Figure 6.16: Spectrum view of two channels (from left: 100G coherent and 40G PD-PSK transmission)

6.5.3 CD Resistance for Coherent and Incoherent Transmission

The chromatic dispersion value increases linearly in relation to line length and is one of the most important parameters that limit system range.

During the tests, the chromatic dispersion value was gradually increased (by adding more fibre to the line) to the point where transmission errors could be observed. Two signals were compared: 40G incoherent and 100G coherent. As expected, the errors were noticed first in the case of 40G transmission. This is because the deployment of coherent transmission for the 100G signal decreases the baud rate and spectral width and, in consequence, provides higher resistance to signal dispersion.

6.5.4 Optical Signal Switching Times

During the tests, the reaction time (i.e. the time taken to switch the optical signal) of the optical protection module was examined. It was tested in two scenarios: protection forced by the NMS and as a consequence of a network fault (fibre cut). An example of the protection module's topology view is shown in Figure 6.17 below.

Figure 6.17: Topology view [ALU materials]

The protection module was tested using 10G transmission. Because the protection module is an independent module and its operation is based on the power level of the input signal, the time taken to switch the optical path was expected to be similar for 40G and 100G transmission.

6.5.4.1 *Protection Forced by NMS*

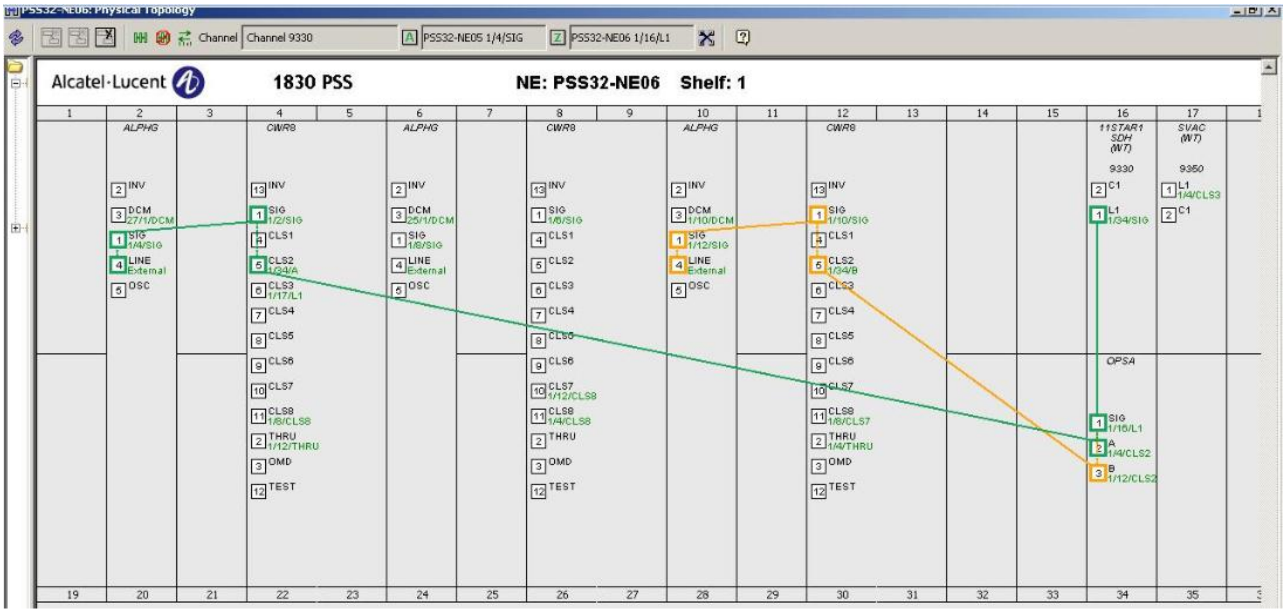


Figure 6.18: NMS view – protected light path

In the process of the manual/forced change of the optical path from primary to secondary by the central NMS, 250 lost frames with 1500 byte (B) length were observed. The data stream was generated by an IP tester (from Ixia). Transmission was realised using 10 Gbit/s LAN/PHY standard, giving a MAC data rate of 10 Gbit/s.

The results show that the interruption time equalled 250 frames * (1500B data + 18B preamble) / 10 Gbit/s = 0.3036 (ms).

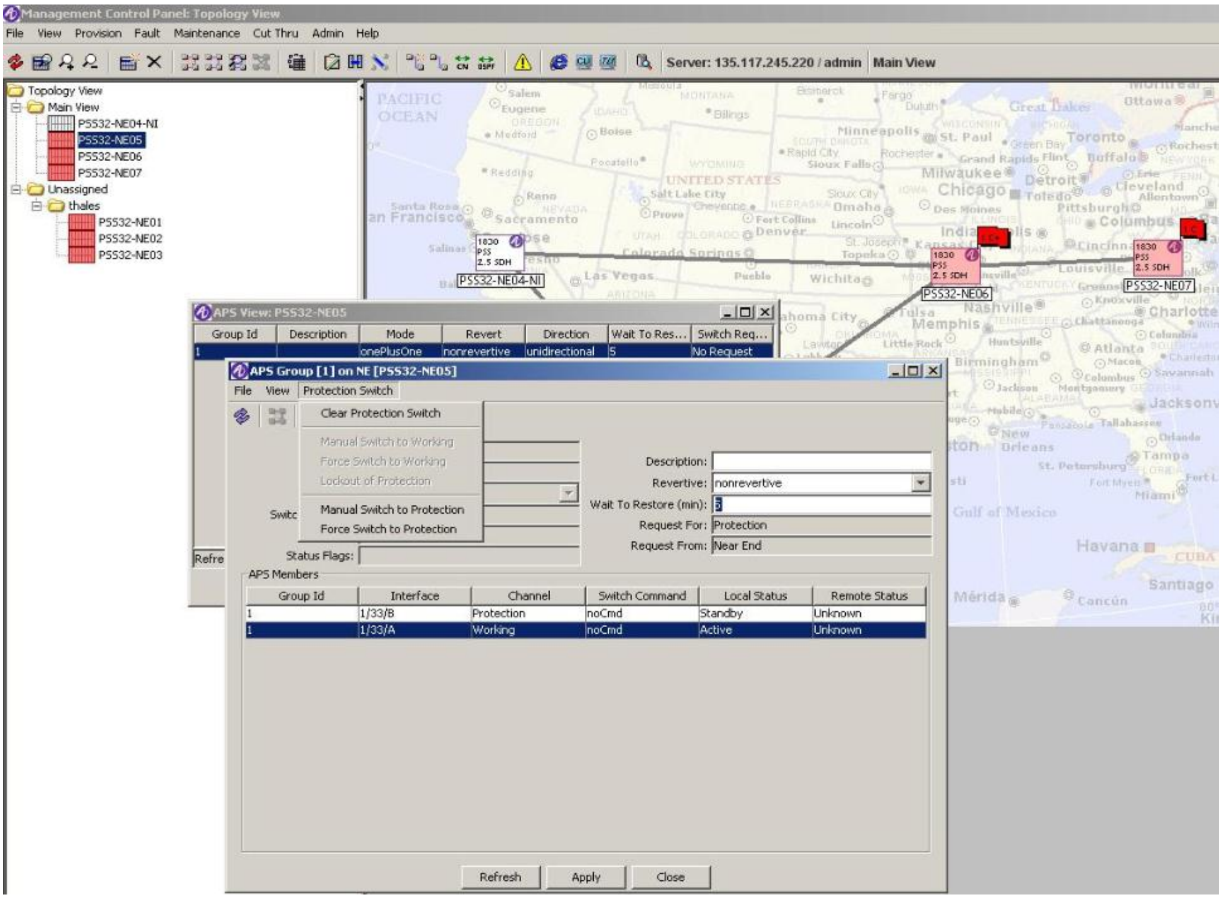


Figure 6.19: NMS view – manual switch to protection

6.5.4.2 *Reaction to Fibre Cut*

Changing the optical path from primary to secondary as a reaction to a simulated fibre cut took about 0.6 seconds (twice as long as when protection was forced by the NMS). This means 500 lost frames with 1500B length. The data stream was again generated by an IP tester (from Ixia). Transmission was realised using 10 Gbit/s LAN/PHY standard, giving a MAC data rate of 10 Gbit/s.

The results show that the interruption time equalled 500 frames * (1500B data + 18B preamble) / 10Gb/s = 0.6072 (ms).

