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Abstract
This deliverable reports on the work carried out by GN4-1 Joint Research Activity 1 Future Network Topologies, Task 1 Current and Future Network Technologies to investigate the trends and technologies in optical transport networks and how these can be managed to help deliver the concept of zero-touch connectivity. It covers increasing utilisation of the photonic layer; spectral sharing and alien waves; frequency and time distribution; and network dynamicity.

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Executive Summary

This white paper reports on the work carried out by GN4-1 Joint Research Activity 1 Future Network Topologies, Task 1 Current and Future Network Technologies (JRA1 T1) to investigate the trends and technologies in optical transport networks and how these can be controlled and managed to help deliver the concept of zero-touch connectivity.

In the future, the National Research and Education Networks (NRENs) will face a number of requirements from user, technology, cost and management perspectives. One way to address some of these requirements is by introducing the concept of zero-touch connectivity (ZTC): the user should have access to a given service with a given quality wherever he is, and whatever the requested data is. While this vision provides simplicity to the user, behind the scenes it requires massive technological advances, interoperability and dense integration.

In order for the zero-touch vision to become a reality, certain strict requirements are imposed on the underlying infrastructure in terms of both high capacity and flexible use. Technologies and approaches for increasing the capacity of the photonic layer investigated by JRA1 T1 include new modulation schemes, such as four-level pulse-amplitude modulation (PAM-4); space-division multiplexing (SDM) technologies, such as multi-core fibres (MCF) and few-mode fibres (FMF); and extending the optical spectrum beyond the C band. The Task has also reviewed the work being done by the standardisation bodies with regard to high bitrate standardisation. Importantly, from the point of view of guiding the deployment of the next generation of NREN infrastructure, the Task has conducted experiments to evaluate these developments in the NREN environment. Based on the successful results of its testing, PSNC has now established and configured two operational 400G links.

With regard to flexible use, the Task has reviewed the results obtained by the GN3plus Open Call project REACTION, which evaluated flexible optical networks (FON); investigated the latest FON developments and experimental research, including transponder interoperability; and surveyed the FON functionalities currently available or planned. A summary of all the results is provided here.

Combining optical waves operated by different administrative entities over the same fibre and the same optical transport network (alien waves and spectral sharing) can lead to significant cost savings. However, these approaches also present a number of challenges from a technical, organisational and procedural point of view. The multi-domain optical modelling tool (MOMoT), originally developed during a GN3plus Open Call project and further developed by JRA1 T1 during GN4-1, helps to meet the technical challenges by predicting the impact of injecting alien waves into a host system. The results have been validated by tests in a production NREN network. Further studies and experiments – including by JRA1 T1 participants – have helped identify prerequisites and best

practice. The reliability and integrity of alien waves have been sufficiently proven for NRENs to have transitioned AW services into production for both client and own use.

Another obvious advantage of the ZTC vision is the ability to seamlessly provide connectivity for high-demanding services. This includes services with extremely high demands for clock stability, which therefore need efficient and accurate synchronisation and distribution of time in several levels and layers, and ultra-stable frequency. Joint experiments with synchronisation between peers into different NREN domains have taken place, together with experiments that investigated by how much it is possible to adjust the precision time protocol while still maintaining the necessary quality in terms of jitter and delay. This work is needed to realise the ZTC vision of being able to seamlessly provide links with given requirements for delay, jitter and synchronisation functions.

Given the above functionalities, the Task has investigated the overall control and orchestration of transport network resources, addressing this challenge both theoretically and experimentally. Software-defined networking (SDN) as a control mechanism for transport networks has gained attention lately, and JRA1 T1 has reviewed the research, including demonstrations of new extensions to the OpenFlow protocol. In practical terms, the Task has carried out tests to evaluate different orchestration mechanisms, including application-based network operations (ABNO), and an open network operating system (ONOS) has been investigated as part of a specific NREN use case to provide efficient – and more optimal – resource utilisation in restoration processes.

This deliverable presents the results of comprehensive research and experimentation by JRA1 T1 into the current trends and technologies in the physical and logical domains of optical transport networks, with the aim of supporting the ZTC vision that will help NRENs to meet the high-demanding requirements they face from user, technology, cost and management perspectives. While challenges and the need for further testing exist in many of the areas analysed, the work has identified several promising solutions and, of particular importance, has assessed these in the NREN environment. This has led to the deployment of enhanced operational services in some NRENs, and it is hoped that the findings will similarly guide other NRENs in the development of their next-generation infrastructure.

1 Introduction

In the future, the National Research and Education Networks (NRENs) will face a number of requirements from user, technology, cost and management perspectives. One way to address some of these requirements is by introducing the concept of zero-touch connectivity (ZTC), which both meets user needs and simplifies the processes for the network operator. In short, the user should have access to a given service with a given quality wherever he is, and whatever the requested data is. This vision provides the user with a much simpler interface to the network. However, behind the scenes it requires massive technological advances, interoperability and dense integration.

GN4-1 Joint Research Activity 1 Future Network Topologies, Task 1 Current and Future Network Technologies (JRA1 T1) addresses a number of these technical challenges and will provide some of the building blocks needed to build automated services and guide the deployment of the next generation of NREN infrastructures. This also means that network borders and domains are becoming dispersed from the user perspective, forcing GÉANT, NREN and commercial service providers to cooperate in a federated manner in order to provide the ZTC.

To fulfil this ZTC vision, it is important to understand and evaluate the current trends and technologies in the physical and logical domains. This deliverable reports on the work carried out in JRA1 Task 1, which investigates the technology trends in optical transport networks and how these can be controlled and managed according to ZTC.

The first and – from the user's point of view – often neglected requirement for ZTC is suitable capacity in the underlying infrastructure. Without this hard physical footprint, not even the best orchestration tool in the world can satisfy the users' needs. The Task has focused significant effort on investigating viable paths to increased capacity, including the physical functionality to utilise this capacity optimally. In this deliverable, the focus is on the latest trends for increasing the capacity of the photonic layer and efficient use within and outside traditional network boundaries and domains. In particular, combining optical waves operated by different administrative entities over the same fibre and the same optical transport network can lead to significant cost savings. However, such alien wave approaches also present a number of challenges from a technical and political point of view. In this deliverable, some of the most important technical challenges are considered, and a modelling and estimation tool to predict the impact of injecting alien waves into a host system, which Task 1 has further developed and validated during GN4-1, is described. Integration of such a tool into the provisioning process can save hours and days of time spent on commissioning new channels and as such can add value to the vision of zero-touch connectivity.

Another obvious advantage of the ZTC vision is the ability to seamlessly provide connectivity for high-demanding services. This includes services with extremely high demands for clock stability, which therefore need efficient and accurate synchronisation and distribution of time in several levels and layers. For example, for atomic clocks, physical layer frequency synchronisation is needed. This is addressed in Section 4 and, among others, joint experiments conducted with synchronisation between peers into different NREN domains are described. In addition, applications such as audio and video with strict quality requirements need a synchronised clock, which for these applications can be achieved with functionality on layer 2 and layer 3. This deliverable reports on experiments that investigated by how much it is possible to adjust the precision time protocol while still maintaining the necessary quality in terms of jitter and delay. This work is needed to realise the ZTC vision of being able to seamlessly provide links with given requirements for delay, jitter and synchronisation functions.

Given the above functionalities it makes sense to discuss the overall control and orchestration of the transport network resources. In its work, the Task has addressed this challenge theoretically and experimentally. Software-defined networking (SDN) as a control mechanism for transport networks has gained attention lately and in this deliverable the research is reviewed and demonstrations of new extensions to the OpenFlow protocol are described. Also, tests to evaluate different orchestration mechanisms are reported. Application-based network operations (ABNO) is investigated as one approach to orchestrate network (in IT) resources, and an open network operating system (ONOS) is investigated as part of a specific use case to provide efficient – and more optimal – resource utilisation in restoration processes. This work is based on some experiments in the NORDUnet network, which was used for the use case.

The deliverable is organised as follows:

- Section 2 discusses the technological trends for increasing the capacity of each symbol, spectrum, core and fibre. The technologies for enabling flexible optical networks are also addressed.
- Section 3 addresses alien waves and spectral sharing. This includes reporting on further development of the multi-domain optical modelling tool (MOMoT) and validation of this. Best practices with regard to alien waves from other projects and NREN partners are also included.
- Section 4 considers time and frequency synchronisation and distribution. It is mainly divided into synchronisation in the physical layer and using protocols in layer 2 and 3.
- Section 5 addresses control and orchestration of resources using SDN, ABNO and ONOS.
- Section 6 aims to draw together the conclusions and recommendations.

In addition, further details about the multi-domain optical modelling tool (MOMoT) are provided in Appendix A, and details of the transport extensions in the OpenFlow protocol are provided in Appendix B.

2 Increasing Utilisation of the Photonic Layer

In order for the zero-touch vision to become a reality, certain strict requirements are imposed on the underlying infrastructure for both the transport network and the photonic layer. These requirements can be grouped into high capacity and flexible use. Although the end user will rarely interact directly with these layers, the importance of the two for capacity and flexibility remains. Without the necessary available capacity, not even the best orchestration mechanism can deliver anything useful to the end user. Furthermore, flexibility mechanisms such as flexible optical networks (FONs) are needed to utilise the provided capacity satisfactorily.

With these requirements in mind, this section addresses the capacity-enabling technologies, which the Task foresees as being needed in the future. Section 2.1 presents a survey of some of the most important trends for increasing the capacity of the fibre, which focus on the core, the spectrum and the bit density. The study includes reports on some partner experiments, which validated the usefulness of the techniques in an NREN context.

Enablers for providing flexibility were evaluated in detail in a previous project: the GN3plus Open Call project Research and Experimental Assessment of Control plane archiTectures for In-Operation flexgrid Network re-optimisation (REACTION). In Section 2.2, the ideas and latest trends are further investigated and in particular the development and interoperability of sliceable bandwidth variable transceivers are studied, based on research by the project partners, in addition to a survey on the available vendor equipment related to FON.

2.1 Growing Capacity Trends

In this section the technologies that enable higher core capacity are reviewed. The emerging modulation schemes allow *more bits per symbol* and four-level pulse-amplitude modulation (PAM-4) is investigated in particular as it is simpler and thus more cost-efficient than its quadrature phase-shift keying (QPSK) and quadrature amplitude modulation (QAM) counterparts. Another way of increasing bandwidth is by providing *more modes per core*, which is why space-division multiplexing (SDM) techniques are investigated in an NREN context, discussed in Section 2.1.1.2. The next step, *more cores per fibre* and *broader spectrum utilisation* is also evaluated (Section 2.1.2). Section 2.1.3 addresses the standardisation trends in the major bodies for high-speed communication and, finally, Section 2.1.4 reports on participating NREN partners' experimental deployments, some of which have been upgraded for the operational networks.

2.1.1 New Formats and Emerging Modulations

2.1.1.1 *Pulse-Amplitude Modulation (PAM)*

Different modulation formats have been discussed in both GN3plus *Deliverable D12.3 (DJ1.1.1) Future Network Architectures* and GN3 *Deliverable DJ1.2.1: State-of-the-Art Photonic Switching Technologies* [1; 2].

High-order modulation formats are today widely used on the line side of the transmissions line, such as dual polarisation QPSK (DP-QPSK) in 100G 50 GHz dense wavelength division multiplexing (DWDM) implementations, but non return to zero (NRZ) is still used on the client side. As a result of the emerging higher bitrate transmissions channel and requirement for even higher bitrate client-side interfaces, the IEEE 802.3bs 400G group, with the objective of defining a 400 Gb/s physical layer specification, decided to use PAM-4 as the new modulation format for the 400G physical layer with reach above 2 km. Using a higher-order modulation format reduces the requirement for higher bandwidth devices. PAM-4 uses four-level amplitude detection to double the transmission capacity with the same bandwidth optical devices, but at the expense of lower signal-to-noise (SNR) performance when compared to NRZ [3; 4].

The traditional NRZ modulation consisting of 1s and 0s may be considered as PAM-2 (pulse-amplitude modulation, two-level). Figure 2.1 shows baseband signalling and eye diagrams for PAM-2-NRZ and PAM-4 [5]

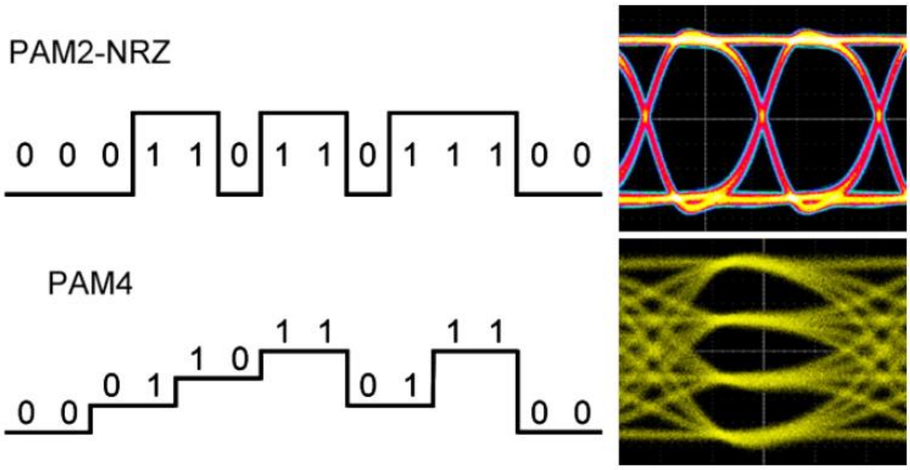


Figure 2.1: PAM-2-NRZ and PAM-4: baseband signalling and eye diagrams [5]

The point to note here is the emerging of higher-order modulation techniques on the client side. In the first stage, the simplest form of it is PAM-4.

2.1.1.2 *Space-Division Multiplexing (SDM)*

The term space-division multiplexing (SDM) is usually used with brand-new technologies, namely multi-core fibres (MCF) and few-mode fibres (FMF). Multi-core and few-mode fibres have been a favourite research topic for a few years now. Amplification techniques are essential for practical deployment of space-division multiplexing and such amplifiers are already available. The European Conference on Optical Communications (ECOC) and the Optical Fibre Communication Conference and Exposition (OFC) are the main events presenting the latest achievements in this area. It is an open question as to whether NRENs want to participate in such SDM experiments, because it seems that 100 Gb/s and 200 G/s systems are sufficient from the capacity point of view, and that there is a greater current need for NRENs to address topics such as software-defined networking and zero-touch networking.

Few-Mode Fibres

When starting to talk about few-mode fibres (FMF), reference may be made to the old and rather well-known multi-mode fibres (MMF). Such fibres support hundreds of "modes" and have been considered as the cheaper and not-so-excellent fellow of single-mode fibres. MMF do transmit different modes, but all of these modes represent a single piece of information and cannot be distinguished until some new compensating techniques, based on digital signal processing (DSP), such as multiple input multiple output (MIMO), are deployed. MIMO techniques are known from wireless and other systems, but their deployment in optical networking is not so common (high frequencies of light compared to radio frequencies). DSP techniques used for modern coherent optical transmission systems have been known for many years and have been used in modems and wireless. It was the terahertz area (i.e. very high speeds) of optical wavelengths that was the main obstacle when realising DSP in silicon or other semiconductors.

However, MMF do support more than 100 spatial modes at the C band – with the same 125 micron cladding diameter, which is very important because standard fusion splicers, connectors and other existing pieces of equipment can be used. Of course, MIMO must deal with the most detrimental effect – crosstalk. *Space-Division Multiplexing: The Future of Fiber-Optic Communications* [6] provides a detailed description of the advantages of this MMF-based SDM, including the use of wavelength selective switches (WSSs) and erbium-doped fibre amplifiers (EDFA) and Raman amplifiers.

The problems with MMF-SDM can be solved when just a few modes are transmitted via optical fibres. Many useful observations can be found in *Optical Amplifiers for Space Division Multiplexed Transmission* [7]. FMF usually support up to 15 modes, but this number is limited to 6 because in the few-mode amplifiers available today, six-mode EDFAs are the highest mode-count EDFA practically demonstrated. The first EDFA supporting three modes was demonstrated in 2011. From this it is apparent that SDM is not a trivial area: adding just three spatial modes takes several years of intense research, and such experiments are demonstrated in only a few excellent research centres around the globe. The limiting factor is differential modal gain (DMG), which must be minimal. The current situation is that 10 spatial modes can be supported with the help of optimisation of Er distribution in the fibre. Different pumping techniques are used to achieve low DMG and both core-pumped and cladding-pumped schemes have been proposed and investigated, with the latter considered to be more promising.

Multi-Core Fibres

Multi-core fibres (MCF) are another promising direction of SDM, but are not without other problems. Fibres with up to 30 cores are available, although matching amplification techniques are difficult to find. Splicing and connecting such fibres are of course also much more challenging.

Nationwide research activities in Japan are summarised in *PAM-4 Design Challenges and the Implications on Test* [4]. High-tech MCF are described, with attenuation of 0.181 dB/km and crosstalk in the order of 90 dB/km has been demonstrated for 7-core fibres. Transmission distances for 32 QAM signals are expected to reach 10,000 km. Few-mode techniques are coupled together with multi-core fibres to achieve even higher spatial channel counts and 36-core and 3-mode fibres have been demonstrated. Coupling of MCF into SMF are described and two methods – free-space and fibre-bundled – are investigated. The latter method is considered to be more suited to cost-effective production. Multi-core and few-mode amplifiers are mentioned and problems are similar to ones described in *Development of Space Division Multiplexing Technologies in Japan* [8].

2.1.2 Extending the Optical Spectrum Beyond the C Band

Data transmission in L band (1570 nm – 1605 nm) represents mature technology. It is used in both coarse wavelength division multiplexing (CWDM) and dense wavelength division multiplexing (DWDM) multiplexes. It benefits from the same technologies as transmission in C band, especially spectral suitability of EDFAs. It is a matter of fact that L-band EDFAs work on the tail of emission Er^{3+} characteristics and due to this lower absorption/emission effectivity they originally required 7–10 times longer doped fibres and high pump powers compared to C band. Long doped fibres suffered from higher polarisation mode dispersion (PMD) and higher influence of non-linearity due to increased four-wave mixing. This problem has been solved by introducing very heavy doped Er fibres, reducing fibre length from 50–100 m to 12 m [9]. Slightly worse performance-to-cost ratio (worse OSNR, more expensive doped fibre and more powerful pumps) of L band over C band transmission is due to the fact that L-band transmission is used solely on G.653 fibres (they are not suitable for DWDM in C band due to the presence of zero chromatic dispersion wavelength in this band) or in combination with traditional C-band transmission. Raman amplification regains interest with the rise of coherent transmission systems and is also available for L band [10]; due to slightly lower pump attenuation it is even more effective than for C band. Practical experience has shown that such necessary L-band parts as transceivers, passives or wavelength cross-connects are manufactured in smaller volumes and therefore available with longer delivery times compared with C-band parts.

The last low-loss transmission band in standard single-mode fibre represents S band (1460 nm – 1530 nm). Unfortunately, due to the unavailability of mature amplification technology complementary to EDFA technology, the S band is not used for DWDM transmission. The proposed thulium-doped fibre amplifiers typically suffer from low efficiency, a high noise figure or the necessity for environmentally sensitive fibres, e.g. fluoride based [11]. The potential of distributed Raman amplification for S band is also limited due to high fibre attenuation at pump wavelength around 1420 nm. Therefore this band is often used for CWDM or passive optical networks.

An alternative solution to improve the bandwidth capacity of optical transport systems is to go further beyond the optical L-band window [12]. Using the 2000 nm range is being extensively discussed between optical transport system vendors and research groups at universities as they actually develop the key components such as amplifiers. Moreover, it is also being discussed between optical transport system vendors and users – telco operators. Such a shift could result in 130 THz of total available bandwidth for the optical transmission system. The required optical equipment, mainly the amplifiers that limit the transmission distance, is already available, namely thulium (TDFA) and holmium (HDFA). The combined amplification window it is possible to achieve is 1650 nm – 2150 nm (TDFA – 34 THz; HDFA – 8.3 THz). The optical fibre technology is also already available. For example, the ZBLAN fibre has minimum attenuation of 0.65 dB/km at 2700 nm. Other material combinations give minimum attenuation at around the 2000 nm range and the theoretical loss of 0.03 dB/km is possible to achieve. High-speed silicon photodetectors for the 2000 nm range already present the desired parameters specification [13]. It can be used in avalanche mode and manufactured in 220 nm silicon-on-insulator (SOI) technology. Silicon photonics, 2D materials (such as graphene and MoS_2) and metamaterials could also further improve transceiver technology and reduce the manufacturing costs, and are already available. One of the examples is low-loss all-optical modulation in a graphene-coated fibre.

As can be seen, existing technologies can lower the manufacturing costs for the new type of equipment and can significantly improve the available bandwidth for the optical transmission system. The most promising aspect is to use technologies and manufacturing techniques for photonic systems that heavily use experience from the silicon industry.

Figure 2.2 shows fibre optic transmission bands with attenuation values for typical SMF fibre. As noted above, attenuation curves are different for each type of advanced fibre.

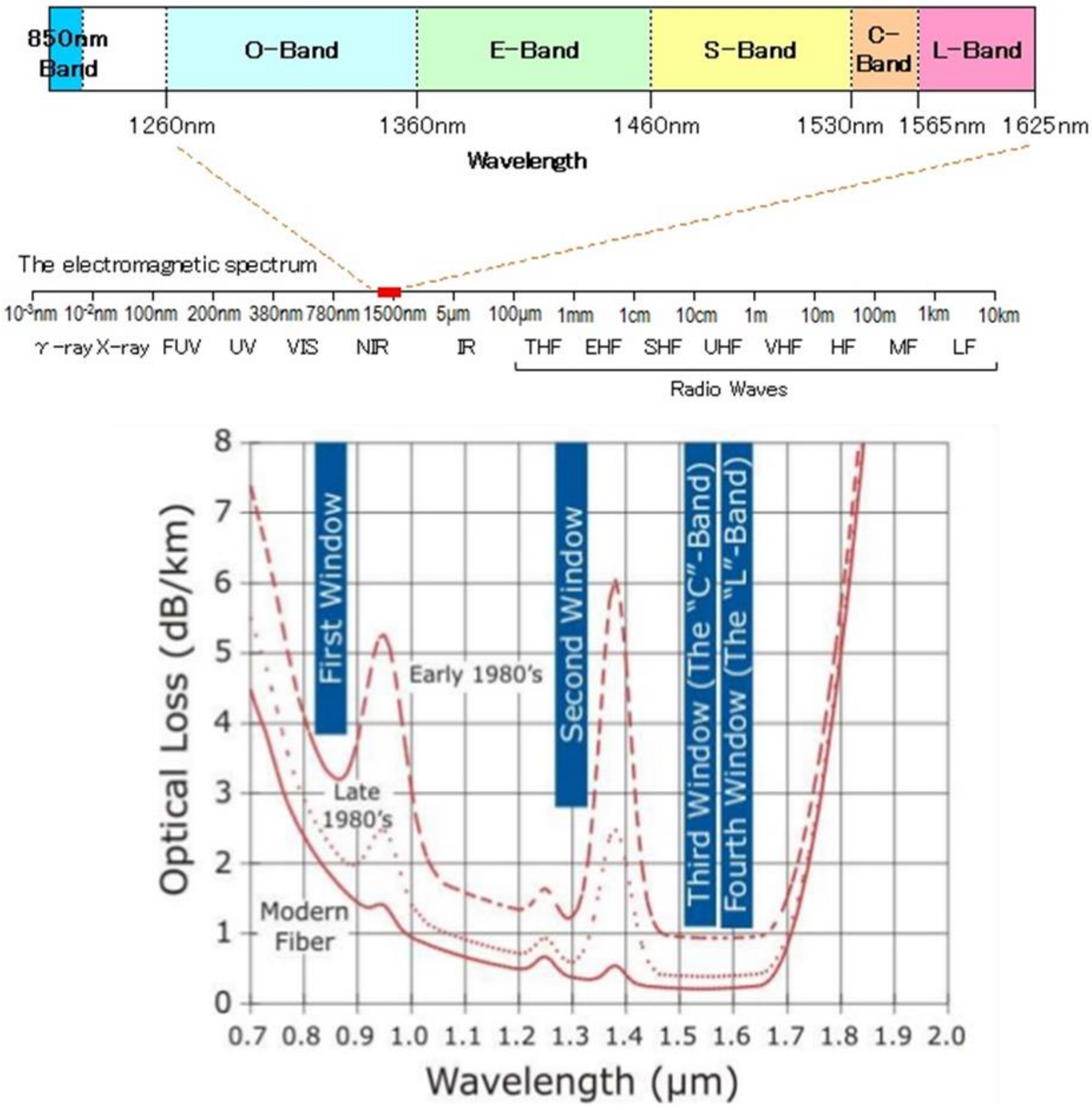


Figure 2.2: Fibre optic transmission bands for standard SMF fibre

An overview of the pros and cons of the different optical bands discussed is provided in Table 2.1.

Band	Pros	Cons
O, S	• Inexpensive transponder technology • Best solution for FTTx systems; performance/cost	• Short to mid range • Limited performance • Cannot be used for DWDM
C, L	• Suitable for high-performance systems • Lowest attenuation for typical optical fibres • Can be used for DWDM	• Expensive transmitter technology

Band	Pros	Cons
	• Large potential for further development • Inexpensive amplifiers	
U/XL and above	• Potentially high bandwidth for high-performance systems	• Currently not used • Requires new fibres and amplifiers • Expensive development

Table 2.1: Overview of different optical bands and properties

2.1.3 High-Bitrate Standardisation and Beyond 100G

Important progress in high-bitrate standardisation is delivered by three standardisation bodies. The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) focuses on LAN network and Ethernet protocols development. The International Telecommunication Union Telecommunication Standardisation Sector (ITU-T) is more involved in transport network protocols. Finally, the Optical Internetworking Forum (OIF) builds on top of IEEE and ITU-T frameworks; OIF involves vendors and interested parties to define details of a specific standard.

2.1.3.1 *Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA)*

The IEEE 802.3 Working Group develops standards for Ethernet networks. IEEE 802.3 has several efforts underway concerning specification of Ethernet operating at rates of 25 Gb/s, 50 Gb/s, (next gen) 100 Gb/s, 200 Gb/s, and 400 Gb/s [14]. These activities are organised under different study groups and task forces. The study groups develop the idea from the early stage and try to obtain Project Authorisation Request (PAR) approval and define its objectives. PAR is the means by which standards projects are started within the IEEE-SA. PARs define the scope, purpose, and contact points for the new project. Task forces takes the idea from the approved PAR stage to when the standard is approved. This process normally takes several years.

Currently there are a number of active study groups and task forces under IEEE 802.3 [14]. Those related to the high bitrate standardisation include:

- IEEE P802.3bs 400 Gb/s Ethernet Task Force.
- IEEE P802.3by 25 Gb/s Ethernet Task Force.
- IEEE 802.3 50 Gb/s Ethernet Over a Single Lane Study Group.
- IEEE 802.3 Next Generation 100 Gb/s Ethernet & 200 Gb/s Ethernet Study Group.

802.3bs Task Force

The scope of the 802.3bs Task Force is to define Ethernet media access control (MAC) parameters, physical layer specifications and management parameters for the transfer of Ethernet format frames at 400 Gb/s. The Call for Interest was held in March 2013 and the first study group meeting was held in May 2013. The study group set objectives to provide physical layer specifications that support link distances of at least 100 m over MMF, at least 500 m over SMF, at least 2 km over SMF and at least

10 km over SMF, and support optional 400 Gb/s attachment unit interfaces (AUIs) for chip-to-chip and chip-to-module applications. Final approval of the standard is planned by the end of 2017.

There have been discussions regarding expanding the scope to apply to Ethernet format frames at 100 Gb/s and 200 Gb/s too.

The development of 50 Gb/s electrical I/O will enable the development of devices and systems capable of supporting multiple Ethernet rates, which are based on integer multiples of 50 Gb/s, such as 100 GbE, 200 GbE, and 400 GbE. The discussions have been on how the multi-lane 100G/200G solutions might be rolled into the 802.3bs project.

50G Project

The primary goal of the 50G project is to choose solutions that provide the lowest cost, lowest power and smallest size for 50G. It has been initiated by two study groups in order to study the two (related) topics of an optimised single-lane project for 50 Gb/s Ethernet and the multiple-lane variants of that.

NG 100/200 GbE Study Group, NGOATH

Progress to date for the IEEE 802.3 Next Generation 100 Gb/s Ethernet & 200 Gb/s Ethernet Study Group [15; 16] includes:

- Some clear consensus around the various 50G single-lane objectives.
- Some clear consensus that some aspects of 200G (logic primarily, maybe AUI, maybe SMF) are all potentially incremental work items that .3bs could take on.
- A lot of confusion around 100G objectives as people realise the challenges of the work due to PMD choices or backwards compatibility issues.
- Some early thinking that some of the multi-lane PMDs that leverage these new 50G single-lane work could be done with the same project as single-lane work (with 100G caveat from above).

Changed Objectives

At the January 2016 interim meeting (a joint meeting of the 50G and NGOATH Study Groups) some major changes to the objectives of the groups mentioned above (50G, NG 100/200 GbE and .3bs) were suggested. The list of changes can be found on the group's web pages at IEEE [17].

According to these changes, P802.3bs should support a MAC data rate of 200 Gb/s in addition to 400 Gb/s, and will provide physical layer specifications that support 200 Gb/s operation over:

- At least 2 km of SMF.
- At least 10 km of SMF.

P802bs support for 400 Gb/s operation over the media and distances below have not changed:

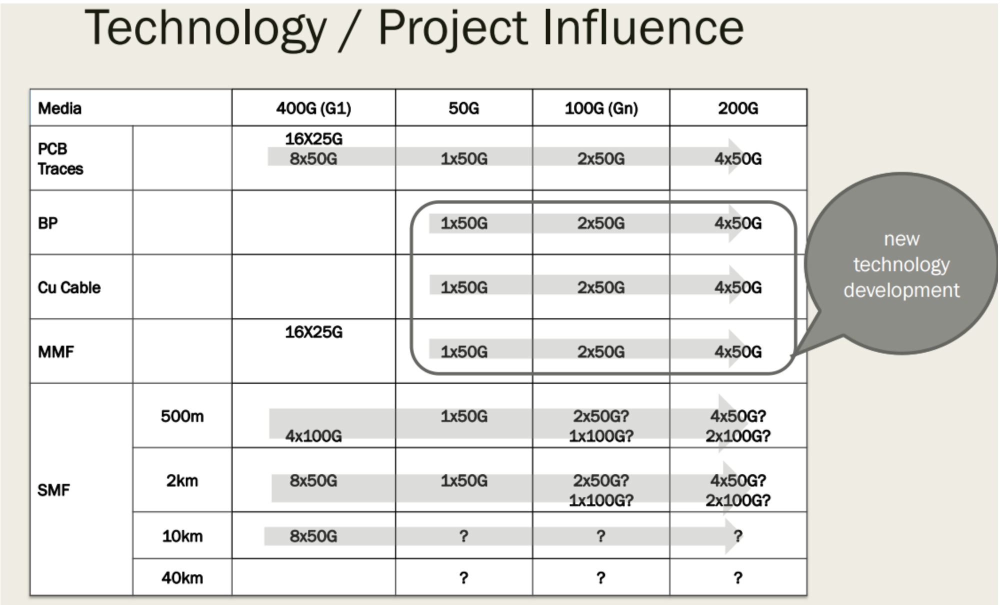
- At least 100 m of over MMF.
- At least 500 m of over SMF.
- At least 2 km of over SMF.

- At least 10 km of over SMF.

As the single-mode specification of 200 Gb/s has moved to 8023.bs, the multi-mode specifications will become part of a new task force that will also tackle 50 Gigabit Ethernet [18].

The new task force will also work with the objectives defined in [17], namely.

1. Define single-lane 50 Gb/s PHY for operation:
    - Over copper twin-axial cables.
    - Printed circuit board backplane.
    - MMF with lengths up to at least 100 m.
    - SMF with lengths up to at least 2 km.
    - SMF with lengths up to at least 10 km.
2. Define 200 Gb/s PHY for operation over:
    - Copper twin-axial cables.
    - Printed circuit board backplane.
    - MMF with lengths up to at least 100 m.
3. Define a two-lane 100 Gb/s PHY for operation over copper twin-axial cables.
4. Define a two-lane 100 Gb/s PHY for operation over a printed circuit board backplane.
5. Define a two-lane 100 Gb/s PHY for operation over MMF with lengths up to at least 100 m.



Media		400G (G1)	50G	100G (Gn)	200G
PCB Traces		16X25G 8x50G	1x50G	2x50G	4x50G
BP			1x50G	2x50G	4x50G
Cu Cable			1x50G	2x50G	4x50G
MMF		16X25G	1x50G	2x50G	4x50G
SMF	500m	4x100G	1x50G	2x50G? 1x100G?	4x50G? 2x100G?
	2km	8x50G	1x50G	2x50G? 1x100G?	4x50G? 2x100G?
	10km	8x50G	?	?	?
	40km		?	?	?

Figure 2.3: Suggested new technology development in 802.3bs [15]

2.1.3.2 *International Telecommunication Union – Telecommunication Standardisation Sector (ITU-T)*

The ITU-T focuses on OTN standardisation (including G.709, G.798, G.872 and other Recommendations). Work is underway on what is referred to as “Beyond 100G” OTN (B100G, for short), which is a more complex landscape than that of 100G where one modulation format addressed a wide variety of applications over almost any reach (100G DP-QPSK in a 50 GHz frequency slot was good up to about 4,000 km). There are emerging new clients above 100G (200 GbE, 400 GbE and Flex Ethernet) that need to be carried, and, in general, the modulation format used and the effective bitrate per wavelength vary according to reach (e.g. the same hardware may support 100G DP-QPSK, 150G DP-8QAM, or 200G DP-16QAM, with the reach decreasing from about 4,000 km to 1,000 km as the bitrate increases). Single wavelength 400G or above is less seen, just because the reach tends to get too short to be interesting. Therefore, in addition to having a variety of wavelength rates, another principle of the B100G work is that new transport containers are defined that are distributed to multiple wavelengths or sub-carriers. What is being worked on is a modular frame format that can be used to describe containers such as the current ODUk in increments of 100G. This container may be mapped over a single wavelength or distributed over several wavelengths.