6.6 Conclusions

With the introduction of commonly available 100G line interfaces, which in the optical domain is ten times more efficient than the current de facto standard of 10G, it is possible to take advantage of the released free channels to create backup optical paths in DWDM networks. Moreover, new protection methods give capabilities for wavelength switching in times similar to those of IP layer switching. This provides capabilities for wavelength-switching functionality based on an optical transmission system and guarantees of full capacity for primary and backup connections at all times (even during simple network faults).

In order for fully flexible optical transmission networks to be realised, they should feature the capability of colourless, directionless operation, and protection and restoration should be based on advanced control planes e.g. GMPLS. The advanced coherent modulation formats make the external dispersion compensation units (DCUs) obsolete, which means that the losses and non-linear effects previously associated with the DCU are greatly reduced. While coherent transmission and uncompensated optical lines are the optimum way to build DWDM networks, it should be noted that to some extent they prohibit the use on a large installed base of legacy DWDM systems and the associated 10G transponders with NRZ modulation format. Strong non-linear effects in non-zero dispersion shifted fibres can be limiting factors for the use of 40G and 100G transmission systems. When developing NGN networks, therefore, these factors should still be taken into account and some limitation of system range and capacity can be expected. The complexity of such networks demands better methods of traversed signal quality, management and monitoring.

NGN network features allow the following functionalities to be achieved:

- Resistance to network section faults, e.g. fibre cut, amplifier failure – possibility of dynamic network reconfiguration without limitation of throughput for end users on primary paths, backup paths and possibility of supporting multiple successive or parallel link failures in the network topology. Testing of dynamic restoration in a live network is described in Chapter 3, where GMPLS-controlled restoration proved to be a robust and fast (below 10 minutes) way to solve fibre cuts and amplifier failures.
- Flexibility – possibility of dynamic or programmed network configuration or topology changes depending on current and future needs.
- Simplicity of alien wavelengths implementation – possibility of resource (channel) assignment. Moreover the alien channel will be switched to the backup path without needing to block channel resource in the entire network, as was the case previously.

7 Photonic Services

7.1 Introduction

The research community pushes innovation forward with its specific requirements from the available resources, including connection to a network that allows the community to communicate and collaborate. Specialised research centres also often depend on unique devices. The uniqueness may arise from a favourable research centre location that cannot be found or replicated anywhere else, or simply from device cost. Therefore remote access, interconnection or even real-time control of such devices is of great interest throughout the community. Most such requests can be satisfied by an end-to-end connection, a Photonic Service, over an all-optical network delivering immense bandwidth with low latency and noise to end users.

This chapter presents the results of the work carried out by the CESNET, RENATER and SURFnet participants of JRA1 Task 2 on Photonic Services (PS). It provides a description of PS, clarifying how they differ from alien wavelength and the GÉANT Lambda Service, and summarising their features and challenges. It goes on to consider examples of demanding applications that require the quality of service delivered by PS, including interactive human collaboration, high-definition video, remote control of instruments and vehicles, comparison of atomic clocks, and ultra-stable frequency transfer, providing parameters and references for each. The chapter then presents the time and frequency transfer tests conducted by the JRA1 Task 2 NRENs, and concludes with a summary of the PS demonstrations they have carried out.

7.2 Description of Photonic Services

A general service for end-to-end connection between two or more points in an optical network can be described by its photonic path and allocated bandwidth. A photonic path is the physical route along which light travels from one end point to the other or to multiple other end points. The allocated bandwidth is the part of the system spectrum that is reserved for the user of the service along the full length of the photonic path. It is important to carry the service over the network with minimal impact, so that the processing at the end point will depend just on the application. Since such services are provided over all-optical networks, they are referred to as Photonic Services (PS). The majority of current NGN networks are all-optical, unless regeneration utilising conversion to electric signal is deployed. These regenerations are used to overcome distances greater than the basic reach of transponders, with the exception of one vendor, which uses regenerations intensively.

Alien wavelength (AW) is a special case of PS. AW is used within optical communications to carry data between two end points over multi-vendor networks. AW is always used as a data carrier in one optical channel and transmission modulation is always selected to fit that channel.

The GÉANT Lambda Service is also a special case of PS. It is limited to a single optical channel and allows electrical regeneration along its path.

A simple comparison of advanced optical network services is presented in Table 7.1 below. (Further information about AW is provided in Chapter 4 *Alien Wavelength* on page 66.)

Service Name	Bandwidth	Data Representation	Comments
Photonic Service	Variable	Application relative	Variable bandwidth will be available with FlexiGrid-like technologies Data representation will be limited only by network transparency and end-points distance
Alien Wavelength	50 GHz/100 GHz	OOK, coherent modulation	End-to-end data transport over multi-vendor networks without OEO
GÉANT Lambda Service	50 GHz/100 GHz	OOK, coherent modulation	End-to-end data transport with OEO

Table 7.1: Advanced optical network services comparison

Some of the applications in the research community that are of interest and relevance to NRENs require low network latency and therefore the shortest photonic path available. More demanding applications even pose limits on latency jitter. All this is provided by a well-controlled all-optical network without optical-to-electrical-to-optical (OEO) conversion. (As mentioned above, the term “photonic” comes from the fact that paths in networks supporting this kind of service should be all-optical.)

7.2.1 Features

The Photonic Services approach offers the future-proof concept of bandwidth and photonic-path provisioning that is transparent to modulation format. Transparency is opening networks to a wide range of possible applications, beyond traditional IP traffic. Photonic Services have the following features:

- Transparency to modulation formats.
- Low transmission delay as the shortest photonic path is formed.
- Future-proof design thanks to gridless or flex-grid bandwidth allocation.
- Constant delay (i.e. negligible latency jitter), because no electrical processing is present.
- Compatibility with GÉANT Lambda Service and alien wavelength.
- Stable service availability due to allocated bandwidth, in contrast to e.g. services over an ISP network, which is often best effort traffic.

The individual features above are not unique to PS, and subsets can be found in other services. The biggest differentiator is the request for gridless or flex-grid bandwidth allocation, which put constraints on the WSS technology deployed. MEMS-based WSSs were able to allocate bandwidth in steps of 50 GHz or 100 GHz but not without a significant attenuation pattern every 50 GHz / 100 GHz due to the physics of the MEMS. WSSs based on Liquid Crystal on Silicon (LCoS) do not exhibit this pattern, and DWDM vendors are now pursuing flex-grid and later gridless operation. The term “super-channel”, used by some DWDM vendors in conjunction with future 400 Gbit/s and 1 Tbit/s signals, often includes a flex-grid approach where bandwidth is allocated as a function of needed reach and used modulation formats.

7.2.2 Challenges

Although Photonic Services over all-optical networks seem to be next logical step in network evolution, there are still challenges for a large-scale deployment. The key missing element is a purely optical regenerator or at least amplifier with minimal noise figure to extend the reach of services. Known issues that remain to be solved include the following:

- Service reach in general is limited due to missing commercially available all-optical regeneration. However, it can be extended with specialised OEO regenerators suitable just for a single application.
- All-optical nodes represented by colourless and directionless Reconfigurable Optical Add-Drop Multiplexers (ROADMs) need to be deployed to fully unlock the potential of PS.
- Absence of global management and operation system or communication between separate management systems.
- Multi-vendor network interoperability, although the first tests have already been successful [CESNETPR9Sept2009].

7.3 Applications

Photonic Services are required by demanding applications that are not feasible (or are feasible only with significant complications) over Internet Service Providers’ (ISPs’) traditional routed IP networks. JRA1 Task 2 has identified critical parameters that characterise specific applications and place requirements on the network. The fluctuation in network latency limit represents the maximum time between any two consecutive pieces of information that will arrive at the destination, and will be referred to in the pages that follow as the latency jitter. The latency jitter is also caused by lags that are introduced by (de)serialisation and buffering during OEO conversion in over-provisioned networks. Although in most applications the penalty for not meeting the latency jitter limits or service failure is mild, there are applications where failure interrupts the whole experiment or even endangers human life. These include:

- Interactive human collaboration.
- High-definition video and cave-to-cave.
- Remote instrument control.
- Remote control of vehicles.

- Comparison of atomic clocks.
- Ultra-stable frequency transfer.

Examples of each of these demanding applications with parameters and relevant references are provided in the sections that follow.

7.3.1 Interactive Human Collaboration

Latency jitter limit:	10–50 ms (adaptive play-out delay buffer)
End-to-end latency:	100–200 ms
Penalty:	Mild (user disappointment)

The simplest case of interactive collaboration is human speech. ITU-T recommendation G.114 [G.114] defines a latency limit of up to 150 ms for high-quality communication. Nevertheless, speech quality is a complex matter and when the echo and loss are not present, it is permissible for latency to be higher. Users do not perceive discomfort up to 300 ms. However, 200 ms is the canonical value cited in many documents.