While many of the signals carried over optical networks (possibly including multiple wavelengths in aggregate) are multiples of 100G in size, some odd rates such as 150G exist. These will be addressed from a management perspective by describing these signals in the 100G modular format but indicating that a certain amount of the payload capacity (represented as a number of “tributary slots”) is unavailable over a particular interface. Since these types of interfaces are single-vendor line-side interfaces, standards will not specify a specific frame format for them, only the information content that needs to be carried over these interfaces [19].

For client interfaces, just as an interface was defined for a client OTU4 that reused the 100 GbE pluggable modules, B100G client interfaces are expected to be specified based on 400 GbE pluggable modules and bonded 100 GbE pluggable modules.

2.1.3.3 *Optical Internetworking Forum (OIF)*

The OIF is focused on flexible Ethernet and flexible coherent DWDM frameworks. Flex Ethernet is a method that supports non-link aggregation group (LAG) bonding of 100G Ethernet PHY to create larger rate flows, and channelisation supporting multiple smaller rate flows (e.g. 10G, 25G) carried over a group of bonded PHYs. One reason this is significant in the higher bitrate discussion is that it was originally envisioned that the first client needing to be carried over OTN larger than 100G would be 400 GbE, which is currently scheduled for completion at the end of 2017. Flex Ethernet may provide >100G clients through the bonding of multiple 100G earlier than this [20]. Another relevant OIF project is the Flex Coherent DWDM framework, which would ensure that the right components are being specified to allow building of the kinds of interfaces that are emerging in OTN networks (DSP-driven interfaces that can support different modulation formats with different effective bitrates depending on reach) [21].

2.1.4 NREN Partner Experiments

2.1.4.1 *PSNC*

In June 2015 PSNC conducted 400G transmission tests in the PIONIER network. The tests were prepared and run together with ADVA Optical Networking. The trial was conducted over the PIONIER network, 385 km of fibre, reaching between two research and education centres in Poznań and

Warsaw. The system transported the data continuously for 14 hours without any block errors. The test system used software-defined optics to deliver flexible data rates and modulation. This means the network can intelligently scale from 200 Gb/s to 300 Gb/s to 400 Gb/s and from QPSK to 8QAM to 16QAM as required. All configuration and modulation options were tested and evaluated by the PSNC team.

The 400 Gb/s trial was conducted using the operational PIONIER network resources. PIONIER is a consortium of Polish research and education organisations and its network is operated domestically by PSNC. For the purpose of the trial, the system was configured with two 200 Gb/s wavelengths operating at 16QAM within an optical super-channel with spectral width of 100 GHz. The system also featured reconfigurable optical add/drop multiplexers (ROADMs) and hybrid amplifiers. During the 14 hours of testing, the trial showed an error-free transmission with optical-signal-to-noise ratios of approximately 20 dB.

During the 400G tests, results were presented live at the TERENA 2015 conference. Following the tests, PSNC has established and configured an operational 400G link between the Poznań and Warsaw nodes. PSNC has also established a second 400G link that is used for its own work and projects.

2.1.4.2 *CESNET*

CESNET tested and worked with the ECI Apollo platform and Czech Light® Open DWDM together [22]. The ECI Apollo system has excellent features and is very compact, which makes testing easier. During the trial, CESNET pushed both Apollo and Czech Light® Open DWDM to their limits by proving that 200 Gb/s DP-16QAM signals can reach further than 2,000 km over the standard single-mode fibre G.652. CESNET and ECI experts also successfully demonstrated alien wavelengths capabilities, which are gaining momentum, not only for NRENs but also in the global telco world.

It should be mentioned that 400G systems are almost exclusively 2x200G, with 200G transmitted over one DWDM channel with DP-16QAM. True 400G signals using DP-64QAM were not available in 2015 (when the CESNET testing took place) and it looks as though almost all vendors went from 100G with DP-QPSK (also known as DP4QAM) to 200G with DP-16QAM, with 400G being considered as the next step for really huge data-demanding applications.

CESNET and ECI also tested transmission over a cascade of narrow DWDM filters, with 200G DP-16QAM signals able to be transported over 8 narrow DWDM multiplexers.

The last important point to note is the mixed scenario whereby “slow” and amplitude-modulated signals such as 10G and 10G Ethernet were tested together with phase-modulated coherent 100G and 200G signals. Again, results were very satisfactory and both encouraging and promising for mutual transmission of high-speed coherent phase-modulated signals and really slow amplitude-modulated signals (i.e. less than 1 Gb/s), which are used by new applications such as accurate time transfer or remote sensing. As far as CESNET is aware, such experiments with real equipment are rather rare.

The main results of the testing trial were:

- The successful extension of all-optical reach to 2,000 km with single-channel 200G DP-16QAM.
- High bitrate traffic can be easily transported as alien wavelengths over CESNET's production network.
- 200 Gb/s signals can be transmitted over 240 km in a single hop, without the challenging, and potentially hazardous, Raman amplification.
- New ways of compensation for chromatic dispersion in dark fibre lines with mixed coherent and legacy amplitude-modulated signals.

2.1.5 Conclusions

A number of new formats and modulations currently offer the ability to increase the capacity of the fibre. This has now evolved to the client side, and the simplest, and thus most cost-effective, form of it at this stage is PAM-4. It uses four-level amplitude detection to double the transmission capacity, but at the expense of lower signal-to-noise (SNR) performance when compared to NRZ, currently the main client-side high-order modulation format.

With regard to increasing capacity by delivering more modes per core and more cores per fibre, the SDM technologies of FMF and MCF are promising, but not without problems. FMF usually support up to 15 modes, but this is limited to 6 because of constraints imposed by the available few-mode amplifiers. MCF with up to 30 cores are available, but again, matching amplification techniques are difficult to find, and splicing and connecting such fibres are much more challenging. Few-mode techniques can be combined with multi-core fibres to achieve even higher spatial channel counts. However, it is debateable whether SDM is currently relevant to NRENs, whose needs today can be met by traditional 100 Gb/s and 200 Gb/s systems.

In respect of broader spectrum utilisation, existing technologies can lower the manufacturing costs for the new type of equipment and can significantly improve the available bandwidth for the optical transmission system. The most promising aspect is to use technologies and manufacturing techniques for photonic systems that heavily use experience from the silicon industry.

Important progress in high-bitrate standardisation is being delivered by three standardisation bodies. Within the IEEE-SA, which focuses on LAN and Ethernet protocols development, the IEEE 802.3 Working Group has several efforts underway concerning specification of Ethernet operating at rates of 25 Gb/s, 50 Gb/s, (next gen) 100 Gb/s, 200 Gb/s, and 400 Gb/s. ITU-T is more involved in OTN network protocols, and work is underway on B100G, where, in general, the modulation format used and the effective bitrate per wavelength vary according to reach. Another principle of the B100G work is that new transport containers are defined that are distributed to multiple wavelengths or sub-carriers. A modular frame format is being worked on that can be used to describe containers such as the current ODUk in increments of 100G.

GÉANT partners PSNC and CESNET have conducted successful 400G transmission experiments. The PSNC test system used software-defined optics to deliver flexible data rates and modulation. This means the network can intelligently scale from 200 Gb/s to 300 Gb/s to 400 Gb/s and from QPSK to 8QAM to 16QAM as required. All configuration and modulation options were tested. Following the tests, PSNC has established and configured two operational 400G links. The CESNET test demonstrated the successful extension of all-optical reach to 2,000 km; that high-bitrate traffic can be easily transported as alien wavelengths over CESNET’s production network; that 200 Gb/s signals can be transmitted over 240 km in a single hop, without Raman amplification; and new ways of compensation for chromatic dispersion in dark fibre lines with mixed coherent and legacy amplitude-modulated signals.

2.2 Flexible Optical Networks

While Section 2.1 addressed technologies and concepts for increasing the available bandwidth, in this section the focus is on the flexible use of the available capacity using flexible optical networks (FON). First, Section 2.2.1 presents a review of the results obtained by the GN3plus Open Call project REACTION, which evaluated FON. This is continued by a survey of the latest FON developments in Section 2.2.2 and experimental research in Section 2.2.3. Finally, Section 2.2.4 reports on some available implementations at commercial vendors.

2.2.1 Results of GN3plus REACTION

The GN3plus Open Call project Research and Experimental Assessment of Control plane archiTectures for In-Operation flexgrid Network re-optimisation (REACTION) [23] designed a flexible optical network scenario enabling software-controlled super-channel transmission. Innovations were introduced in the context of data plane, control plane, and routing and spectrum allocation strategies.

2.2.1.1 *Bandwidth Variable Transponders*

Before reviewing the results of the REACTION project, it is useful to discuss one of the key building blocks in flexible optical networks, namely, bandwidth variable transponders (BVT). BVT have been recently deployed in vendor multi-rate transponders. BVT make it possible to tune a certain set of transponder functions in a point-to-point connection (one flow and one destination). A further development of BVT has led to sliceable bandwidth variable transponders (S-BVT), which are not commercially available yet. S-BVT provide the ability to allocate a certain amount of capacity on one or several independent flows and transfer the flows to multiple destinations. The S-BVT also make it possible to select from among different modulation formats, forward error correction (FEC) types, baud rates and optical spectrum occupancy (12.5 GHz granularity, flexi-grid). Enabling flexi-grid and super-channel features in S-BVT requires that all nodes along the link path support flexi-grid functionalities, but the other variables in S-BVT could be implemented in a fixed-grid network environment.

Figure 2.4: Transponder evolution path

2.2.1.2 *Results*

Data Plane

From a data plane architectural perspective, the REACTION project enhanced a bandwidth variable transponder supporting 1 Tb/s multi-carrier transmission to support, in addition to dynamic adaptation of transmission parameters, the sliceable functionality. Specifically, such sliceable BVT are capable of creating multiple optical flow units (i.e. sub-carriers) that can be aggregated or independently routed according to the traffic requirements.

The use of sliceability during provisioning and restoration in flexible grid optical networks was addressed. Specifically, a scheme was proposed to exploit the possibility of establishing/recovering an optical connection as a single super-channel or as a number of independent sub-carriers. Both centralised and distributed implementations of the proposed schemes were evaluated through simulations in a GMPLS-based scenario.

Results showed that, despite the introduced spectrum overbuild, the utilisation of sliceability permits the amount of established/recovered traffic to increase.

Control Plane

From the control plane perspective, the REACTION project developed a solution relying on a GMPLS-based distributed control plane with a path computation element (PCE) architecture. Specifically, a novel PCE architecture was investigated. The architecture relies on an active stateful front-end PCE, in charge of routing and spectrum allocation (RSA) computations and a back-end PCE in charge of performing complex network re-optimisation solutions. The PCE architecture also relies on the northbound distribution of link-state (LS) and traffic-engineering (TE) information through border gateway protocol (BGP) (i.e. BGP-LS), utilised to provide the PCE architecture (also in the context of a hierarchical implementation for multi-domain scenarios) with adequate networking information.

Routing and Spectrum Allocation

Novel routing and spectrum allocation (RSA) algorithms were designed and evaluated in the context of flexible optical networks and, specifically, to be encompassed within the proposed PCE architecture.

S-BVT capabilities were evaluated in the context of restoration and for in-operation network planning operations:

- **Restoration**: multi-path recovery and bitrate squeezing were applied to maximise the amount of restored bitrate, also exploiting limited portions of spectrum resources along multiple routes. A software-defined network (SDN) architecture was introduced to adequately support the S-BVT configuration. The SDN architecture was applied to experimentally assess that the overall re-configuration time upon failure detection was concluded within two seconds, largely dominated by the proprietary control of optical nodes.
- **In-operation network planning** operations were considered. To increase traffic restorability in flexi-grid networks, a multi-path after-failure repair optimisation (MP-AFRO) algorithm was applied to reduce the sub-connections count by aggregating those belonging to the same original connection and rerouting the resulting connection to release spectral resources. A heuristic algorithm was deployed inside an in-operation planning tool in the form of back-end PCE (bPCE) inside the application-based network operations (ABNO) architecture controlling a network. The bPCE was connected to the centralised active stateful PCE.

Additionally, the benefits of flexi-grid were evaluated in the context of the UNINETT NREN network. The expected evolution of the NREN traffic matrix was assumed to evaluate the benefits provided by the adoption of high-rate transmission systems with and without the flexi-grid technology. Results showed that fibre exhaustion will occur after around seven years from now, further postponed in the case of flexi-grid networks [1].

2.2.2 Recent Developments on FON

Flexible optical networks maximise spectral efficiency through use of super-channels on a flexible channel grid. Super-channels receive a negative penalty through non-linear interactions of closely spaced sub-carriers and pass-band narrowing in network ROADMs. Numerical analyses have been carried out to evaluate super-channel optimisation to maximise product of spectral efficiency and optical reach [24]. Non-linear interactions are minimised by sub-carrier power optimisation where edge sub-carriers have smaller launch power (see Figure 2.4). The pass-band narrowing penalty is optimised by introducing a guard band around every super-channel. The best performance in terms of product of spectral efficiency and optical reach is achieved for a super-channel guard band of 6 GHz (although 12.5 GHz tends to be the minimal granularity). Sub-channels within a super-channel may be Nyquist-shaped by an optical inverse-Gaussian filter of order 2 to improve the sub-channels' bandwidth utilisation. Such optimised super-channels will benefit from the minimal frequency granularity of filtering elements of 3.125 GHz that are already available on the market [25].

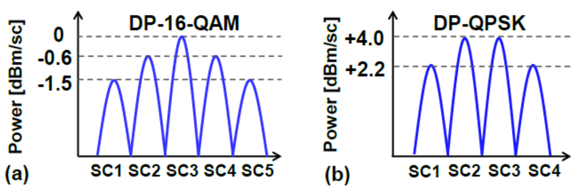


Figure 2.5: Optimum sub-carriers launch power for 1 Tb/s 5-SC-DP-16-QAM and 400 Gb/s 4SC-DP-QPSK super-channels for sub-carrier power pre-emphasis (SCPP) method

Although many vendors offer turn-key network solutions for backbone networks, there is increasing need for vendor interoperability for network subsystems, or even elements, in order to reduce overall cost. For the future flexible optical network, an important requirement is a common network management platform with an identical access to all network elements, independently of their origin. On top of it, flexible planning tools are proposed to fully optimise resource use in the network [26]. New network management systems are therefore needed sooner than new optical fibres. Available capacity of the current fibre footprint is expected to last till the end of the next decade [27].

2.2.3 Transponder Interoperability

Currently, most system integrators are about to develop transceivers beyond 100 Gb/s. Although "black link" (BL) standardisation at 100 Gb/s is not yet fully accomplished, now is the right time to begin thinking about and investigating how to realise BL interoperability at even higher channel speeds.

NREN networks often consist of equipment purchased from different system vendors. Interconnection of terminals (e.g. routers and switches) with a dense-wavelength-division-multiplexing (DWDM)-based optical network has traditionally been realised through the deployment of transponders with an intrinsic demarcation between the transport network and the client layer. This interconnection can also be achieved by removing one grey short-reach transmitter (TX) and receiver (RX) pair per channel (eliminating the transponders and substituting them with so-called coloured interfaces in the packet machines) with associated cost savings. This configuration is known as the BL approach, and related multi-vendor interoperable specifications are already part of the ITU-T's Recommendations G.698.1 and G.698.2 for DWDM links with and without optical line amplifiers, respectively. This configuration is often referred to as an "alien wavelength" concept when the DWDM TX and the DWDM RX are provided by the same vendor A. The alien wave concept is discussed in more detail in Section 3.

The DWDM link consists of fibres and optical network elements – e.g. optical (de)multiplexers, amplifiers, and (reconfigurable) optical add/drop multiplexers [(R)OADMs] – and is considered as "black" if the design details are proprietary to the BL designer. However, the overall worst-case BL transfer characteristics must be specified, e.g. minimum/maximum accumulated dispersion, maximum differential group delay, and maximum optical signal-to-noise ratio (OSNR) path penalty. In the in-force version of G.698.2 [28], application codes for non-return-to-zero modulated signals with channel data rates up to a nominal 10.71 Gb/s have been standardised. Currently, ITU-T's G.698.2 BL work focuses on 100 Gb/s polarisation-multiplexed quadrature phase shift keying (PM-QPSK) modulated signals. This modulation format requires clear definitions and specification methodologies for parameters not present in existing optical interface standards, such as error vector magnitude (EVM) or spectral excursion.

In the case of a single carrier communication, the following main transmission parameters have to be considered (see [29]):

- *Modulation format*. Multiple types of modulation formats may be supported, enabled by the use of a digital to analog converter at the transmitter. Possible formats include binary PSK (BPSK), QPSK, m-quadrature amplitude modulation (QAM), etc.
- *Sampling rate and analog bandwidth*. To achieve interoperability, minimum hardware requirements in terms of sampling rate, ADC resolution, and analog bandwidth have to be guaranteed.