The most demanding examples of this application are probably remote fine arts lessons such as piano or violin lessons, where the teacher's ability to guide her students is dependent on the visual and aural experience delivered over the network. Fine arts lessons have been tested in Brazil across the Atlantic Ocean (Brazil and Spain) with success and presented at the Customer Empowered Fibre Workshop 2010 in Prague [Carvalho].

Here again it is important to distinguish negligible latency from latency to which the user can adapt. The negligible latencies are produced by sound propagation into air: for example, from about 5 ms for a chamber orchestra to 40 ms for a symphony orchestra. Nevertheless, 100 ms is a value to which the user can adapt easily. Some experiments are described in [LOLA].

The overall quality is strongly dependent on the codec used. Generally, two techniques are applied to improve packet-loss robustness and sensitivity to a variation in the delay of received packets. The packet-loss concealment technique masks the effects of packet loss; the simplest forms are based on repeating the last received frame, while the most sophisticated algorithms apply Hide Markov Models (HMMs). An adaptive mode of play-out delay buffer dynamically adjusts to the amount of jitter present; the value is always calculated as the duration of one frame multiplied by an integer number.

7.3.2 High-Definition Video and Cave-to-Cave

Latency jitter limit:	20 ms (buffer dependent)
End-to-end latency:	150 ms
Penalty:	Mild (user disappointment)

Cave-to-cave and high-definition (HD) video have recently enabled doctors and students of medicine to watch an operation with their own eyes, and enjoy the high-precision work of top surgeons throughout the world, using real-time high-resolution video. These high-bandwidth demanding applications usually require a dedicated lambda to provide users with the full experience. In June 2010 CESNET performed a real-time 3D full HD stereo broadcast of a kidney surgery performed by a da Vinci robot [CESNETPR18June2010]. The HD data stream was transferred by a dedicated optical channel over a link 150 km long, with total delay of 1 ms. The data stream reached transfer speeds of 2.5 Gbit/s during the demonstration. In October 2010, the transmission distance was doubled in a similar demonstration over the CESNET2 network [CESNETPR13Oct2010]. In November of 2010, CESNET conducted a real-time 3D full HD stereo Internet transmission of an operation between the Czech Republic and Japan. The time delay was 150 ms, caused by light propagation time [CESNETPR23Nov2010].

7.3.3 Remote Instrument Control

Latency jitter limit:	20 ms
End-to-end latency:	100 ms
Penalty:	Depends on application (can be severe in case of tele-surgery)

New unique instruments and facilities are often built at the most suitable places in the world, which may not be easily accessible. Examples include the unique observatory in India that was built over 4,500 metres above sea level in the barren desert of Ladakh [IndianAO], or the highly specialised robot-assisted surgery system da Vinci, located only in the most famous hospitals in the world [daVinci]. The remote control of such instruments can save the time and expense involved in relocating experts to work directly on the site. A hospital in Strasburg conducted a tele-surgery in 2001. The robotic tele-surgery connected a surgeon from New York to a patient in Strasburg [Tele-surgery]. It is worth mentioning that there were also experts on site ready to take manual control of the robot in case of network failure. The latency for robotic surgery is considered negligible when it is about 100 ms, but the limit of adaptability can be up to 400 ms. A more detailed study can be found in [HAVE].

Most recently, professionals from CESNET and the Masaryk Hospital in Ústí nad Labem have demonstrated their experience of the transmission of robotic operations to their colleagues in Japan [CESNETPR23Nov2010].

In general this type of application has mild requirements on bandwidth and network latency. Once tele-presence surgery proceeds to regular use, it will be unacceptable to interrupt the connection, because the operation will be incomplete and interruption could directly endanger the patient’s life. These prerequisites will barely be met by standard networks where the necessary Quality of Service (QoS) parameters are provided via so-called over-provisioning of bandwidth. They will probably demand a dedicated optical channel.

7.3.4 Remote Control of Vehicles

Latency jitter limit:	50 ms
End-to-end latency:	TBD
Penalty:	Not acceptable (vehicle crash)

Many projects all around the globe are investigating intelligent transportation systems that would assist or replace vehicle drivers to increase transportation safety and efficiency. Numerous tasks in future vehicle communication have been identified. Many of them should warn a vehicle driver or operator about and address environmental warnings such as hazardous location, traffic signal violation or slow vehicle notice. Emergency warnings such as pre-crash sensing have stringent latency requirements of around 50 ms with the unacceptable penalty of vehicle crash. Although the exchange of information among vehicles and infrastructure will be wireless, the availability of data from infrastructure will be essential [ITS].

7.3.5 Comparison of Atomic Clocks

Latency jitter limit:	50 ps (short time, typically over 1000 s) and 1 ns (long time fluctuation, typically over days)
End-to-end latency:	Should be minimised to the optical signal propagation delay
Penalty:	Mild (experiment failure)

The time standard is usually provided by caesium clock and then distributed across the country. In the past, the preferred method for achieving the most accurate comparison of different clocks was by radio signal over a dedicated satellite channel that requires complex instruments. Advances in optical networking opened a new comparison option by using light pulses that are timed precisely once per second with a resolution in the order of tenths of nanoseconds or better. An early experiment is described in [CESNETPR1April2010].

7.3.6 Ultra-Stable Frequency Transfer

Latency jitter limit:	N/A
End-to-end latency:	Should be minimised to the optical signal propagation delay
Penalty:	Mild (experiment failure)

The transfer of ultra-stable frequency between two distant places is required by experts from the fields of time and frequency metrology, astrophysics, particle accelerators and fundamental physics. The simplest and most beneficial approach is to utilise NRENs that already connect many research institutes and universities. Successful transfer of ultra-stable frequency has been demonstrated over networks with live traffic. This application requires dedicated equipment in network nodes, but it is possible to run it alongside standard long-haul equipment. In the case of optical clocks, the frequency is not transferred as a modulated optical signal; instead, the wavelength is the subject of transmission. Any usual OEO conversion would violate this service, since frequency transfer requires special continuous-wave narrow single-mode lasers.

7.4 Time Transfer Test

7.4.1 Introduction

A local approximation of the Coordinated Universal Time (UTC) standard is realised in every country by a free-running atomic clock, which usually takes the form of a set of several caesium clocks. Each laboratory has to compare their time scale with others in order to determine the current time offset between UTC and its national approximation UTC(k).

Traditional methods utilise satellites for time transfer, either directly via radio frequencies or indirectly through global navigation systems, typically Global Positioning System (GPS). Recent advances in the photonic industry have enabled optical transmission also. In addition to the use of telecommunication protocols, e.g. Synchronous Digital Hierarchy (SDH), a variety of methods based on photonic fibres have been reported, for example, the transmission of solitons, pulses from femtosecond lasers carrier-modulated by RF or direct transfer of stable carrier frequency [Piester]. Although the deployment of dedicated infrastructure over long distances is very challenging from an economic point of view, NRENs can offer available lambda channels in their DWDM systems. Once the systems are capable of photonic services (and especially are transparent for optical signals), these lambda channels can provide alternative infrastructure for precise time transfer.

This section describes the time transfer tests carried out by CESNET, summarising the system setup and then detailing the tests themselves.

7.4.2 System Setup

A time transfer system [Lopez] has been developed in CESNET that implements a two-way transfer method that relies on symmetrical transport delay in both directions. In such a system, two adapters are connected by a bi-directional optical link. Adapters are based on a Field Programmable Gate Array (FPGA) Virtex-5 chip, using Small Form-factor Pluggable (SFP) transceivers for electro-optical conversion. Figure 7.1 below shows a working example of the developed adapter.

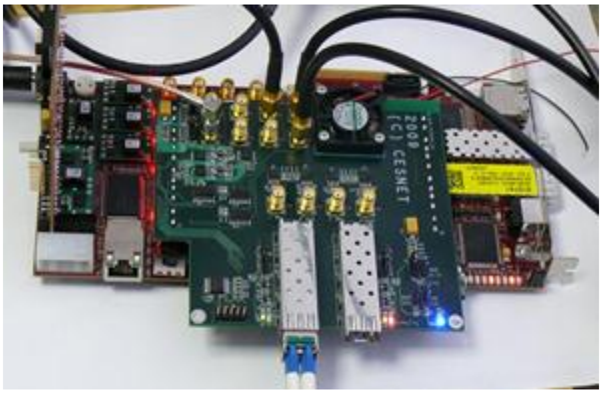


Figure 7.1 Working example of two-way transfer adapter

7.4.3 Tests

The goal of the first network experiment was to measure the delay of a long optical loop in order to predict the influence of the fibre thermal dilatation. A 1 pulse per second (PPS) signal from a rubidium clock was transmitted in both directions over an all-optical lambda 744 km long. The lambda was created within a DWDM system between cities Prague–Brno–Olomouc–Hradec Kralove–Prague, as shown in Figure 2.43.