- *DSP algorithms*. DSP may require standardisation in the case of data-aided algorithms because the training sequences need to be agreed upon between the TX and RX. On the other hand, if blind DSP algorithms are employed, less standardisation effort is expected.
- *Optical layer parameters*. To achieve interoperability, optical parameters have to be defined within a strict range of working conditions. The range of output power values at the transmitter (i.e. launch power) and receiver (i.e. maximum values of the overall and per-channel received optical power and input power sensitivity) require dedicated standardisation.
- *Frequency slot*. The supported wavelength tunability range, slot-width granularity, and the actual nominal central frequency have to be specified, together with the possible required optical cross connections and their filter characteristics. In addition to TX and RX, this information has to be provided to intermediate switching nodes.

In addition to these per-carrier parameters, the following information has to be considered in super-channel connections consisting of multiple sub-carriers:

- *Number of sub-carriers*. The number of supported sub-carriers has to be specified (e.g. eight or four sub-carriers in the case of a 1 Tb/s channel).
- *Sub-carrier spacing*. Sub-carrier spacing should be compliant with flexible grid specifications (e.g. the granularity of 6.25 GHz).

The interoperability of two S-BVT implementations has been recently demonstrated on a pan-European multi-domain multi-vendor elastic optical network (EON) testbed [30] within the IDEALIST project [31]. Two S-BVT implementations from the Inter-University National Consortium for Telecommunications (CNIT)/Ericsson and Coriant, with hard-decision (HD) and soft-decision (SD) FECs, were evaluated. The control architecture was able to configure the S-BVTs so the multi-vendor transmission reach is failure-free up to 300 km with current FEC standards. The testbed, illustrated in Figure 2.6, consisted of data and control planes.

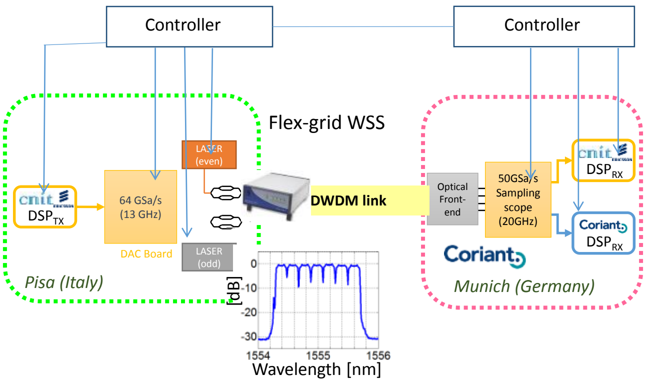


Figure 2.6: Multi-partner pan-European testbed

The data plane setup consists of flexi-grid nodes, based on configurable spectrum selective switches (SSS), a CNIT/Ericsson DSP unit at the Tx and two different ones (CNIT/Ericsson and Coriant) at the Rx as part of an optical coherent testbed. The Tx is able to provide a super-channel with different configurable numbers of carriers and capacity (i.e. 1 carrier for 100 Gb/s, 3 carriers for 400 Gb/s, and

7 carriers for 1 Tb/s). At 1 Tb/s, PM-16QAM Nyquist-shaped signals shaped by a roll-off = 0.05 and symbol rate = 23 GBd were adopted.

The control plane is performed via controllers located at each physical node of the network. Controllers are connected with the data plane testbed (i.e., SSS, Tx and Rx) by means of USB, serial and GPIB interfaces. Controllers are able to automatically configure SSS (i.e. filter shape as the reserved frequency slot), transponders parameters (i.e. symbol rate, number of carriers, sub-carrier central frequencies) and DSP parameters (i.e. modulation format, FEC). Multi-vendor interoperability between CNIT/Ericsson and Coriant DSPs was achieved by the exchange of novel application code (AC) and transponder class (TC) attributes, in line with ITU recommendations [28].

Figure 2.7 reports the transmission performance of the single-vendor ($CNIT_{TX} \rightarrow CNIT_{RX}$ - SV) and cross-vendor ($CNIT_{TX} \rightarrow COR_{RX}$ - CV), where COR stands for Coriant. In both cases, blind-DSP algorithms [32] were used because an interoperability scenario would not allow the usage of algorithms that require knowledge of the link [33] or of training sequences [34].

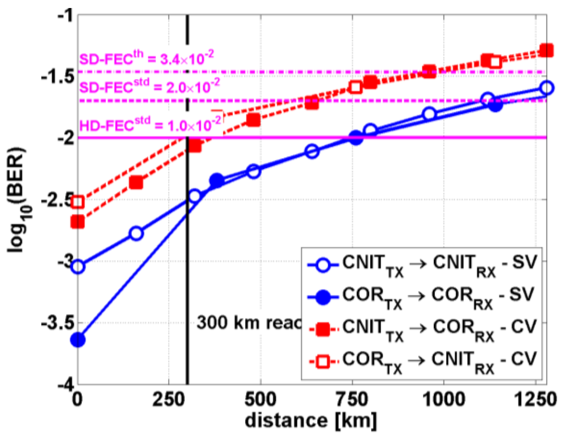


Figure 2.7: BER performance

If the cross-vendor (CV) solution is selected, only already standardised FEC can be used. For example, the ITU standard G975.1 hard-decision super-FEC^{std} ($HD\text{-}FEC^{std}$) with 20% overhead could use a pre-FEC BER threshold = 1×10^{-2}. This value could increase, if new SD-FEC become standard, up to a reasonable pre-FEC BER threshold = 2×10^{-2}. Based on the pre-FEC thresholds, the following conclusions can be drawn concerning the experiment carried out by employing the testbed depicted in Figure 2.6. If the usage of already standardised $HD\text{-}FEC^{std}$ is assumed, transmission up to ~750 km in the case of SV transmission is guaranteed. This halves in cross-vendor mode. Although the system performance has been significantly reduced, such a scenario would still guarantee error-free transmission, with CV transmission, over the majority of European links. Moreover, if a standardised FEC ($SD\text{-}FEC^{std}$) could be adopted, the reach would approach 1,100 km for SV transmission, and ~600 km for CV transmission. Finally, in the case of proprietary FEC, the transmission distances would be ~1,800 km [35], and once again about half for CV transmission. These values are summarised in Table 2.2.

	Reach [km]		
Case	**HD-FEC^{std}**	**SD-FEC^{std}**	**SD-FECth**
SV	750	1100	1800
CV	300	600	900

Table 2.2: Performance results

In addition to the results of the conducted experiment, Figure 2.7 also displays the results obtained within a second experiment that has been reported in [29; 32]. In this previous analysis, the vendor configuration was mirrored by having ($COR_{TX} \rightarrow COR_{RX}$ - SV) and cross-vendor ($COR_{TX} \rightarrow CNIT_{RX}$ - CV). In [29; 35] the channel configuration was slightly different (32 GBd and 38 GHz channel spacing). The performance of this experiment is reported by the curves with filled markers in Figure 2.7 and in this comparison, it is clearly visible that the two single-vendor scenarios and two cross-vendor-ones, between them, achieve similar performance. From a DSP perspective, the degraded performance of CV could be associated to the lack of knowledge of the system, such as for example Tx / Rx I/Q skew compensation. The CV transmission, with standard HD-FEC, can reach ~300 km, and therefore if longer distances are needed, a solution concerning standardisation on SD-FEC must be agreed within the ITU panels.

2.2.4 FON Vendor Available Implementations

In order to meet the future capacity demand on optical networks and to gain more capacity and network efficiency, introducing flexibility into the network is the most cost-efficient strategy to choose [1; 31]. Taking a longer perspective, to enable 1 Tb/s client signals in transport networks the only cost-efficient option is to migrate the fixed network to a flexible optical network.

In today's commercially available flexi-rate transponders (BVT), a subset of the functionalities mentioned in Section 2.2.1 are available. JRA1 T1 conducted a vendor survey during the GN4-1 project to identify the functionalities currently available and those coming in a two-year term. There are a variety of solutions and implementations, but a subset of common functionalities could be found in more or less all vendor implementations. Table 2.3 shows these subsets.

FEC type	Modulation format	Spectral occupancy	Line rate	Number of carriers	Baud rate
G-FEC **HG-FEC** **SD-FEC** **E-FEC** **U-FEC**	BP-BPSK BP-QPSK BP-8QAM BP-16QAM	37.5 GHz up to 200 GHz with 12.5G Hz granularity	50G 100G 200G 400G	1–2	25 Gbaud – 32 Gbaud

Table 2.3: Tunable parameters in today's vendors' multi-rate transponder implementations

Not all of these parameters are supported by all vendors. There are some minor differences between them. Modulation format and FEC are the most basic common building blocks in already-existing multi-rate transponders. Spectral occupancy and Baud rate, on the other hand, have been implemented slightly differently from vendor to vendor. Regarding spectral occupancy, both transponders with limited spectral tuning flexibility and transponders that give the ability to tune the granularity by 0.5 GHz can be seen.

The advantage of flexi-rate transponders is that they give the network operators the ability to tune the transponder parameters in order to support a certain service with the highest network utilisation rate. For example, if operators want to deliver a 400G service over a short distance, the most optimised way to deliver the service is to choose the highest possible modulation format, with SD-FEC in order to minimise spectral occupancy usage.

Forward Error Correction

Different FEC types add some overhead to the transmission channel. The amount of overhead can vary from 7% to more than 20%. More overhead means more coding gain. The FEC types used in transponders are usually vendor proprietary and this means that it is not possible to run transponders from different vendors with each other. The exceptions are G-FEC and high-gain (HG) multi-vendor FEC.

2.2.5 Conclusions

With regard to enabling effective, optimal use of the availability capacity through flexible optical networks (FON), the GN3plus Open Call project REACTION introduced significant innovations in the context of data plane (support for sliceability), control plane (novel PCE architecture), and routing and spectrum allocation strategies (novel RSA algorithms). In each case, results confirmed the capacity-utilisation benefits of a flexible network over a fixed network, including postponing fibre exhaustion. Developments since REACTION have further enhanced FON's ability to maximise spectral efficiency and reach by minimising the negative penalties to which super-channels are susceptible, namely interactions of closely spaced sub-carriers and pass-band narrowing in network ROADMs. For the future, there is increasing need for vendor interoperability for network subsystems, or even elements, and hence for a common network management platform that permits identical type of access to all network elements, independently of their origin, together with flexible planning tools to fully optimise resource use in the network.

The interoperability of two S-BVT implementations has been recently demonstrated on a pan-European multi-domain multi-vendor elastic optical network (EON) testbed within the IDEALIST project. Experiments proved the need for a new soft-decision FEC standard which would significantly increase reach in single- and cross-vendor transmission.

A survey of BVT vendors showed a subset of common functionalities, though with implementations – particularly of spectral occupancy and Baud rate – varying from vendor to vendor.

3 Spectral Sharing and Alien Waves

In Section 2 the physical media and the enabling technologies for increasing the capacity were addressed. A special type of spectrum utilisation is the alien wave (or alien wavelength) and alien spectrum, where the spectrum is opened and waves from other equipment and/or entities are injected into a system. This section deals with these types of networks and the focus is on the further development of a modelling tool for estimating the viability of alien waves as well as reporting on experiments with alien waves for, among other purposes, validating the modelling tool.

Hence, Section 3.1 provides an overview of the advantages of alien waves and shared spectrum, and it forms the basis for the rest of the section. In Section 3.2 the multi-domain optical modelling tool (MOMoT) is described, with the latest extensions, followed in Section 3.3 by a report on best practices with alien waves and, in particular, the deployment of an alien wave-based optical transport layer. Section 3.4 describes experimental scenarios and results to validate the estimations provided by the MOMoT modelling tool.

3.1 Advantages of Alien Waves and Shared Spectrum

Alien waves (AW) are wavelengths that are unknown to the network domain and that share the spectrum with native wavelengths. Spectral sharing is another term used for alien wavelengths. The topic has been discussed within the NREN community for a number of years and is now finally gaining momentum as AWs are deployed more and more throughout the NREN networks.

As research is increasingly becoming a global effort, research networks equally need to become more dynamic and flexible by extending their resources and capabilities beyond single countries, regions or domains. To accommodate future research projects and global partnerships, research networks can be developed in a more open and federated way. Instead of creating new multi-domain services in the traditional “cross border” type of manner, where information is typically exchanged at the bare minimum information level (e.g. back-to-back information exchange on a black-and-white interface), research networks can tear down the boundaries by looking at what the available resources are, and by opening up access to these resources (e.g. by the exchange of information on OTN level or access to spectrum in another network).

One way of doing this for the individual research networks could be by opening up access to the DWDM spectrum and thereby offering a means of utilising foreign infrastructure. An example is alien wavelengths, in which resources from a carrier network are being utilised to transport optical channels, not controllable by the carrier.

In the past there have been some studies and experiments on alien wavelength communication in the research communities. In particular, JRA1 T1 participants SURFnet and NORDUnet have partnered up to turn these experiments into real-life production services that are now being used for stabilising and expanding their networks.

As SURFnet and NORDUnet's partnership on developing alien wavelength services was established some time ago, a lot of testing has been carried out in order to establish the reliability and integrity of the optical signal interaction. Furthermore, planning and development effort was put into defining the correct responsibilities, suitable procedures, and proper monitoring tools for putting the services into production.

Although vendors traditionally take a more conservative view on sharing their network capabilities (as it typically diminishes their revenues), there has been a tendency for the industry to open up to the concept after all. Ciena's DWDM platform (6500) has a setting for adding "Foreign" wavelength channels and can even control its power along the system. Other vendors, such as Alcatel Lucent (with their 1626LM platform) and ADVA (with their FSP 2000 / FSP 3000 systems) can also take in alien wavelengths. Infinera also supports AW networking, but in a less scalable configuration.

The latest trend is that some of the vendors seem to be taking the concept even further, as will be discussed in Sections 3.3.2 and 3.3.3.

3.2 Modelling Tool Development

In GN3plus, the Open Call project MOMoT [36] developed a multi-domain optical modelling tool (MOMoT) to estimate and predict AW performance and assess the implications for existing traffic in the network path. During GN4-1, the modelling tool has been further developed by JRA1 T1 and new functions have been added. The following sub-sections introduce the modelling tool and the extensions developed, provide guidelines on how to use the tool, and outline the basic principles, capabilities and assumptions of its adopted models. The main advances compared with the version of the MOMoT tool delivered by the GN3plus MOMoT Open Call project are also summarised.

3.2.1 Introduction to the Tool

The MOMoT tool enables users to input certain characteristic parameters, such as length from A to B, wavelength, input power, bitrate, etc., and based on these the tool will estimate whether or not the connection is likely to be successful and what the impact on existing services may be. The tool will serve as a "back-of-the-envelope" calculation and evaluation of the feasibility to deploy an AW in a given network scenario. Development of the tool has been done with speed and effectiveness in mind, so instead of doing fully detailed and time-consuming multi-channel simulations, a safe-zone approach has been applied. The tool makes a quick assessment of multi-channel effects, without a deep simulation, and warns the user of any likely implications.

The modelling tool estimates the bit error rate (BER) of alien wavelengths in circuit-switched optical networks with reference to the following modulation formats:

- On-off keying (OOK) with direct detection.
- Polarisation multiplexing quadrature phase shift keying (PM-QPSK) with coherent detection.

Thus, typical bitrates to be considered can be 10 Gb/s and 100 Gb/s.

3.2.2 Guidelines on How to Use the Tool

The modelling tool is software (.exe) providing a user-friendly interface where link, native and alien wavelength parameters can be set. Based on the provided input parameters, the software outputs bit error rate estimation.

3.2.2.1 *Operation of the Tool*

The user can input various parameters, among others the bitrate of the alien wavelength, the channel spacing, the modulation format and power levels. In combination with information on the location of dispersion compensating fibre (DCF), the tool provides the following output:

- Evaluated BER pre-FEC: in this field the estimated BER of the (alien) wavelength is reported.
- Warning if the power of the alien wavelength exceeds the threshold of 2 dBm. This has been introduced since the level of power may be too high and it may induce excessive cross-phase modulation (XPM) on active wavelengths.
- In the case of injecting a PM-QPSK alien wave into an OOK native network, output messages will report the BER of the alien wave at varying guard band between the alien wave and a native OOK.

  Indeed, the BER of a PM-QPSK is strongly affected by the presence of OOK neighbours because of XPM. Thus, by spacing out PM-QPSK and OOK, the performance of the PM-QPSK improves. Guard band is defined as the number of free channels between a PM-QPSK and an OOK. Another kind of output message is reported if the performance is strongly affected by the PMD.

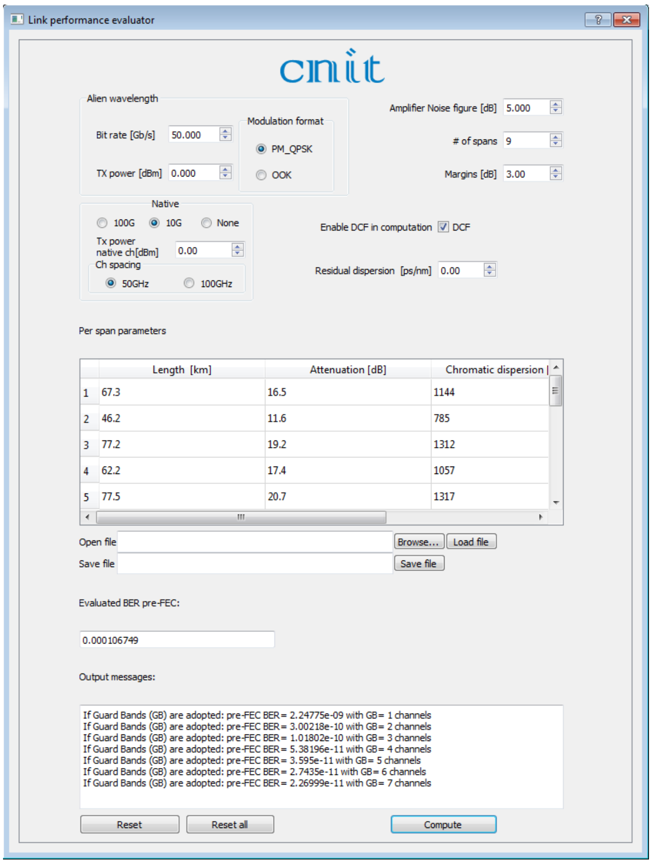


Figure 3.1: Modelling tool interface and output messages including guard band information

3.2.3 Basic Principles, Capabilities and Assumptions of the Tool

The modelling tool is based on an analytical model for BER estimation detailed in *Modeling and Distributed Provisioning in 10–40–100-Gb/s Multirate Wavelength Switched Optical Networks* [37]. Two models are adopted for the two different transmission techniques considered:

1. OOK with direct detection: e.g. suitable for 10 Gb/s.
2. PM-QPSK with coherent detection: e.g. suitable for 100 Gb/s.

The model aims at providing the estimated value of BER before forward error correction (pre-FEC BER) for both the alien wavelength and the native lightpaths active in the network. The model and the modelling tool are built based on assumptions described in [37], and summarised here:

- Amplifier noise figure is assumed to be the same for all spans.
- The following fibre parameters are the same for all spans and are not visible to the user: effective area of 80 µm^2, PMD parameter 0.1 ps/sqrt(km).
- The digital signal processing (DSP) at the receiver, for PM-QPSK signals, can completely compensate for linear impairments (i.e., both polarisation mode dispersion (PMD) and chromatic dispersion (CD)).

- Four-wave mixing (FWM), stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) are not explicitly included in the model. These can be considered as worst-case margins (e.g. lower than 1 dB as optical signal-to-noise ratio (OSNR) penalty [37]). In any case, the power levels typically used in telecom networks are low enough to consider these effects as negligible.
- Other effects such as ageing, filtering effects, etc. are considered as margins to the OSNR in the computations that can be configured through the interface. A typical value for the margins can be 3 dB

In general, the adopted models account for the following physical impairments:

- Amplified spontaneous emission (ASE).
- PMD.
- CD.
- Self-phase modulation (SPM).
- Cross-phase modulation (XPM). XPM is particularly relevant when a PM-QPSK alien wavelength is surrounded by OOK wavelengths.
- As stated earlier, other physical impairments are considered through the configurable worst-case margins.

For more details on the adopted models, please refer to [37]. Also, a more detailed description of the inputs, outputs and the operation can be found in Appendix A.

3.2.4 Extensions to the Tool

In this sub-section, the main advances with respect to the version of the tool delivered by the GN3plus Open Call MOMoT project are summarised:

- Enabled the 10G OOK BER computation.
- Included margins as an input parameter of the system.
- Unlocked the bitrate in case of 10G OOK.
- Modified the horizontal header of the table.
- Solved a bug when loading some configuration files: introduced a check validating the structure of the configuration file (avoiding the tool crash at start-up).
- Solved a problem related to both “warning: VOA attenuation” and “Error 2” error messages (avoiding problem with specific configuration files with high power): such warning and error messages are avoided.

The modelling tool developed in the GN3plus Open Call MOMoT project estimates, for a subset of available modulations, the impact and viability of injecting alien waves into host optical transport networks. The tool has been further developed in the context of GN4-1 and, among others, 10G OOK BER computation has been added, which was specifically requested in GN3plus by NRENs. The tool provides a simple graphical user interface and accounts for a wide range of physical impairments, which are relevant when transporting alien waves.

3.3 Best Practices from Other Projects

In order to gain practical experience and develop guidelines on how to design, commission and maintain alien wave services, different trials and studies have been performed in the NREN communities. This section outlines general best practice, and the lessons learned from AW trials by JRA1 T1 NREN third-party participants SUNET and UNINETT, and from NREN operators’ experiences.

3.3.1 General Best Practice

Setting up alien waves between two research networks essentially comes down to the technicalities of how well the actual platforms support adopting and managing alien wavelengths. Despite this, there is an equal challenge in simply partnering up with other research networks. It is crucial that service deployment aspects, such as agreeing responsibilities or defining the operational procedures, are handled collaboratively, and at an early stage of the partnering. Further essential factors include: definition of standards and agreements on the technical details for the service deployment; documenting all the design parameters and build values (e.g. launch powers, receive inputs, etc.); sufficient monitoring of the alien wave services; and reporting of alarms and problems in a clear fashion to each partner.

The concept of sharing network resources and opening up for non-native signals does not have to be restricted to single-signal adoption. Instead of merely assigning a designated input point on a dedicated channel, a slice of the native spectrum (or even the full spectrum) can be shared with the partner, thus giving them better possibilities for expansion. This concept is typically referred to as spectrum sharing.

3.3.2 SUNET Alien Wave-Based Network

During the design phase of SUNET’s (the Swedish research network) new network, it was decided to take a new approach in terms of establishing router connectivity between the universities.

Instead of relying on the traditional way of building networks, in which expensive transponders are utilised for the connectivity, SUNET are planning to use coherent coloured interfaces in the routers. Specifically, these coherent interfaces are 100G Juniper line cards with CFP2 client interfaces, which will be connected directly towards the next university site (the red line in Figure 3.2 below) as alien waves via optical amplifiers from ADVA. Furthermore, backbone routers are likewise connected via alien waves (the blue lines in Figure 3.2).

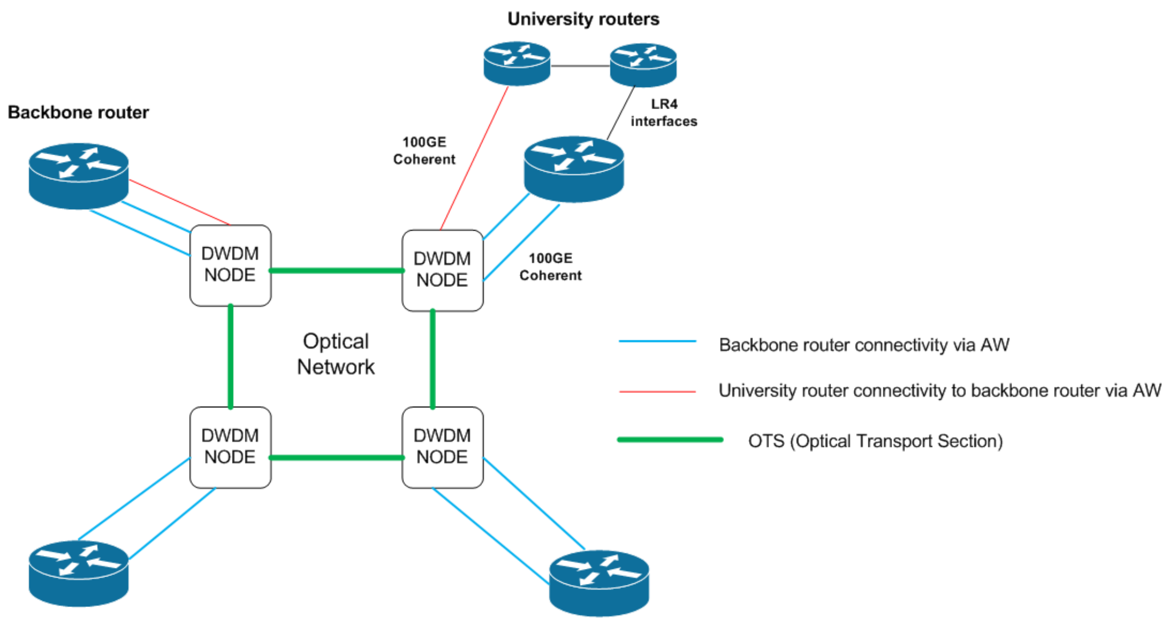


Figure 3.2: Optical network setup

The effective channels (originating in the Juniper line cards) will therefore be “alien” to the ADVA platform. The plan is to control and manage the spectrum in a collaborative manner, by utilising a GMPLS control plane interworking on the ADVA and Juniper systems.

The 100G coherent line cards from Juniper are beta version and SUNET is one of the first customers in the world to try them out. The process of building this network has started and the first link has been established; finalisation of the complete network is expected to continue until October 2016.

3.3.3 UNINETT 100G Alien Wavelength Cisco–Juniper Interoperability Test

The purpose of the test was to verify support of 100G alien wavelengths in UNINETT’s (Norway’s NREN) optical network. In addition, UNINETT wanted to gain some experience with new 100G OTN/DWDM cards from Juniper and Cisco, and prove the interoperability between them. The following tests have been performed:

- 100G single-vendor alien wavelength (AW) test over Coriant hiT 7300 platform.
- 100G multi-vendor AW test over Coriant hiT 7300 platform.

3.3.3.1 *Test Layout and Equipment*

The DWDM path of the link was established over two point-to-point DWDM systems based on a Coriant hiT 7300 platform between Trondheim and Oslo. As shown in Figure 3.3 below, the DWDM systems on the Oslo side are connected to each other by using dedicated dark fibre between mux and demux.

Both routers are located in Trondheim but in different locations. A Spirent test generator with 10G interface and logical loop was used on the routers in order to create 40 Gb/s of traffic over the 100G AW link.

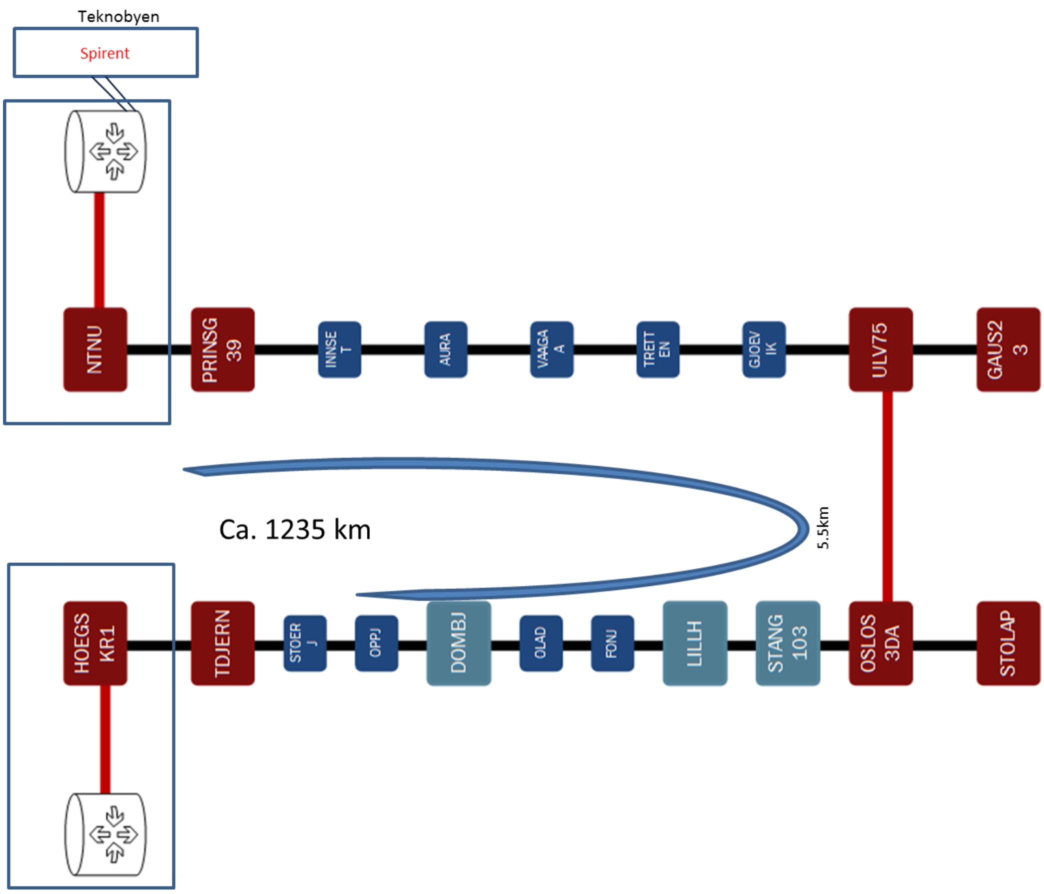


Figure 3.3: UNINETT Cisco–Juniper interoperability test scenario

The total length of the test DWDM path is 1,235 km, and it consists of nine "optical line repeater" NEs, six OADMs and two terminals. One of the DWDM systems is based on 100 GHz spacing and the other on 50 GHz spacing. The system utilisation on both systems is over 50%, running a mix of 10G and 100G operational wavelengths. 100G and 10G wavelengths are grouped in separate optical bands with 200 GHz of guard band between them. The total OSNR is about 16.2 dB.

The 100G DWDM MX MIC is based on the 100G CFP2-ACO coherent pluggable optics technology. Both routers were configured with HG-FEC (multi-vendor) on 193 THz frequency channel. 40 Gb/s of load was generated on the 100G AW link and the test ran over several days. Figure 3.4 and Figure 3.5 shows the results on the Juniper interfaces.

As shown in the figures, neither packet loss nor post-FEC errors were registered. The minimum and maximum pre-FEC BER measured during a 1-second interval over a 15-minute period are shown in Figure 3.4.

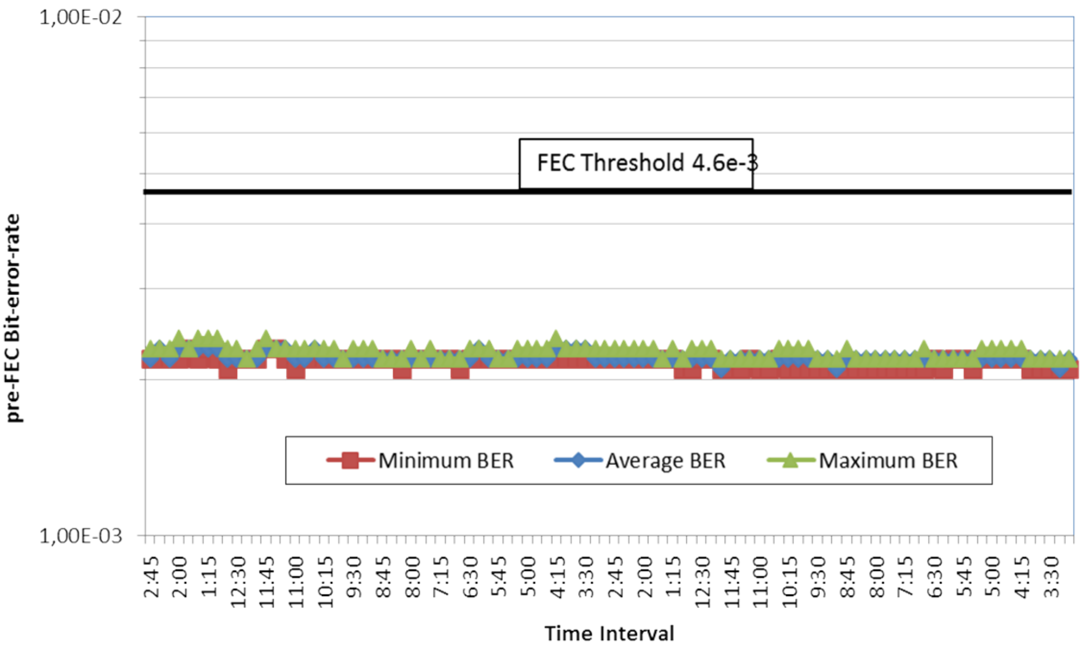


Figure 3.4: Pre-FEC bit error rate on Juniper router

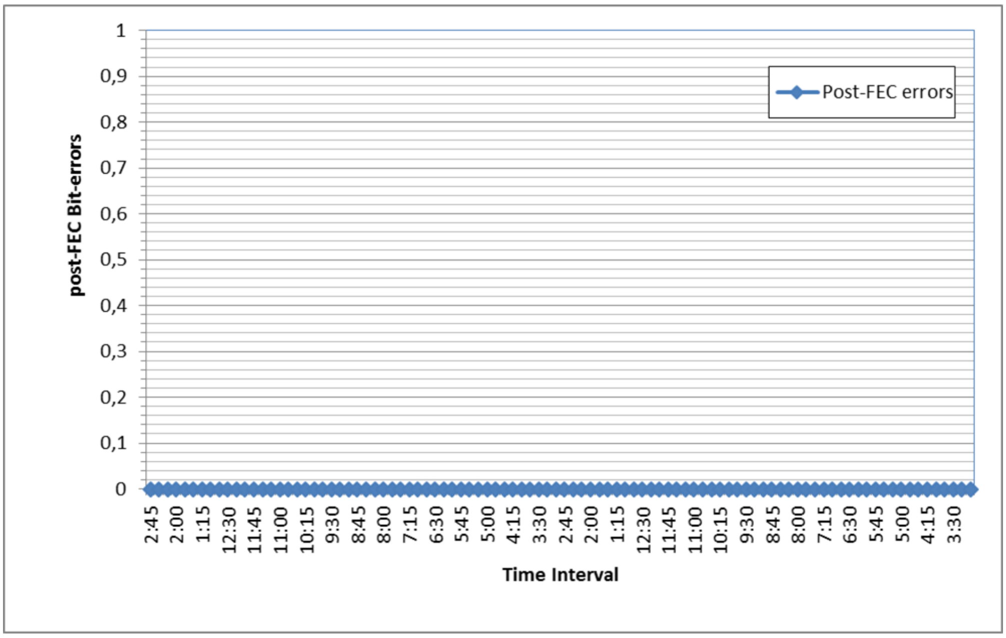


Figure 3.5: Post-FEC bit errors on Juniper router

3.3.3.2 *Interoperability Test Conclusion*

The test result was better than expected. Configuration of the routers and DWDM was done in accordance with the procedure and without any obstacles. Even if the DWDM system had an OSNR value close to the limit of HG-FEC operation, there was no pre-FEC bit error and packet loss.