Figure 7.2 below displays the stability of the time transfer in terms of time deviation, denoted as TDEV or $\sigma x(\tau)$. It can be seen that for averaging intervals up to 200 s, the white phase modulation noise $\sigma x(\tau) \approx 100$ ps/$\sqrt{\tau}$ prevails. It is assumed this noise originates in the modulation/demodulation of the carrier signal and output circuits of the adapters. The lowest value of ~8.1 ps for averaging time 500 s has been observed. Details of this experiment are described in [Smotlacha1].

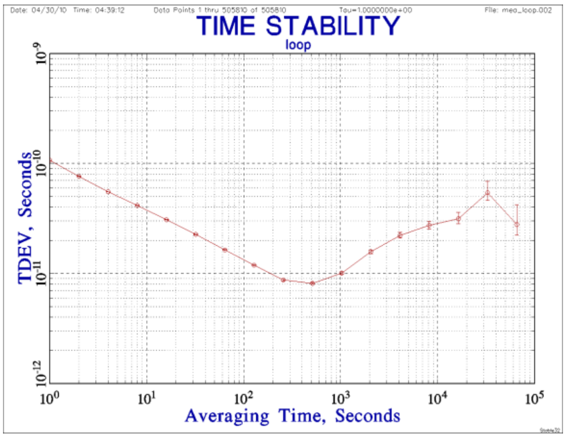


Figure 7.2: Time stability, lambda loop of 744 km

In spring 2010, CESNET successfully demonstrated time transfer between atomic clocks in Prague and in Vienna [CESNETPR1April2010]. The all-optical path was created across an operational DWDM network and

DWDM experimental link, operating a so-called “hut-skipping” design (i.e. without inline amplifiers) over 220 km. The full setup is shown in Figure 7.3 below.

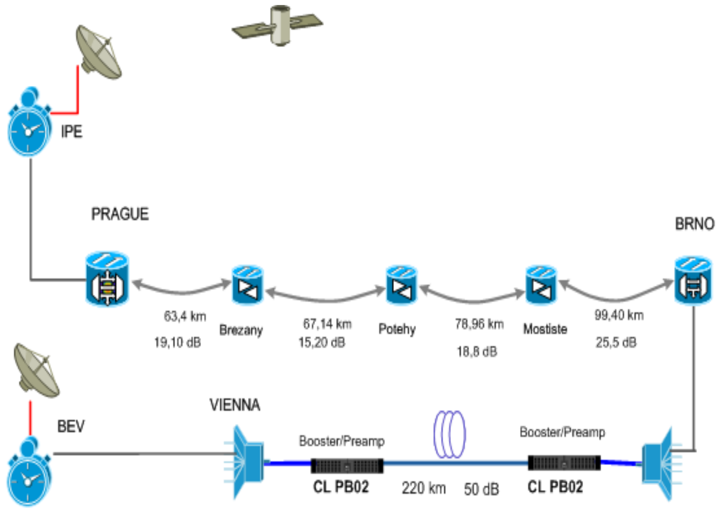


Figure 7.3: IPE–BEV all-optical path

The “comparison of timescales” service" between Czech and Austrian national time and frequency laboratories in Prague and Vienna was brought into operation in August 2011. The photonic path between the Institute of Photonics and Electronics (IPE) in Prague and 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 dedicated DWDM channels in the CESNET2 production network. The link between Brno and Vienna University uses another DWDM channel in the cross-border link joining CESNET and ACOnet. Both national laboratories overcome last mile to point of presence through rented dark fibre lines. The path is amplified with 7 Erbium Doped Fibre Amplifiers (EDFAs) and uses the same wavelength 1551.72 nm (i.e. C band, ITU channel #32) in both directions. A description of the individual segments is summarised in Table 7.2.

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 7.2: Photonic path segments

This optical method has been compared with standard method Common View (CV) GPS. Very good correlation between both time transfer methods has been observed – the difference did not exceed 4 nanoseconds in a 3-month period and optical time transfer had significantly lower noise. An overview of all results is shown in the graph in Figure 7.4. Red points represent optical measurement data, green points are GPS data, and the blue line shows the time offset computed according to the published list of offsets, Circular-T [BIPM]. Other results, e.g. stability and delay variation, can be found in [Smotlacha2].

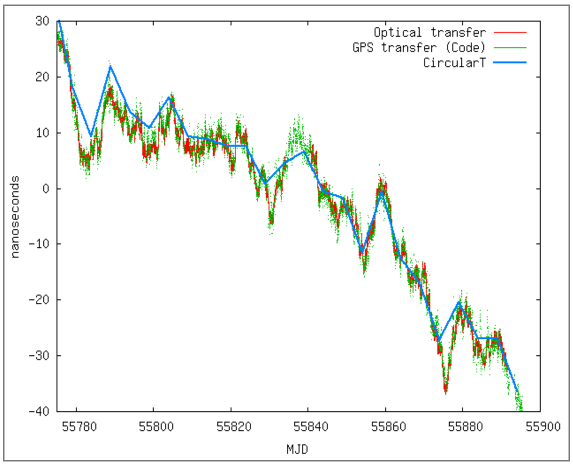


Figure 7.4: Time difference UTC(TP) − UTC(BEV) measured using optical link (red), via GPS (green) and from BIPM Circular-T (blue)

7.5 Frequency Transfer Test

7.5.1 Introduction

This section describes the frequency transfer tests carried out by RENATER for the Metrological Fibre Network with European Vocation (MEFINEV+) project and the work performed to establish a connection between Laboratoire national de métrologie et d'essais – Système de Références Temps-Espace (LNE-SYRTE) and Laboratoire de Physique des Lasers (LPL) laboratories. It presents an overview of the projects, describes how the backbone links of the RENATER-5 network were adapted and what factors were considered to add the project wavelength. Finally it summarises next steps and provides some conclusions.

7.5.2 LNE-SYRTE to LPL Tests

In spring 2010 and 2011, the LNE-SYRTE and LPL laboratories realised successful ultra-stable frequency transfers on the RENATER-5 live network by using a dedicated ITU-T DWDM wavelength.

- A first transmission test between SYRTE and LPL was conducted in 2009 on 90 km of urban dark fibre in the Paris area to validate the stabilised laser system used for the photonic service.
- The path was then extended in 2010 on 193 km between the Paris Observatory and Nogent l'Artaud to validate the process of bypassing RENATER optical devices in the national backbone. Repeater prototypes were also evaluated.

- In 2011, a frequency signal was transmitted on 540 km from Paris to Reims using 468 km of RENATER fibre and bypassing two in-line amplification sites. In the Reims point of presence, the ultra-stable signal coming from one of the fibres was looped back to the other fibre to the LPL. The circuit is shown in Figure 7.5 below. In this way, both link end points were located in LPL, making it easier to evaluate the transmission and stability performance of the optical link. Stability of the transmitted clock signal was at least 10 fs (residual phase fluctuations in a 10 Hz filter). This result demonstrates the feasibility of the architecture deployed to achieve a long-haul circuit.

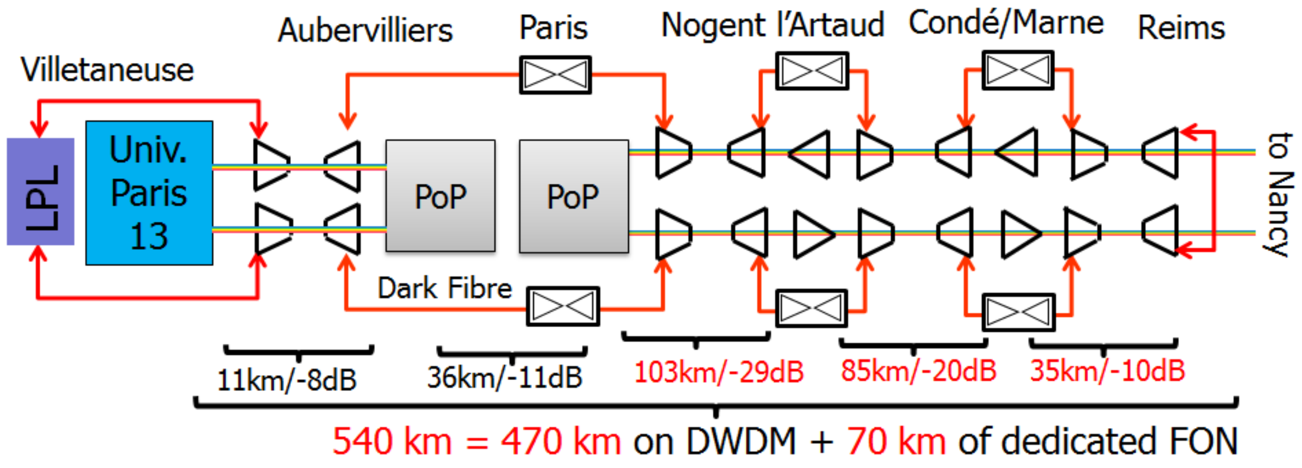


Figure 7.5: Circuit deployed in RENATER in 2011

- A new extension has already been deployed to Nancy (1,100 km). Bi-directional amplifiers will be installed on the link in 2012. The middle-term goal is to reach the German border to interconnect to an ultra-stable signal coming from German laboratories, as shown in Figure 7.6 below.