3.3.4 Operator Experiences with Alien Waves

There are definitely many possibilities in alien waves and spectrum sharing and it has a lot of potential in the research communities. As mentioned in Section 3.1, SURFnet and NORDUnet have already implemented some of their services as alien waves and the stability of these services has been proven in their production environment for a couple of years now.

The willingness to implement wavelengths from other vendors (operated by other systems and other operating centres) is founded on past simulations, experiments and trials by NRENs and within the GÉANT context that have given the confidence to commence real implementation.

During the experiments and simulations mentioned above, it was investigated whether or not it was possible to find an optimum power area for the native and alien signals' interaction. Clearly, the non-linear effects become evident when the signal intensities are relatively increased, and the results of the experiments showed both cross-phase and self-phase modulation problems when using too high signal powers or having too little guard band.

Apart from these findings, it was concluded that the operational challenges in partnering up for sharing waves or spectrum are just as important as solving technical problems at the commissioning stage.

3.4 Experimental Scenarios and Key Results

Several experimental deployments have been conducted with and without the JRA1 T1 partners' participation. The results of these are useful for gaining confidence and for providing some engineering rules of thumb for optimal implementation.

Another matter is how to determine the actual design parameters and the specific physical values that are needed when the alien waves are adopted.

It is here that the MOMoT tool can be very useful and, conveniently, can calculate the effect of the alien/native signal interaction. It is easy to model the production environment, and then calculate concrete values to be used on commissioning of the alien waves.

However, in order to have confidence in these values, verification testing has been performed to check the integrity of the tool and, if necessary, make corrections and improvements. The initial verification testing was performed in GN3plus through a trial with SURFnet and Dante, which was compared with the estimations from the MOMoT tool.

In order to gain more verification assurance, it is desirable to have multiple trials to confirm the integrity of the tool and thus more trials was performed in NORDUnet's live production network with BER vs. launch power as a performance criterion.

3.4.1 Experiments in NORDUnet

3.4.1.1 *1st Trial Copenhagen–Hamburg and Back*

In the first trial NORDUnet connected two transponders (at the same site in Copenhagen 1), and then set up up a channel going uni-directionally from Copenhagen to Hamburg and back to Copenhagen again. The link from Copenhagen 2 to Hamburg 1 goes via Fyen and down towards Germany. The other link, from Hamburg 2 back to Copenhagen 1, goes via Sealand and thus the total coverage is approximately 1,000 km.

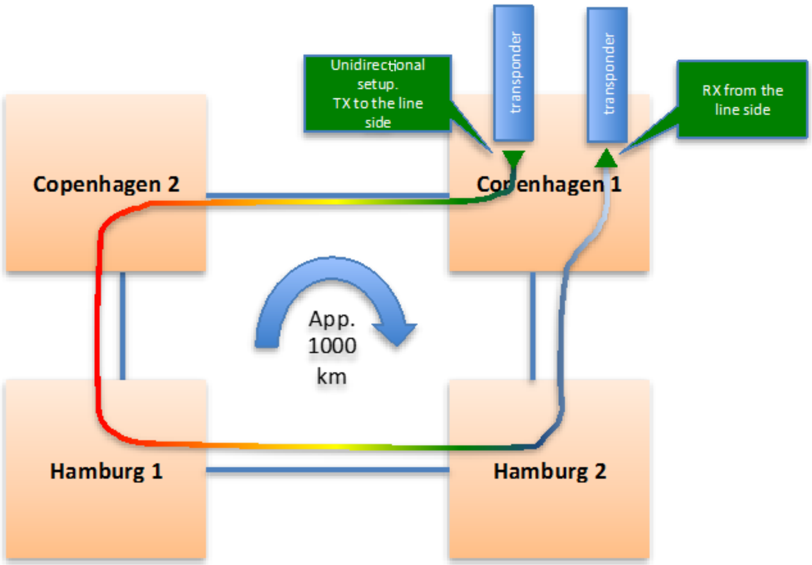


Figure 3.6: Test scenario between Copenhagen and Hamburg

Unfortunately the reach of the transponders that were available for the trial was not long enough, and it was not possible to successfully compare the results with the MOMoT tool. Due to this reach limitation, it was soon decided to create another trial in the same network but covering a shorter distance.

3.4.1.2 *2nd Trial Copenhagen–Gothenburg*

The second trial was approximately 300 km long, going from Copenhagen, Denmark to Gothenburg, Sweden. As in the first trial, two transponders were connected in a traditional point-to-point uni-directional setup (see Figure 3.7). Again, a channel was added along with the normal production services with a guard band of 500 GHz. The channel was manually power-adjusted to fit the rest of the spectrum throughout the three nodes, and kept static after the links were balanced. RX pre-FEC values were measured in the Gothenburg end point B, as a function of launch-power variation in Copenhagen 1 end point A.

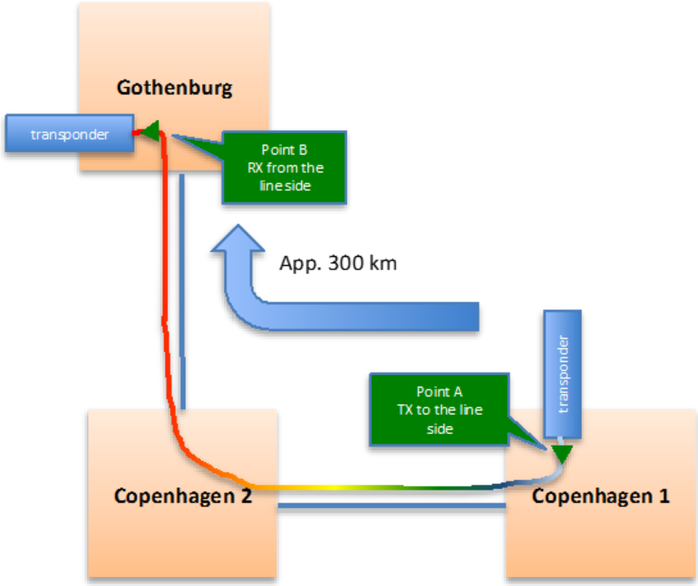


Figure 3.7: 300 km test scenario between Copenhagen and Gothenburg

In order to verify the predictions of the MOMoT tool, the Gothenburg link values, such as span lengths, launch power, bitrate and modulation format, were used as input.

Figure 3.8 shows the comparison of the actual link measurements and three graphs that represent 3 different scenarios calculated by the tool. The margin *M* and the noise figure *NF* were varied in pairs: (*M* = 3, *NF* = 3), (*M* = 3, *NF* = 7) and (*M* = 7, *NF* = 7). The margin is a parameter that takes fibre ageing and other non-modelled factors into account. Typically, a value of around 3 is a good representation for an average optical link. The noise figure of the amplifiers is often known for optical networks. However, in this case, its value was not verified so two variations were chosen.

In Figure 3.8 the tool resemblance with the actual measurements looks fairly reasonable when compared with the (*M* = 3, *NF* = 7) tool curve. At input powers above 1 dB, however, the lab curve is bending off. This can be explained by the power limitation that takes place in the link. Due to amplifier gain management in the link, the effect of further increases in the power is reduced. Also, it should be mentioned that the lab results curve was parallel-shifted 5 dB to the left in this graph, which accounts for losses occurring in the initial phase of the transmission and underway in a wavelength selective switch. In terms of an AW link evaluation where these losses are unknown, the link quality estimation would not overestimate the quality, but rather be pessimistic about the success of the link. Minimising the insertion losses or being aware of these so they can be taken into account is therefore always preferred.

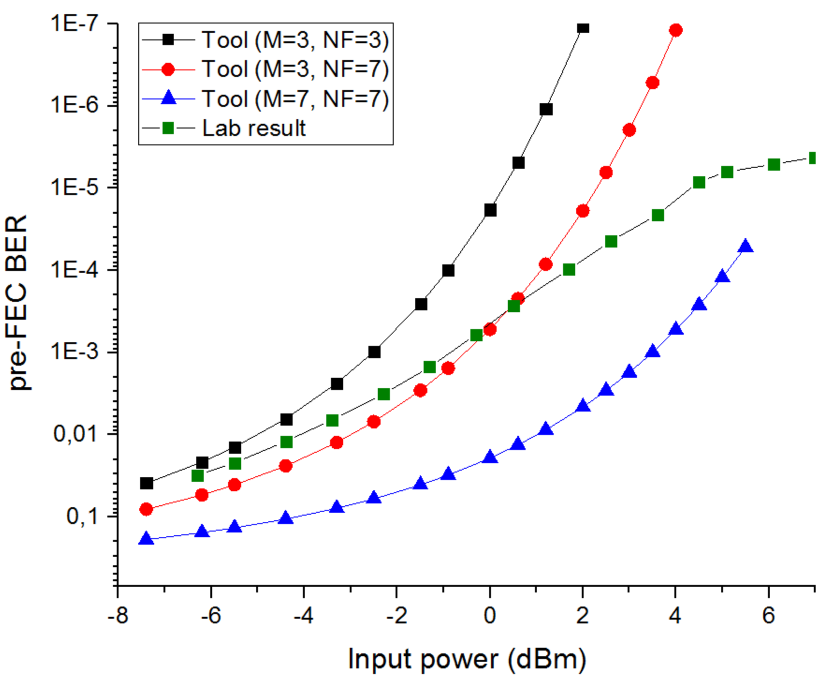


Figure 3.8: The figure compares the pre-FEC BER curves of the field trial (lab) measurements and three curves produced by the MOMoT tool

3.5 Conclusions

Alien waves and spectral sharing are gaining momentum among NRENs as one way of becoming more dynamic, flexible and open in order to meet R&E needs and potentially provide savings on fibre deployment. Studies and experiments – including by JRA1 T1 participants SURFnet and NORDUnet – have helped identify prerequisites and best practice not simply in terms of technology but also in terms of definition of responsibilities, standards, procedures, documenting design parameters and build values, monitoring and reporting. The reliability and integrity of alien waves have been sufficiently proven for SURFnet and NORDUnet to have transitioned AW services into production for both client and own use.

Valuable results have been obtained on defining an optimum power area for the native and alien signals' interaction: the non-linear effects become evident when the signal intensities are relatively increased, and both cross-phase and self-phase modulation problems are encountered when using too high signal powers or having too little guard band.

The multi-domain optical modelling tool (MOMoT), originally developed during a GN3plus Open Call project and further developed during GN4-1, helps determine these and other design parameters and specific physical values needed for AW adoption. Verification tests in NORDUnet's live production network, with BER vs. launch power as a criterion, showed a reasonable correlation between MOMoT's predictions and actual measurements, and indicated that the tool would underestimate link quality rather than overestimate; minimising the insertion losses or being aware of these so they can be taken into account is always preferred.

4 Frequency and Time Distribution

In order to provide zero-touch connectivity and to facilitate a number of high-demanding applications, it is necessary to provide mechanisms to synchronise and distribute time and frequency information among laboratories and users. Solutions to the challenge can be sought in different layers, and in this section the issue is addressed in both the physical layer and in layer 2/3.

In Section 4.1, the concepts are described for distribution of accurate time and stable frequency in the physical layer. Different conceptual architectures are explained and several joint inter-NREN experiments described, which were carried out over links ranging up to 1,500 km. The results indicate the viability of the concepts, and an overview of the future challenges is also provided.

While the physical time transfers are the costly and accurate highways, the precise transfer of time information can also be supported in the higher layers. This is investigated in Section 4.2 with audio and video as the candidate applications. In particular, precision time protocol (PTP) is investigated, and how it can work for connections running on top of MPLS tunnels. Also, a joint experiment evaluating PTP over a standard Internet connection on a 500 km link between Erlangen and Prague is discussed.

4.1 Distribution on the Lowest Layer

Accurate time or stable frequency is required by many applications in navigation, metrology, telecommunications, geodesy, astronomy and other scientific and industrial areas. One source of accurate time is often a Global Navigation Satellite System (GNSS) receiver providing the one pulse per second (1PPS) signal. However, such a solution is scalable only with difficulty and is sometimes not possible due to problems with antenna installation (e.g. large buildings, tunnels). Furthermore, time and frequency distribution over optical links allows significant improvements of uncertainty and stability compared with GNSS methods [38; 39].

Precise time and ultra-stable frequency transfer opens the possibility to set up experiments with a high level of precision that has not been attainable to date. Without being exhaustive, examples include:

- Antenna networking in astrophysics.
- Fundamental constants measurements (e.g. Boltzmann constant).

- Satellite link tests (e.g. Metrological Fibre Network with European Vocation + (REFIMEVE+) signal could be used by the European Space Agency's (ESA) spatial atomic clock program PHARAO/ACES within the next few years).
- Fundamental physics tests [40; 41] (e.g. spectroscopy of hydrogen and its derivatives, high-resolution spectroscopy in the physics of atoms, ions and molecules, the search for parity violation effect in molecules).
- Geodesic applications (tidal measurements, seismology).

4.1.1 Physical Layer

Standard transmission over fibre pairs is used in telecom applications, but due to many effects, transmission delay is changing, e.g. thermal dependence of the refractive index, thermal material expansion, polarisation mode dispersion, etc. This is not an issue for data transmission. However, for extremely precise time or ultra-stable frequency transmission, the propagation delay must be stable. It can be achieved using the same physical path (fibre, amplifiers, muxes, etc.) for both directions of propagation and further improved via additional propagation time stabilisation.

From this point of view, distribution can be either over a pair of uni-directional channels or over one bi-directional channel. Further, the channel can use dedicated fibre or lambda as follows:

- Metrological institutes can lease their own dark fibre infrastructure to transmit metrological signals, independently of any carrier or R&E network. For instance, the PTB in Germany acquired fibre IRUs from Braunschweig to Munich (920 km) and to Strasbourg (700 km) and built a communication network from them. Also, project OPTIME in Poland is based on the usage of dedicated fibres. This solution gives great autonomy to the experiment and to use non-standard DWDM transmission systems, such as research and development materials or, for instance, Brillouin amplifiers instead of erbium amplifiers. But for the metrology laboratory, the main drawback of this approach is the need for specific competences to launch RFQs, to operate the fibre network and, above all, the need for additional funding for IRUs.

- The second approach consists of spectrum sharing between a partner (e.g. an NREN), which leases dark fibres, and a metrological laboratory, to which is given the opportunity of using NREN fibres to transmit its metrological signal. In this WDM infrastructure, the metrological signal is considered as "alien" and can be a WDM wavelength or a broader part of the spectrum. This fibre mutualisation and therefore the cost sharing between partners is a main advantage of this solution. Moreover, the metrological laboratory relies on NREN competences to operate the network and can concentrate solely on its core "business". However, spectrum sharing between different kinds of optical signals can lead to architecture and performance compromises.

Obviously, establishing a bi-directional channel over dedicated fibre requires some specialised equipment, e.g. bi-directional amplifiers. Similarly, when fibre is shared with legacy DWDM, all legacy uni-directional components must be bypassed (see Figure 4.1).

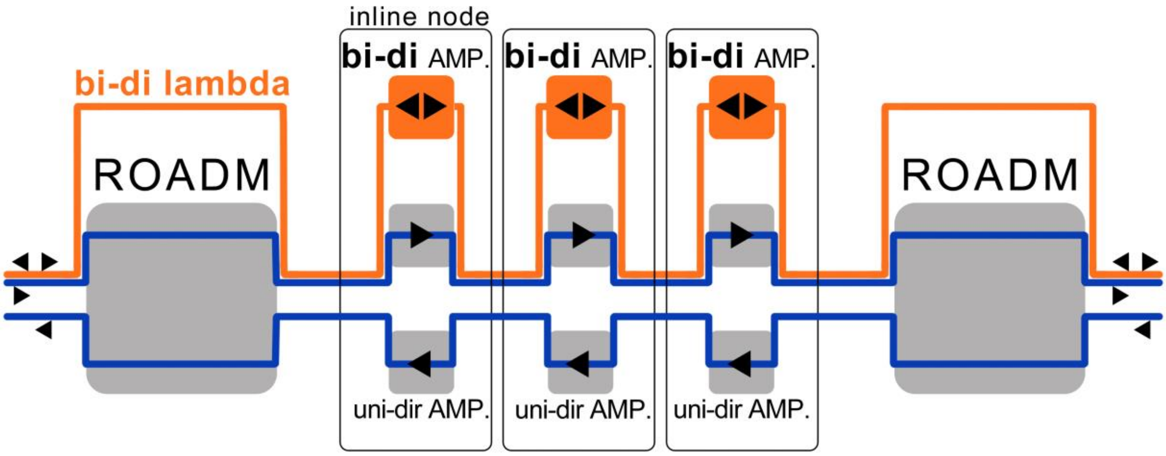


Figure 4.1: Bi-directional channel in legacy DWDM transmission system

Different kinds of mutualised architecture can be built. In the following sub-sections, bi-directional alien lambda and uni-directional alien lambdas are considered in detail.

4.1.1.1 *Bi-Directional Alien Lambda*

From a practical point of view, a bi-directional alien lambda/lambdas can be established in CWDM or passive DWDM systems only; all telecommunications using optical amplifiers contain isolators preventing bi-directional operation. This fact limits reach. However, multiple passive spans can be concatenated together and amplified outside. Such concatenated lambda for precise time transmission, established in the CESNET network in 2013, was reported in *All optical two-way time transfer in strongly heterogeneous networks* [42]. It consists of CWDM and DWDM parts showing total attenuation of 22+21 dB, as shown in Figure 4.2.

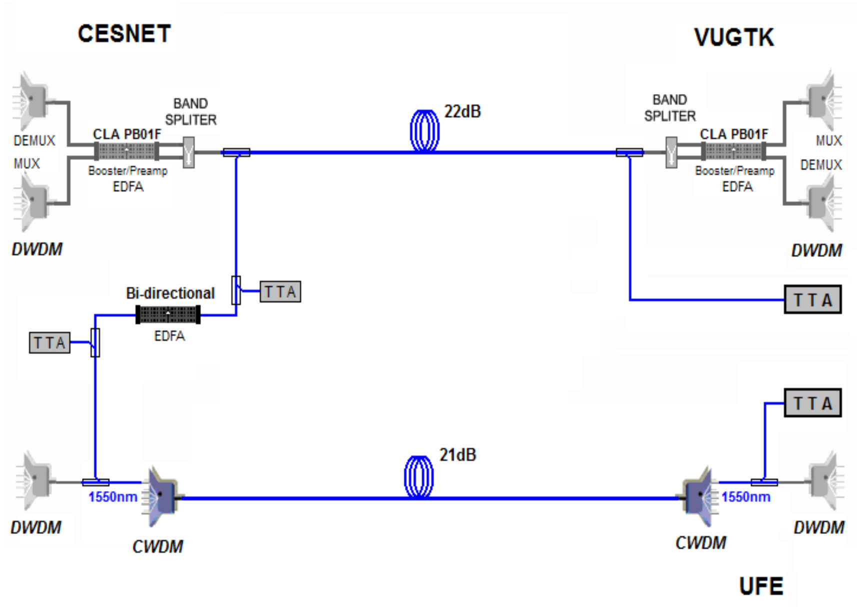


Figure 4.2: Path UFE (Praha) – VUGKT (Pecny): concatenation of passive lambdas

4.1.1.2 *Bi-Directional Alien Lambda Bypassing DWDM Devices*

This architecture is mainly used within the REFIMEVE+ project in France, aiming to deploy a national infrastructure on RENATER DWDM backbone to disseminate an ultra-stable frequency towards scientific laboratories. The metrological signal is transmitted bi-directionally through each dark fibre to compensate it precisely, so this solution is not compliant with usual DWDM technology, which requires isolators.

Figure 4.3 depicts the Nancy–Reims link on RENATER, equipped for REFIMEVE+ transmission.

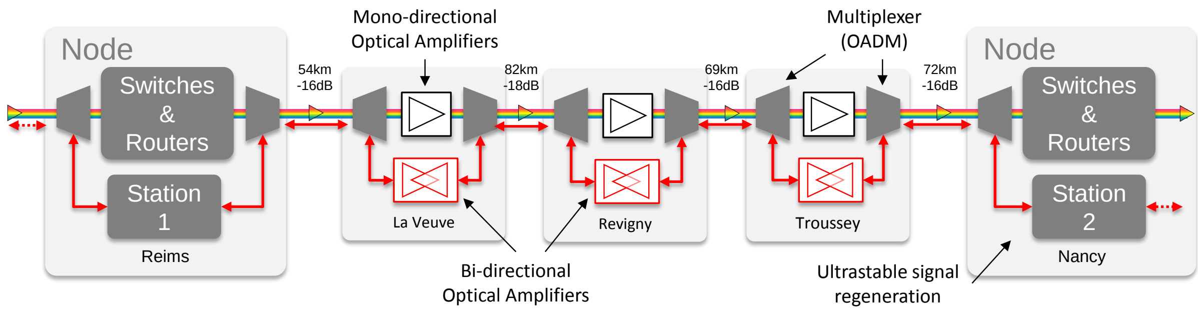


Figure 4.3: Detailed scheme of a span between Reims and Nancy

Dedicated OADMs are installed on each PoP and in-line amplifier (ILA) to make the metrological signal (in red) bypass DWDM equipment. Once extracted in ILAs, the signal is reamplified separately from the NREN signal. This insertion of OADM causes an extra attenuation of 1.6 dB on each span.

CESNET reported in 2014 on precise time transmission over the 306 km line Praha–Brno [42]. This line features both C- and L-band transmission systems. The excessive attenuation of 27 dB in the span Praha–Potehy was solved by creation of a bi-directional ILA site only.

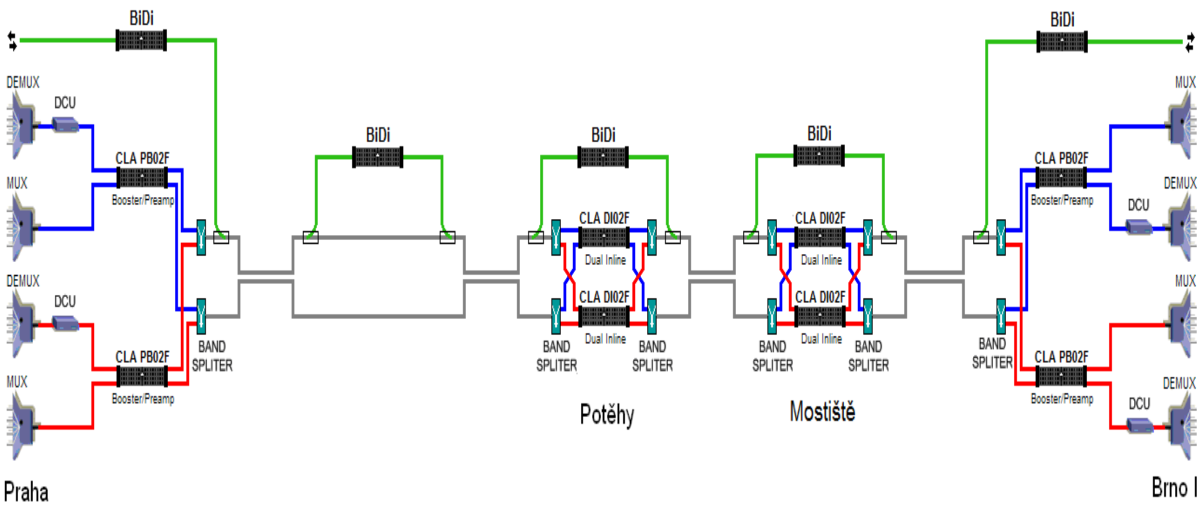


Figure 4.4: Praha–Brno line, C- and L-band systems deployed, 306 km

4.1.1.3 *Uni-Directional Alien Lambda*

The uni-directional alien lambda solution, less accurate than bi-directional solutions (10^{-16} instead of 10^{-20} for 1,000 km), avoids the problem of coping with transmission devices uncompliant with DWDM equipment. The metrological signal is transmitted through the whole photonic layer provided by the NREN/carrier, including through uni-directional EDFA.

Precise time transmission between Praha and Vienna over uni-directional lambdas has operated successfully since 2011 [42]. Lambdas pass through two different transmission systems, allowing comparison of national approximation of UTC: UTC(TP) and UTC (BEV).

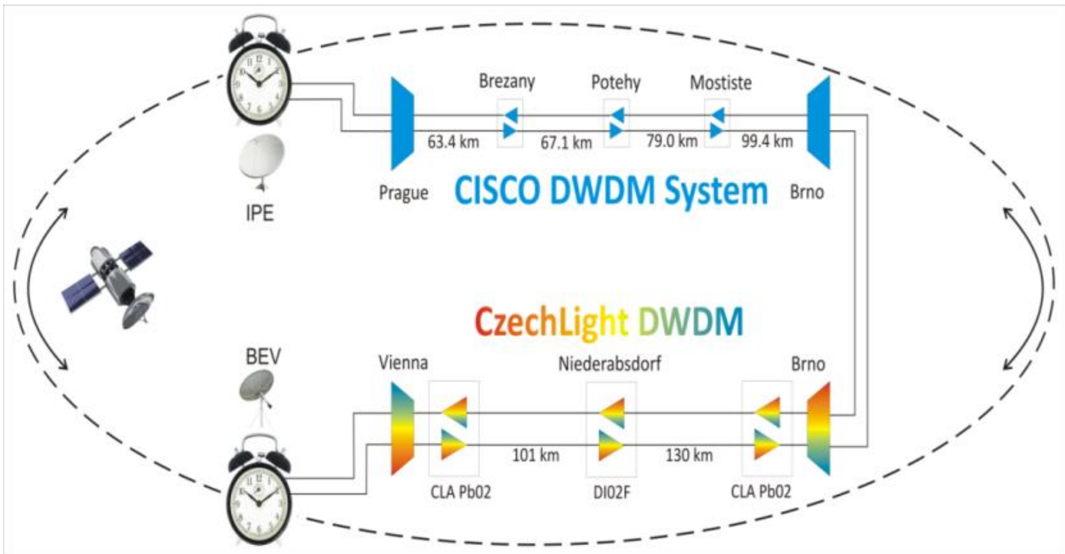


Figure 4.5: Two uni-directional lambdas used for time transmission between Praha–Vienna, 2 x 550 km

4.1.2 Experimental Results

4.1.2.1 *Paris–Strasbourg: Frequency Transfer*

In 2015, a performance evaluation was realised on the first branch of the REFIMEVE+ network, from Paris to Strasbourg [43]:

- Paris–Nancy–Paris (1,100 km).
- Paris–Strasbourg–Paris (1,480 km): extension of Paris–Nancy link.

On Paris–Nancy–Paris, a frequency stability of 4×10^{-16} at 1 s integration time was demonstrated, which averages down to 5×10^{-20} at 60,000 s integration time. This stability performance allows the best optical clocks to be compared after only 100 s.

Figure 4.6 shows fractional frequency instability versus averaging time of the Villetaneuse–Nancy–Villetaneuse 1,100 km compensated optical link (red squares) and of its extension to Strasbourg (blue circles). The stabilities are calculated from -type data using modified Allan[1] deviation.

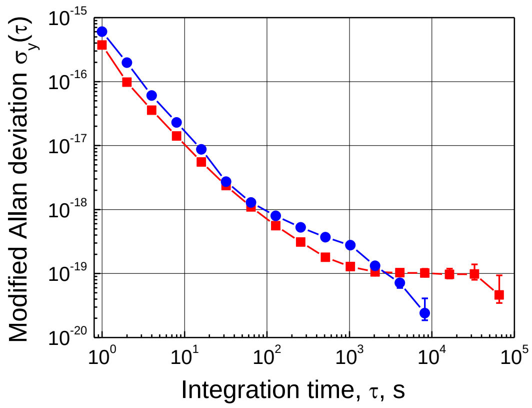


Figure 4.6: Fractional frequency instability versus averaging time of REFIMEVE+ network branch

On Paris–Strasbourg–Nancy, long-term stable operation of the link was more difficult than with the Nancy link. The REFIMEVE+ team observed instabilities of EDFA gains caused by the room-temperature variations. As the input optical signal can be very weak, the link stabilisation becomes more difficult to implement. At present this restricts long-term operation of the optical link, requiring unavoidable readjustment sessions.

4.1.2.2 *Paris–Strasbourg–Braunschweig: Sr Atomic Clock Comparison*

The REFIMEVE+ branch Paris–Strasbourg and the PTB link Braunschweig–Strasbourg join at the RENATER PoP in Strasbourg, where frequency comparison equipment is housed. In 2015 this setup made it possible to accomplish the first comparison of two strontium atomic clocks by long-haul fibre links, between two National Metrology Institutes (NMIs).

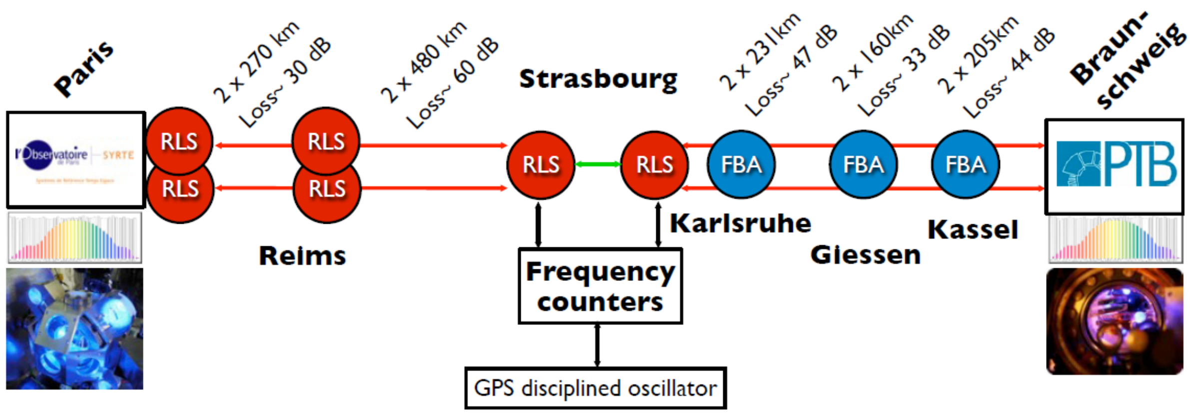


Figure 4.7: Topology of Paris–Braunschweig link with frequency comparison in Strasbourg

[1] Allan deviation is a measure of frequency stability in clocks, oscillators and amplifiers. For details see [44].

The French and German links, described in Figure 4.7, are built upon different transmission technologies. On the French side, the signal is periodically reamplified by repeater laser stations (RLS) and EDFA amplifiers, whereas the PTB use fibre Brillouin amplification (FBA).

Two independent frequencies are emitted from the French and German atomic clocks and those are compared in Strasbourg, where a GPS makes it possible to evaluate the frequency instability Sr_{PTB}-Sr_{SYRTE} as represented in Figure 4.8 below [45]:

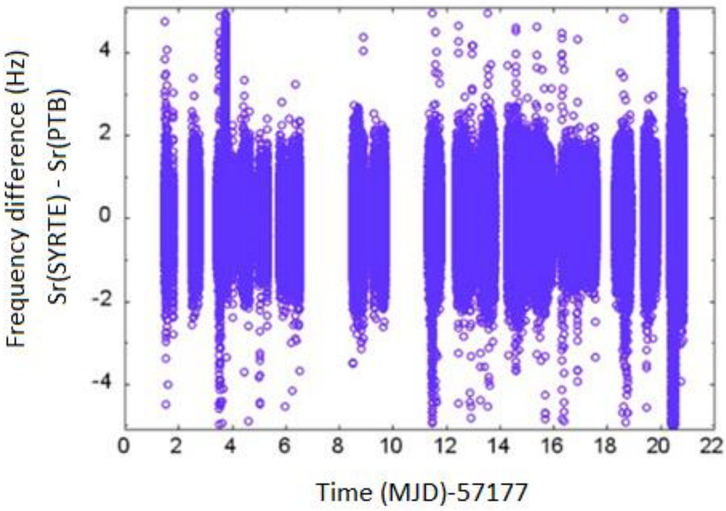


Figure 4.8: 25-day comparison of Paris and Braunschweig atomic clocks in Strasbourg

The frequency instability can also be expressed with the total Allan deviation, as in Figure 4.9, where one can see a statistical uncertainty lower than $3x10^{-17}$ during measurement over one day, and of $2x10^{-17}$ from 5,000 to 50,000 seconds.