Figure 7.6: Links re-engineered for SYRTE project in RENATER (2010-2011)

7.5.3 MEFINEV+ Project

RENATER, LNE-SYRTE and LPL among other organisations applied successfully for funds to launch, in 2012, a project called Metrological Fibre Network with European Vocation (MEFINEV+). The purpose of this project is to build a national infrastructure on RENATER fibre, capable of disseminating ultra-stable frequency signals to scientific laboratories that need to work with high-accuracy instruments. European interconnections by cross-border fibres will also be studied within this project.

As illustrated in Figure 7.7 below, ultra-stable signals will be emitted at the Paris Observatory and then disseminated to French laboratories.

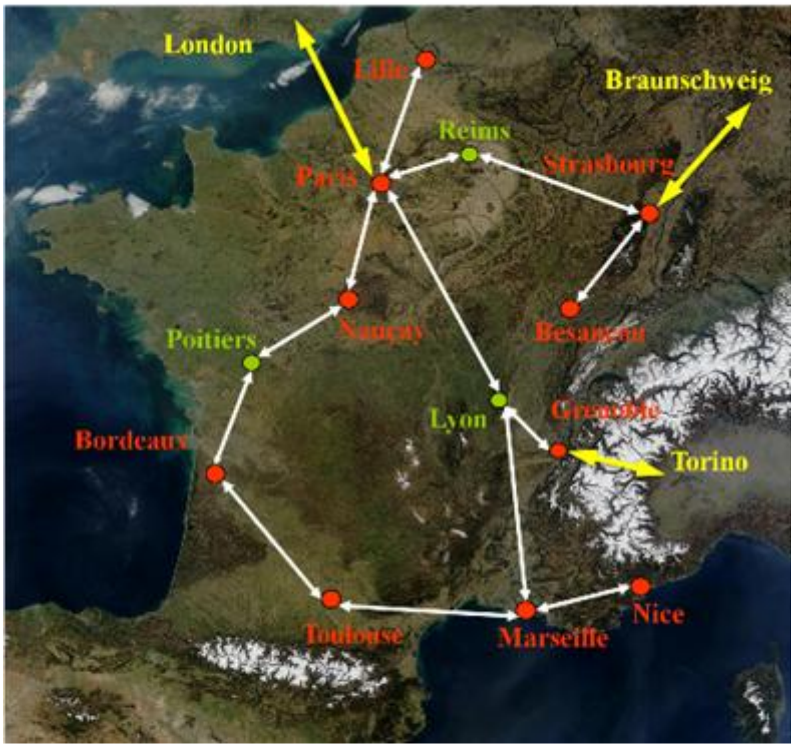


Figure 7.7: MEFINEV+ project infrastructure

Other key features of the project include the following:

- A closed loop will be built between Paris, Bordeaux, Marseille and Lyon to explore the physical behaviour of transmitted signals (Sagnac effect).
- French scientific laboratories (represented by red circles in Figure 7.7) will also be served by the project's circuit to benefit from the ultra-stable frequency.
- The existing FR-DE cross-border fibre will be used to reach German laboratories and a new CBF will be built in 2012–2013 between France and Italy to interconnect to Italian scientists.
- Discussions are also ongoing between SYRTE, LPL and DANTE to find a solution to reach the UK using GÉANT's dark fibre.

The construction of this architecture was anticipated in 2010 and 2011 with a first deployment of equipment in the Paris area and from Paris to Reims (see Section 7.5.2).

7.5.4 Adaptation of Backbone Links

Two technical solutions were studied to add the project wavelength to the RENATER backbone. The transmission medium could be made either of dark fibres newly bought for the project or of existing DWDM links from the RENATER backbone. The latter approach was selected, enabling SYRTE and LPL to benefit from RENATER's mesh and connectivity while avoiding the costs due to fibre location or Indefeasible Right of Use (IRU).

Consideration was then given to the selection of DWDM channel used to transmit the project signal. As the RENATER-5 architecture had been conceived for DWDM transmission on C band (1565 nm to 1530 nm), a wavelength from this spectrum part was reserved to minimise disturbance to production traffic. Channel availability was studied on each backbone link, to avoid, as far as possible, selecting a wavelength that required the modification of too many existing DWDM circuits. Moreover, the viability of interconnection with neighbouring NRENs was ensured by selecting the same #44 DWDM channel.

In order to inject the project DWDM channel into the dark fibre, dedicated Optical Add-Drop Multiplexers (OADMs) were inserted in each fibre segment between the RENATER optical devices already in production (see Figure 7.8). A review of optical budgets on each impacted link was made in RENATER to guarantee the continuity of existing DWDM circuits while inserting new equipment and therefore adding losses to links. From this design review, it was possible to derive the power adjustments necessary on the transceivers and amplifiers during the deployment. Finally and as expected, a loss average of 3 dB was observed between the RENATER equipment on each end point. During link re-engineering a further check was made to ensure that the link capacity (maximum amount of DWDM channels supported by the network design) would not be affected by the OADM insertions.

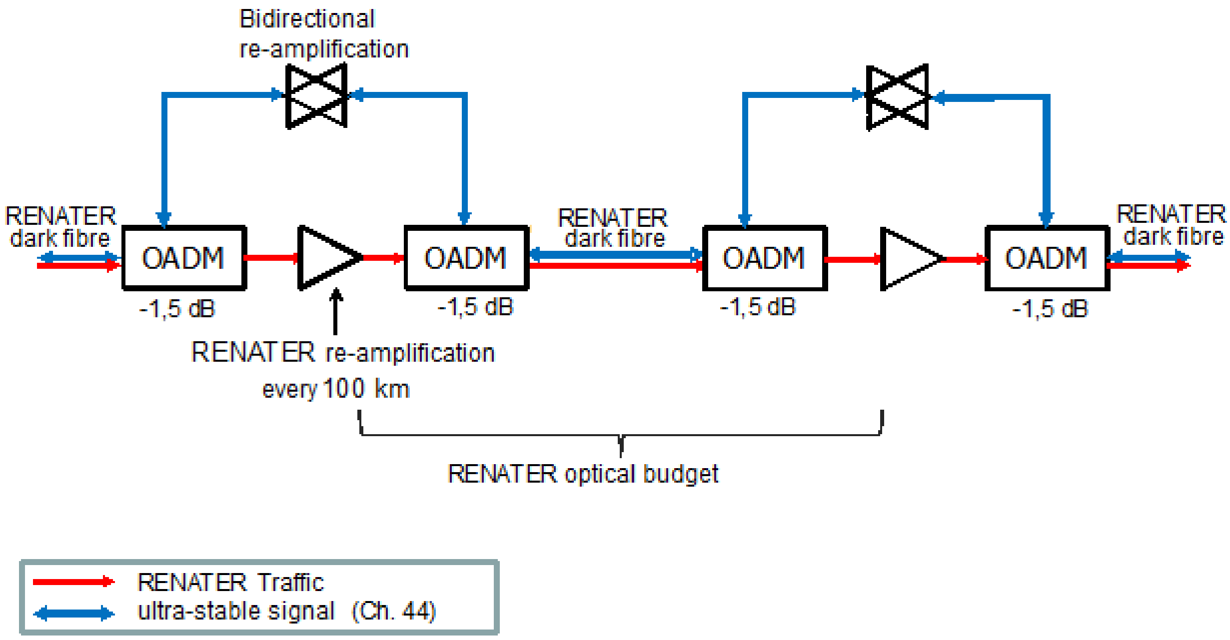


Figure 7.8: RENATER equipment bypassing

Moreover, a theoretical study verified that no impact on the optical supervision channel should have been expected. This channel, which uses a 1510 nm wavelength, cannot be re-amplified by the EDFA classically used by telecommunication networks and therefore an additional loss on optical budgets could have been harmful to its transmission.

7.5.5 Next Steps

Following these first successful transmissions of an ultra-stable frequency on long-haul links between Paris and Reims, the next step is to complete the deployment of the MEFINEV+ national infrastructure to ensure the capacity of the project partners to develop a scalable solution. Among other actions, it will be necessary to define solutions and procedures to manage a pool of third-party optical devices (transceivers, repeaters) deployed in RENATER. Consideration will also be given to partner responsibilities, for example, to define workflows to troubleshoot a circuit incident involving fibre operators, several optical-device manufacturers, scientific laboratories and RENATER.

A study will also be required to evaluate the impact of Raman amplification on the ultra-stable signal, because this type of amplification is frequently used on RENATER links in some specific regions.

7.5.6 Summary

It was demonstrated that RENATER's DWDM backbone could be adapted for the transport of photonic services dedicated to specific scientific projects, provided that the allocated wavelengths respect the ITU-T DWDM grid and that emitted powers can be tolerated by backbone equipment. Moreover, the production traffic was not disrupted by link re-engineering.

A new technique of ultra-stable optical link was demonstrated (see Section 7.5.2), which should make it possible to interconnect European metrology laboratories and to compare a very large number of optical clocks. The best frequency references developed in these metrology laboratories then becomes available to any laboratory, opening the way to a wide range of applications in the field of high-accuracy measurement: beacon networking in astrophysics, fundamental constants measurements, satellite link tests, fundamental physics tests, geodesic applications, etc.

7.6 Conclusions

This chapter has proposed a new photonic approach to network services, with the emphasis on pilot and expected applications. Parameters for these applications have been identified and some have been demonstrated by European NRENs. Current trends indicate that the research and education community requires new non-standard applications that are not supported by ISPs. Only the collective effort of European NRENs can deliver such applications on a large scale to the research and education community.

8 Conclusions

Optical networks have seen rapid development during the course of the GN3 project. Coherent modulation formats for 40G and 100G are now commodity and advanced control planes, allowing restoration in the optical domain, are under development from almost all vendors. The next steps with regard to capacity are 400G and 1T, which are already in the pipeline. In addition, the concept of gridless WSS components is gaining momentum, enabling sub-band allocation rather than channel allocation for newer DWDM networks in the near future, opening the way for more efficient use of the optical spectrum. The vendors of DWDM equipment appear, to some extent, to have embraced the concept of open optical systems, allowing alien wavelengths or other photonic services to traverse their systems and, in some cases, even to benefit from the features of their control plane.

The individual chapters in this report have touched on many of the topics mentioned above, and show the NREN community's increasingly mature understanding of the new requirements and opportunities that the next generation of optical networks will bring. The most highly promoted feature of the new systems is the arrival of 100G transmission cards, which, in principle, could free 90% of the channels used within a 10G system. A critical question is how the 100G channel behaves in a legacy system that consists of dispersion compensated lines and 10G neighbour channels. JRA1 Task 2 has performed extensive testing to explore this issue, in both laboratory and field environments, and found that, in general, 100G can traverse legacy 10G networks with a performance similar to that of existing 10G connections.

The 100G tests described in Chapter 2 demonstrated that it is possible to introduce new modulation formats within an existing network. Furthermore, two of the 100G field tests were conducted within an "alien wavelength" environment, where the 100G signal source was emitted by a manufacturer other than the legacy system. These tests were conducted under strict supervision, to avoid interference to the live traffic on the legacy network. Nonetheless, it is important to highlight that support for alien waves is incomplete, with further work needed to improve support for OAM&P and joint engineering rules for the mixed modulation formats. A better understanding of alien wavelengths is therefore important for the NREN community if new modulation formats are to traverse their networks on a regular basis.

Chapter 4 investigated the obstacles that are currently blocking the way to alien wavelengths as a service, and found that a multi-vendor, multi-domain simulation tool is needed in order to be able to build reliable and predictable alien waves. JRA1 Task 2 created a simulation tool for a specific alien wavelength running between Amsterdam and Hamburg, and compared its simulated properties with the results from the field test. The work revealed that achieving an accurate match between the results of the simulations and the field tests it highly complex, as even small inaccuracies in the power settings of amplifiers or optical channels can have a disproportionate impact on non-linear effects. The simulations and field tests both showed strong XPM and

SPM for the mix of 40G PM-QPSK and 10G OOK NRZ modulation formats, indicating that careful engineering is required on such a link. CAPEX / OPEX considerations were also investigated, and the authors found that a significant CAPEX reduction can be achieved by deploying alien wavelengths.

An understanding of alien wavelengths and the underlying photonic mechanisms is even more important when the optical network is used to carry non-transmission signals such as time and frequency synchronisation signals. The use of alien wavelengths by these types of signals is motivated not by reasons of cost but because they are purpose-specific applications that require an open optical design with unhindered access to the optical spectrum. As described in Chapter 7, JRA1 Task 2 is engaged in several photonic service activities that demonstrate it is possible to adapt legacy DWDM networks to meet these services' demanding requirements.

The implementation of Photonic Services benefits from open optical platforms that allow access to the optical spectrum without imposing too many restrictions on the incoming signals with regard to bit rate, modulation format, grid placing and power level. While gridless operation remains a feature for the future, most of the necessary functionalities were present in the laboratory tests performed on one of the newest DWDM platforms, the ALU 1830 PSS, which were described in Chapter 6. The tests covered not only deployment of Photonic Services, but also traffic and protection tests, as well as an in-depth look at the colourless and directionless structure of the product. In the context of Photonic Services and alien waves, the investigation demonstrated that this vendor has the ability to mark and track alien waves through the use of a card that adds a small amplitude modulation to all incoming signals, enabling the system to manage and control the alien wave, including restoration through GMPLS (although this was not available at the time of testing). It is important to note that the automated control and tracking of alien waves is novel, and their introduction could lead to a general acceptance of the idea of an open optical spectrum.

GMPLS, with its associated automation and restoration capabilities, is regarded by many as a key enabling factor for introducing automated multi-domain path creation into the optical domain. Taking into consideration also the fact that new optical systems will operate at 100G (and above in the near future), multiplexing at the optical node level will be needed in order to provide 10G services to the customer. JRA1 Task 2 therefore thought it important to investigate the performance of GMPLS within the optical domain. The tests described in Chapter 3 demonstrated that GMPLS performs well, with restoration times similar to those observed in Layer 3 devices when the number of tunable devices is limited. The restoration time is independent of fibre length and number of ILAs but increases by roughly 30 seconds per ROADM. In the context of automated path creation, the restoration times are equal to the time it would take to provision an optical path end to end, and the 4 minutes measured for a path consisting of 6 ROADMs is a significant improvement compared to today's procedures. The test demonstrated that GMPLS is now a robust and reliable control plane in the optical domain, and can be used as the foundation for introducing automation into the optical domain.

A requirement for the efficient use of GMPLS, and automation in general, is the property of the optical node to be both colourless and directionless in order to switch/restore channels from one direction to another. This property usually comes at the expense of a more complex node structure, with additional components and increased power consumption. The newer coherent modulation formats simplify the general DWDM design by removing DCUs but this comes at the expense of increased power consumption in the transponders. Therefore while the new generation of DWDM systems have many additional features from an optical perspective, the question as to whether they reduce the CO2 footprint remains open. Chapter 5 presented the Consumption Indicator, which can be used to evaluate optical systems' power consumption. Vendors of communication equipment are already aware that the rapid increase of energy consumption associated with global communication cannot continue, and have started cross-vendor initiatives such as GreenTouch “to increase network energy efficiency by a factor of 1000 from current levels” [GreenTouch]. (GreenTouch is addressing ICT as a whole, including servers, mobile devices, transmission equipment, etc.) Optical networks are possibly not the initial targets of these efforts, but if rules like those imposed in British Columbia, Canada (where all public sector institutions have to be carbon neutral [StArnaud]) become widespread, then the CI value will be an important consideration in procurement as part of the assessment of needed features versus the OPEX associated with power and CO2 taxes.

This document only focuses on topics related to the optical layer and as such cannot be regarded as fully representative of typical NREN networks, which usually also consist of an IP and electrical/ethernet switching layer. The latter have also been investigated in GN3 and a combination of the reports from all these investigations is needed to obtain a complete overview of possible future networking topologies.

Designing NREN optical networks is complex, and depends on many variables such as offered services, number of customers, legacy network, etc. These make it difficult to give a general recommendation for the NREN community. Each NREN is different, and historically they have chosen many different approaches. JRA1 Task 2 has therefore not analysed or benchmarked any network topology with regard to the investigated topics. However, the document does indicate that, if an all-optical network is pursued, the following features have been tested and can be implemented:

- Optical transparency – allowing alien wavelengths and, to some extent, photonic services.
- Directionless and colourless features – allowing better control and switching of wavelengths, alien as well as native.
- Advanced control plane, e.g. GMPLS – allowing automation and restoration of optical paths.
- Coherent transmission – allowing support for future modulation formats, but care must be taken if photonic services needing chromatic dispersion compensation are implemented.
- Mixing NRZ and coherent signals – allowing coherent signals on legacy networks. An optical simulation tool is recommended to check possible non-linear effects, especially in 655 fibres.

As with any investigation, new questions and ideas have arisen in the course of JRA1 Task 2’s research that require further attention. The Task has been granted resources for an additional year (GN3 Y4) to investigate a subset of topics of interest, including:

- End-to-end provisioning of Photonic Services.
- Transmission speeds above 100G.
- Extension and expansion of the alien wavelength tests, to include more NRENs and additionally to implement an OAM&P solution.

With the rapid speed of developments in optical systems, research-oriented activities must be flexible and ready to alter course if common trends change. That was the case with JRA1 Task 2 with regard to investigating transverse compatibility between transponders at the start of GN3, where the focus was switched to optical transparency and open optical systems. It is hoped that further topics of significance and interest to

NRENs that emerge during GN3 Y4 will be investigated in the successor project GN3+, the planning of which is well under way.

Each chapter and set of conclusions in this document can be regarded as guidelines for the NREN community with regard to near-future optical network builds. The topics addressed and investigated closely follow the trends and roadmaps of the majority of optical vendors, and special emphasis has been placed on topics that are important to the NREN community. Taking into consideration the economic crisis and the declining revenues of optical vendors, the level of vendor involvement JRA1 Task 2 has achieved is encouraging. It indicates that the vendors consider the NREN community to be a worthy partner in research-oriented projects, and that coordination through GN3 strengthens their voice. While NRENs may not be able to influence the vendors' roadmaps as customers, collaboration through projects such as GN3 enables a better flow of ideas and requirements between NREN users with specific use cases and the vendors' R&D. The results and conclusions of such collaboration are difficult to measure, but it is the authors' opinion that the vendors' understanding of the NREN community as a whole has grown substantially during the course of GN3.

Appendix A 100G Circuit Deployment

A.1 Optical Equipment and Software Activities Detail

A.1.1 Software Upgrade

The initial software available on the DWDM equipment installed in 2008, and the management software (Site Manager, OMEA), were not compatible with the equipment needed to deploy a 100G circuit. The 2008 tender requirements stipulated that equipment and software had to provide support for 40G lambdas, 100G equipment not being available at the time of the green-field installation. Also, the 100G Ethernet IEEE 802.3ba standard, to be used on 100G client interfaces, was still in the development stage.

On OME 6500, in-service software upgrade is supported. The management software (Site Manager) used on management workstations needed to be upgraded too, in order to have compatibility with the new equipment software and new 100G equipment.

Upgrading the software on OME 6500 involved the following phases:

1. Preparatory phase:
    - Prepare new software to be available on a computer with the new version of Site Manager already installed or on an OMEA server.
    - Verify existing cards' compatibility with the new software version.
    - Backup all existing configurations, disable scheduled backup operations and stop any maintenance and provisioning activities.
    - Prepare a table with relevant information about the nodes to be upgraded (e.g. IP addresses, node name, running software version, etc.).
    - Minimal software removal from the file-system of the OME 6500 shelf processor to be upgraded; old unused software releases, if any, are deleted too.
    - Deliver minimal new software to OME 6500 using Site Manager or OMEA.
2. Upgrade phase:
    - Check upgrade – hardware baseline compatibility check, verify new software files are present and have correct checksums (5 minutes).

    - Load upgrade – check upgrade is done again; if it is OK, then the new software is copied from SP file system to secondary flash (10 minutes).
    - First invoke upgrade – SP is restarted with the new software from the flash memory (10–15 minutes).
    - Second invoke upgrade – if the new software contains loads for existing cards, these are delivered to the cards (20–35 minutes).
    - Commit upgrade – all circuit cards and SP are committed, new software is copied to the primary flash zone (10 minutes).

3. Post-upgrade phase:
    - Fully delete old software version and fully deliver new software to SP.
    - Cold restart circuit cards that have new firmware; this includes the 100G cards.
    - Backup all systems data.

To save time, it is recommended that some activities in the upgrade phase are done outside the maintenance window. This does not include first and second invoke upgrade sub-phases. The upgrade phase takes about 70–80 minutes, from which about 20–25 minutes can be saved if the remaining eligible actions are done outside the maintenance window. The pre- and post-upgrade phase durations depend on various factors, the most important ones being network size and the hardware configuration of each node.

A.1.2 Shelf Processor SP-2

The shelf processor (SP) is the central part of OME 6500 and performs important activities such as:

- Manages and monitors software for all installed circuit cards.
- Manages communications with other equipment.
- Maintains shelf provisioning database.
- Maintains security and event history.
- Generates alarms.

According to Ciena documentation, the SPs initially installed in the RoEduNet DWDM network OME6500 were not suitable for 100G due to hardware/software compatibility issues, and a shelf processor upgrade was needed for the OME 6500 installed in NOC Iasi. The new OME 6500 needed for NOC NAT was ordered with SP-2.

The SP-2 shelf processor is an enhanced version of the SP shelf processor, and offers improvements related to computational speed, memory and storage. Related to this, the main differences between SP and SP-2 are:

- Computational speed x2.5.
- Storage x10.
- Memory x4.

A.1.3 OCLD Card

The line side of the 100G circuit is provided by the OCLD card. This card uses electronic dispersion compensation. Key 100G OCLD general characteristics are:

- One fixed OTU4 line tunable interface, compliant to C band 50 GHz DWDM grid.
- Uses CO-FDM dual polarisation QPSK modulation.
- High polarisation mode dispersion (PMD) tolerance and compensation.
- Automatic VOA and EDFA control on the line interface receiver.
- Support for performance monitoring of OTU4, ODU4, physical layer.

The 100G OCLD card occupies 2 slots. In the OME6500 equipment with 14 slots available in RoEduNet, for the given situation, the 100G OCLD card may be installed only in slots 5-6 and 11-12. Other types of installation, such as regeneration cases, permit OCLD card pairs in slots 3-4/5-6 and 9-10/11-12.

Technical specifications for OCLD (as specified by Ciena) used in the RoEduNet installation are shown in Table 8.1.

<table>
<tr><td colspan="2">Connector type</td><td colspan="2">LC</td></tr>
<tr><td colspan="2">Power consumption</td><td colspan="2">285 W typical, 316 W maximum</td></tr>
<tr><td colspan="2">Chromatic dispersion</td><td colspan="2">±32000 ps/nm</td></tr>
<tr><td colspan="2">PMD tolerance</td><td colspan="2">10 ps</td></tr>
<tr><td colspan="2">Reachability</td><td colspan="2">1000 km</td></tr>
<tr><td colspan="2">End-to-end unidirectional latency through 100G pack</td><td colspan="2">66 us</td></tr>
<tr><th colspan="2">Transmitter</th><th colspan="2">Receiver</th></tr>
<tr><td>LASER modulation</td><td>eDC100 CO-FDM dual polarisation QPSK</td><td>Receiver type</td><td>coherent</td></tr>
<tr><td>Line rate</td><td>116.4 Gbit/s</td><td></td><td></td></tr>
<tr><td>Tunable wavelength range</td><td>1527.99 nm to 1565.50 nm, 50 GHz spacing</td><td>Wavelength range</td><td>1527.99 nm to 1565.50 nm</td></tr>
<tr><td>Transmit power</td><td>-11 dBm to -1 dBm</td><td>Operating range</td><td>-26 dBm to 7 dBm</td></tr>
<tr><td></td><td></td><td>Damage level</td><td>16 dBm</td></tr>
<tr><td>Tx monitor accuracy</td><td>±0.8 dB</td><td>Rx monitor accuracy</td><td>±0.5 dB</td></tr>
</table>

		Rx OSNR	14.5 dB

Table 8.1: 100G OCLD characteristics

Although 100G OCLD cards are also available with 600 km reachability, which fits the distance between the installed 100G circuit endpoints, the 1000 km type was preferred so that another, longer path could be used to move the circuit if necessary.

A.1.4 OCI Card

The client part of the 100G transceiver is provided by an OCI card. Options for the OCI card were 10 x 10G and 100G; RoEduNet opted to use the 100G OCI.

This type of card is used to map a 100GE client onto an adjacent 100G OCLD line interface card at 104.8 Gbit/s via the OME 6500 backplane. The OCI card must be equipped with a CFP optical module that supports 100G Ethernet. RoEduNet uses 100GBASE-LR4 CFP (~1310 nm, LAN WDM, 800 GHz) modules with SC connectors for the client side.

Performance monitoring for the OCI card supports ODU4 layer and Ethernet 100G facilities information collecting.

Like the OCLD card, the 100G OCI card also occupies 2 slots. In 14-slot OME 6500 it may be installed in slot positions 3-4 and 9-10, i.e. to the left of the OCLD card. The same power requirements as for OCLD must be considered. Typical power consumption for a 100G OCI card is 78 W; for power budget calculations a maximum value of 94 W must be considered. Also, CFP power needs to be added; this means 21 W for typical consumption and 24 W for maximum power needed. (See also Table 2.2 on page 36.)

A.2 100G Circuit Provisioning and Installation Detail

Site Manager software was used in order to complete the following software configuration steps:

- Physical installation of 100G components, e.g. OCLD and OCI cards, including CFP module. The cards were installed in slots 3-6 in NOC Iasi and slots 9-12 in NOC NAT.
- Configure ODU cross-connect between OCLD and OCI.
- Edit OCLD OTM4 Tx parameters (wavelength, Tx power).
- Add client facility and edit parameters, if needed.
- Connect at both circuit ends the line (service) interface of the OCLD card to CMD.
- Create the logical definition of the new circuit. This involves adding photonic cross-connects at each ROADM site in the circuit path where the circuit changes the optical domain.
- Define Tx/Rx adjacencies for the new lambda. Here some important parameters are configured for each direction:

  - Tx – type of transmitting equipment, circuit identifier, expected far-end address, modulation class, paired Rx.
  - Rx – type of receiver, expected far-end address, paired Tx.
- Add newly defined circuit to the optical domain controller system (ODC), which automatically optimises and adapts the optical parameters of the circuit.

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Glossary

A/D	Analog/Digital
AFEC	Advanced Forward Error Correction
ALU	Alcatel-Lucent
ASE	Amplified Spontaneous Emission
AW	Alien Wavelength
B	Byte
BPSK	Binary Phase-Shift Keying
BEC	Bit Errors Corrected
BER	Bit Error Rate (or Ratio)
BERT	Bit Error Rate Test/Testing
BEV	Bundesamt für Eich- und Vermessungswesen
CAPEX	Capital Expenditure
CBF	Cross-Border Fibre
CBR	Constant Bit Rate
CC-IN2P3	Computing Centre of the National Institute of Nuclear Physics and Particle Physics
CD	Chromatic Dispersion
CERN	European Organisation for Nuclear Research
CFP	C Form-factor Pluggable
Ch.	Channel
CI	Consumption Indicator
CLI	Command Line Interface
CMD	Channel Mux/Demux
CO-FDM	Coherent Optical Frequency-Division Multiplexing
CPL	Common Photonic Layer
CRS	Carrier Routing System
CV	Common View
DC	Dispersion Compensating or Compensation
DCF	Dispersion Compensating Fibres
DCM	Dispersion Compensation Module
DCU	Dispersion Compensation Unit
DF	Dark Fibre
DGD	Differential Group Delay
DP-QPSK	Dual Polarisation Quadrature Phase-Shift Keying
DSP	Digital Signal Processing or Processor
DTU	Technical University of Denmark

DWDM	Dense Wavelength-Division Multiplexing/Multiplexed
E2EMon	End-to-End Monitoring System
EM	Element Manager
E-NNI	External Network-to-Network Interface
eDC	electronic Dispersion Compensation
EDFA	Erbium Doped Fibre Amplifier
FBG	Fibre Bragg Gratings
FC	Fibre Channel
FDM	Frequency-Division Multiplexing
FE	Fast Ethernet
FEC	Forward Error Correction
FPGA	Field Programmable Gate Array
FSP	Fibre Service Platform
G	Gigabit
GbE	Gigabit Ethernet
Gbit/s	Gigabit per second
GE	Gigabit Ethernet
GMD	Group Mux/Demux
GMPLS	Generalised Multi-Protocol Label Switching
GPS	Global Positioning System
HD	High Definition
HD-SDI	High-Definition Serial Digital Interface
HMM	Hide Markov Model
I/O	In/Out
IaDI	Intra-Domain Interface
ICMP	Internet Control Message Protocol
ICT	Information and Communication Technology
ILA	In-Line Amplifier
IPE	Institute of Photonics and Electronics
IPTV	Internet Protocol television
IrDI	Inter-Domain Interface
IRU	Indefeasible Right of Use
ISP	Internet Service Provider
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardisation Sector
JRA1	GN3 Joint Research Activity 1, Future Networks
JRA1 Task 2	JRA1 Task 2, Photonic Switching and Experimental Photonic Facilities
LAN	Local Area Network
LCoS	Liquid Crystal on Silicon
LHC	Large Hadron Collider
LM	Light Manager
LNE-SYRTE	Laboratoire national de métrologie et d'essais – Système de Références Temps-Espace
LPL	Laboratoire de Physique des Lasers
LOS	Loss of Signal
MAC	Medium Access Control

MEFINEV+	Metrological Fibre Network with European Vocation
MEMS	Micro Electro-Mechanical Systems
MS	Metrospan
ms	Millisecond
MSA	Multi-Source Agreement
MSC	Modular Service Card
MSTP	Multiservice Transport Platform
MUX	Multiplexer
MVAC	Multiple Variable Attenuator Card
MW	Megawatt
MWh	Megawatt Hour
NE	Network Element
NF	Noise Figure
NGN	Next-Generation Network
NLE	Non-Linear Effect
nm	nanometre
NOC	Network Operations Centre
NOC NAT	National NOC
NREN	National Research and Education Network
NRZ	Non-Return-to-Zero
OADC	Optical Add/Drop Coupler
OADM	Optical Add-Drop Multiplexer
OAM&P	Operation, Administration, Maintenance and Provisioning
OBS	Optical Burst Switching
OC	Optical Carrier
OCI	Optical Channel Interface
OCLD	Optical Channel Laser Detector
OCS	Optical Circuit Switching
ODC	Optical Domain Controller
ODUk	Optical Channel Data Unit where k=1/2/2e/3/3e2/4
OEO	Optical-to-Electrical-to-Optical
OIF	Optical Internetworking Forum
OME	Optical Multiservice Edge
OMEA	Optical Manager Element Adapter
OMS	Optical Multiplex Section
OOK	On-Off Keying
OPEX	Operating Expenditure
OPS	Optical Packet Switches or Switching
OSA	Optical Spectrum Analyser
OSI	Open Systems Interconnection
OSNR	Optical Signal-to-Noise Ratio
OSS	Operations Support System
OTM	Optical Transport Module
OTN	Optical Transport Network
OTS	Optical Transport Section

OTU	Optical Transport Unit
PDF	Probability Density Function
PDM	Polarisation-Division Multiplexing
PHY	Physical Layer
PIC	Photonic Integrated Circuit
PMD	Polarisation Mode Dispersion
PolMux	Polarisation Multiplexing
PoP	Point of Presence
PPS	Pulse per Second
PS	Photonic Service or Services
ps	picosecond
PSM	Protection Switching Module
PSS	Photonic Service Switch
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
R	Receiver
R&D	Research and Development
R&E	Research and Education
RF	Radio Frequency
ROADM	Reconfigurable Optical Add-Drop Multiplexer or Multiplexing
RU	Rack Unit
SAN	Storage Area Network
SDH	Synchronous Digital Hierarchy
SDI	Serial Digital Interface
SER	Symbol Error Rate
SFP	Small Form-factor Pluggable
SP	Shelf Processor
SPM	Self-Phase Modulation
SSA	Small Switch Array
STM	Synchronous Transport Module
SVAC	Single Variable Attenuator Card
T	Transmitter
TcCFR	SC Telecomunicatii CFR SA
TDEV	Time Deviation
TRV	Transceiver
TWRS	TrueWave Reduced Slope
ULH	Ultra-Long Haul
UNI	User Network Interface
UTC	Coordinated Universal Time
VOA	Variable Optical Attenuator
VoIP	Voice over IP
VPI	VPItransmissionMaker
W	Watt
WAN	Wide Area Network
WB	Wavelength Blocker

WDM	Wavelength-Division Multiplexing
WLCG	Worldwide LHC Computing Grid
WSS	Wavelength Selective Switch
XFP	10 Gigabit Small Form Factor Pluggable
XPM	Cross-Phase Modulation