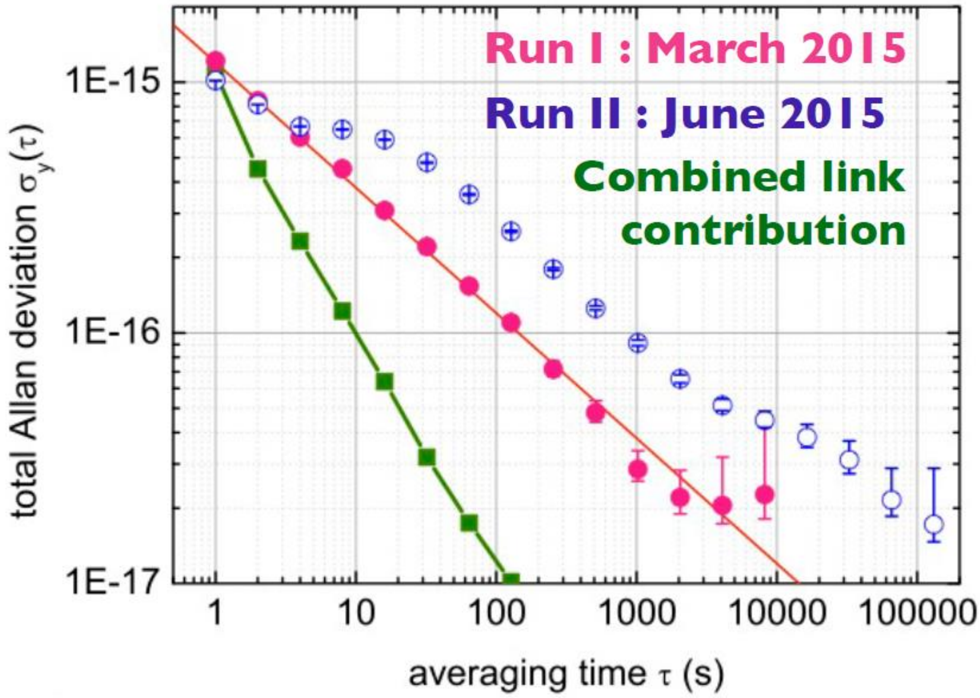


Figure 4.9: Frequency instability during two phases of experimentation

The stability of time transfer is usually expressed in terms of Time Deviation (TDEV), introduced for the first time in *All optical two-way time transfer in strongly heterogeneous networks* [42]. A comparison of uncertainty between optical time transfer and GPS-based methods at the link Praha–Vienna (as in Figure 4.5) is shown in Figure 4.10. The link connects Czech and Austrian laboratories of the National Time and Frequency Standard. In both of them GPS calibration receivers are installed, allowing comparison of national representation of timescales: UTC(TP) in Praha and UTC(BEV) in Vienna. This way optical time transfer (red line) can be directly compared with GPS-based time transfer. The green line is TDEV of the Common View (CV GPS) method, when the signal of the same GPS satellite, visible from both sites, is compared. The blue line shows the results of the precise point positioning (PPP) technique, which uses GPS phase and code observations for data post-processing.

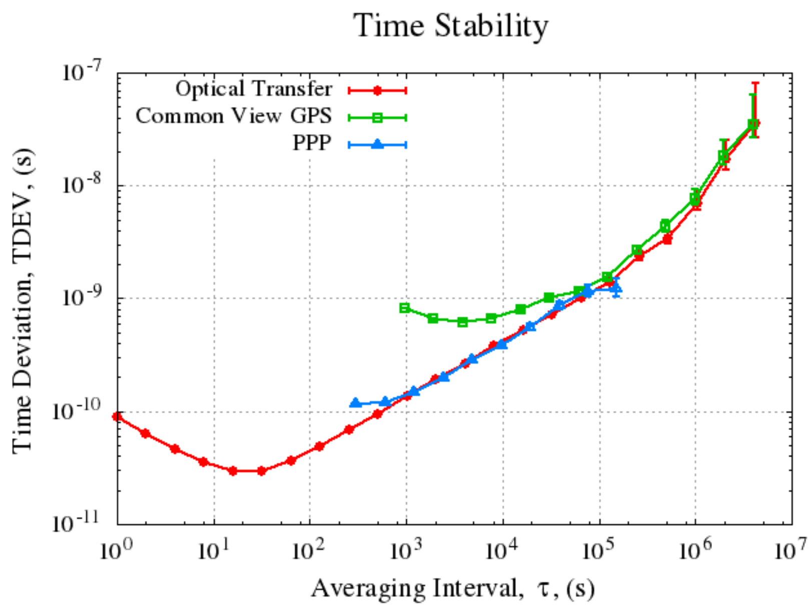


Figure 4.10: Optical and GPS time transfer Praha–Vienna, 550 km

Time transfer stability measured between two atomic clocks (a caesium clock in Praha and a hydrogen maser in Brno, with the link as in Figure 4.4) is shown in Figure 4.11. The descending part of the graph is typical for white phase noise, which is reduced as the averaging interval increases. For intervals longer than 10 s, the white frequency clock (ascending part of graph) of the used clocks dominates and therefore the influence of noise produced by the time transfer system is hidden. According to Figure 4.11, the smallest uncertainty attained for Praha–Brno time transfer is 17 ps over an averaging interval of 8 s.

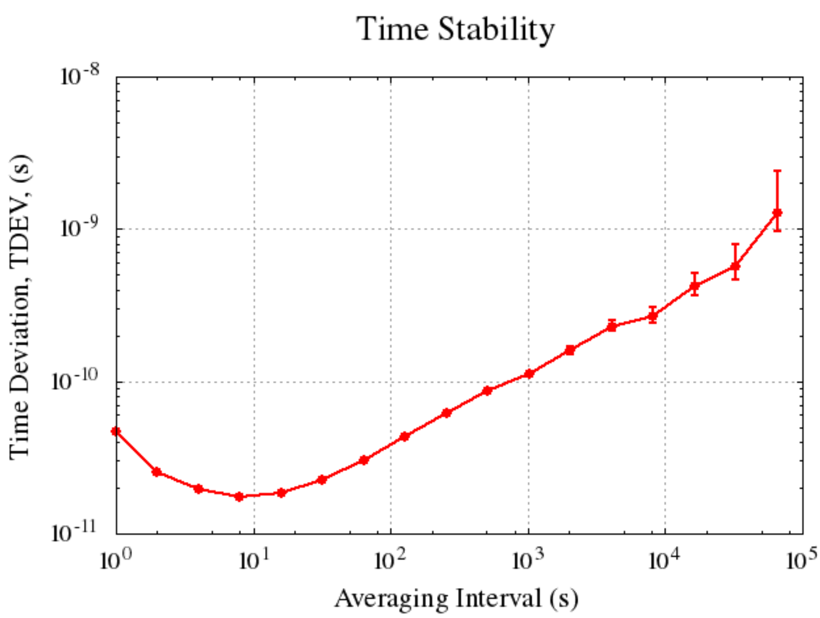


Figure 4.11: Time transfer Praha–Brno

4.1.3 Conclusions: Management of Waves for Frequency Distribution

Transmission using uni-directional waves can be handled with mature technology, using common alien waves at high performance, which still out-performs GNSS methods.

The precise time and ultra-stable frequency transmission as a bi-directional alien wavelength is in its infancy. Most deployed links are point-to-point on a fixed wavelength. It is difficult to regenerate a signal to a different wavelength because of the price of the precise lasers and transceiver stations, and because most amplifiers and transmission equipment are prototypes and need to be industrialised.

Consequently, several challenges need to be solved to pave the way to a remotely controlled, automated and flexible metrological network:

- To be able to "multicast" the ultra-stable frequency to different PoPs (a first experimentation was performed in 2015 within the REFIMEVE+ project [46]).
- To be able to monitor these signals at the optical layer, given that they are narrow and bi-directional.
- To create and to test SNMP MIBs and/or an alternative solution to remotely monitor metrological equipment.
- To find a reliable and cost-effective way to monitor third-party equipment (i.e. metrological in-line amplifiers) in NREN ILAs.
- To define best practices for metrological network configuration (amplifier gains, optical powers to be chosen to achieve the best performance without disturbing NREN traffic) in order to model metrological alien wavelengths on NREN DWDM infrastructures.
- To understand the kinds of incidents that can occur on a metrological network, to train efficiently the NREN and GÉANT NOCs.

4.2 Time Distribution in Layer 3

For the synchronisation of clocks throughout a network, the precision time protocol (PTP) (IEEE 1588 protocol) was proposed to obtain clock accuracy in LANs in the sub-microsecond range. With such accuracy, PTP is suitable for measurement and control systems [47] and provides precision beyond network time protocol (NTP). PTP also has the advantage that costs for GPS receivers can be reduced, as not all nodes in the network need to have access to GPS signals: PTP slaves (for example, at locations where GPS signals are inaccessible) can be used, which obtain their clock synchronisation by using the reference of a GPS-based PTP grandmaster clock at another location within the network.

Since PTP was initially designed for LANs, several experiments were conducted during GN4-1 to determine the level of clock synchronisation with PTP over wide area networks where longer distances with higher delays are involved, which will affect PTP's delay-based algorithm. The following sections describe experiments over MPLS tunnels, as well as long-term tests of PTP synchronisation over the Internet.

4.2.1 PTP Validation over MPLS Tunnels

IEEE 1588 / PTP was developed to distribute high-precision time and frequency over packet-switched networks. Such high precision can only be achieved if all network elements (in particular, all switches and routers) support PTP on the hardware layer. Currently, most of the installed switches and routers in a network do not support PTP.

MPLS is a common technology for network providers (e.g. NRENs or commercial providers) to offer IP or Ethernet services to different customers or separate networks logically, in particular for wide area networks (WANs). The following measurements investigate the potential and properties of a typical MPLS service to transport time-sensitive data and the corresponding time synchronisation via PTP.

4.2.1.1 *Network Environment of the Test and Results*

The WAN consists of Cisco routers connected via 10 GE links. An MPLS tunnel was established between Munich and Frankfurt and between Frankfurt and Berlin. The bandwidth of these tunnels was not limited. L2 measurements were taken to evaluate the characteristics of these tunnels; results showed the packet jitter was within a range of 50 – 60 us.

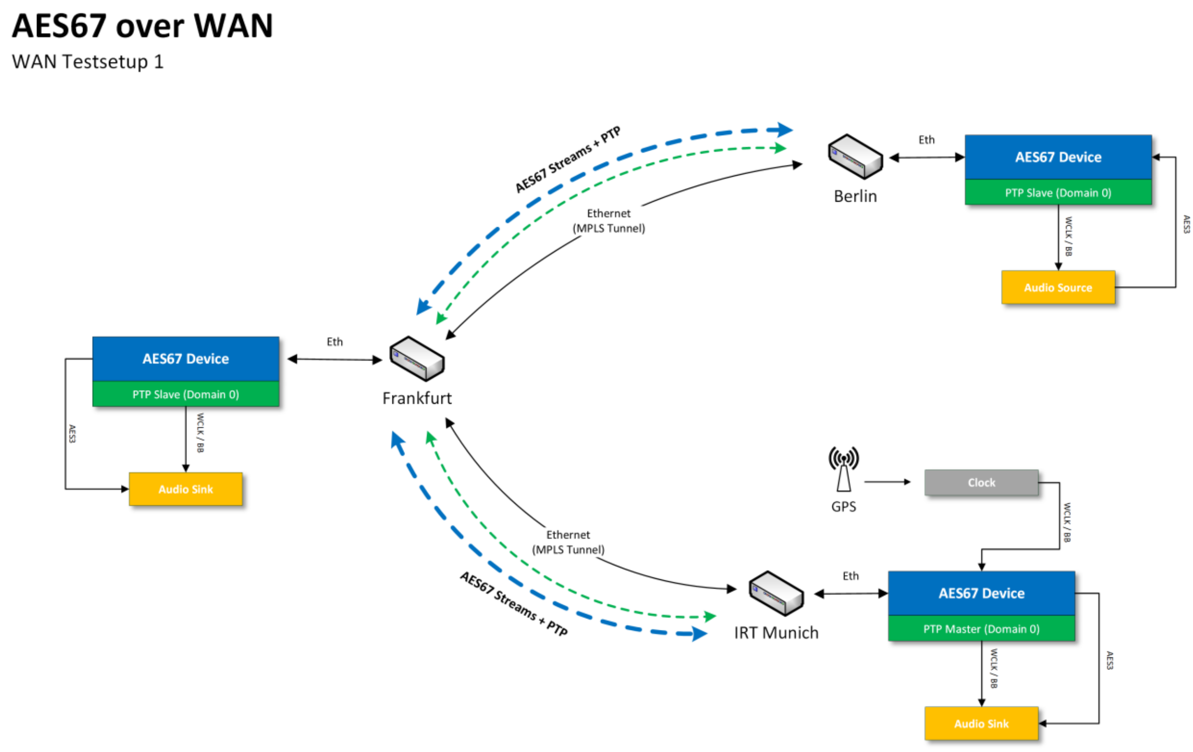


Figure 4.12: Test setup 1 in AES over WAN tests

A linear audio stream (based on AES67-Standard) was used as a time-sensitive data application.

In test setup 1 (shown in Figure 4.12), the PTP grandmaster (GPS synchronised) was located in Munich. PTP traffic was transmitted in-band, and transmitted at the same tunnel as the audio traffic.

Every audio source and sink was synchronised via PTP. However, it was not possible to set up an error-free audio transmission and audio click noises could be heard permanently. As the quality of the audio signal was distorted to such a high extent, it was not even necessary to use any audio measurements to evaluate the audio quality.

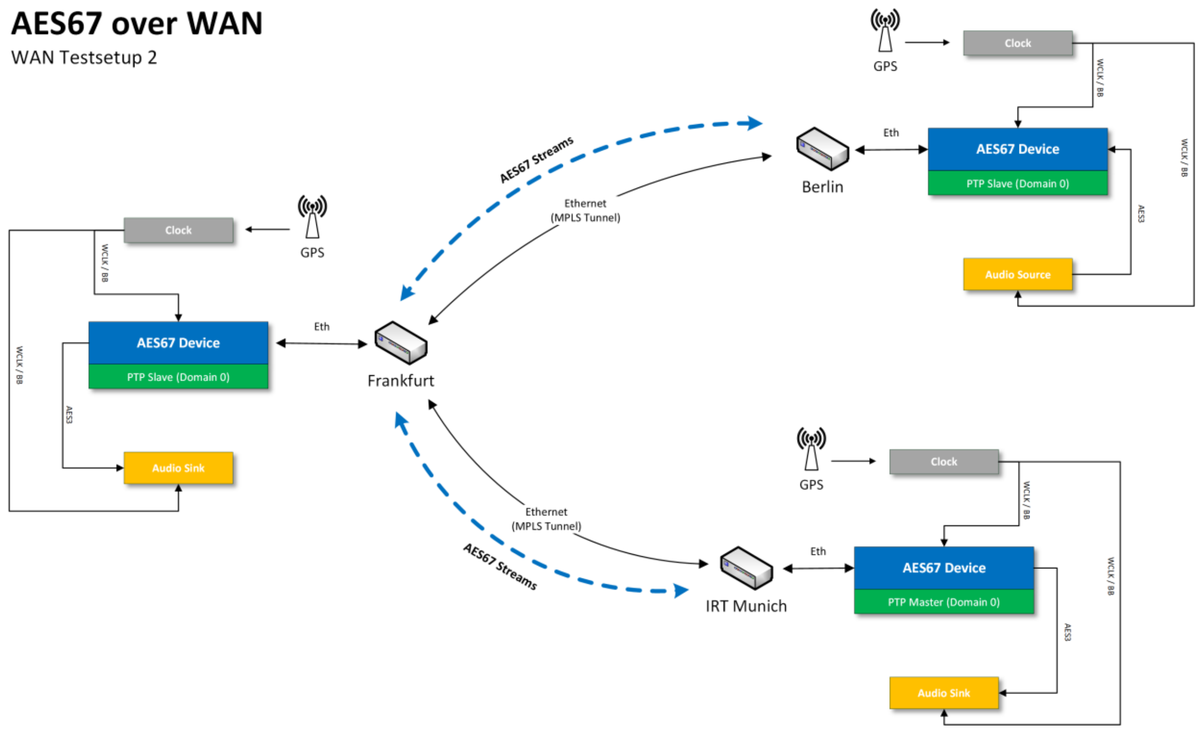


Figure 4.13: Test setup 2 in AES over WAN tests

In test setup 2 (shown in Figure 4.13), a PTP grandmaster (GPS synchronised) was located at every location. The time and frequency synchronisation was done out-band via GPS and not via the MPLS tunnel. In contrast to test setup 1, an error-free audio transmission was possible. Audio clicks were not heard and measurements of audio quality levels confirmed the subjective impression.

There are two possibilities to explain such different behaviour: first, the PTP synchronisation via an MPLS tunnel was not precise enough. Second, it could also be the case that PTP implementation of the audio (AES67) equipment was limited in some way.

In a LAN environment, the AES67 devices worked without error. A back-to-back test of the AES67 devices with series-connected WAN emulator indicated that a PTP packet jitter of 50 us caused permanent audio clicks as described above.

Currently, the tests described here are being repeated using different AES67 devices. To reduce the PTP packet jitter, the network design will also be changed.

Existing standards and recommendations do not describe the necessary accuracy of PTP for provisional audio and video applications.

4.2.2 Long-Term PTP Tests over Standard Internet Connection

Over the course of several weeks, PTP tests were also conducted over the Internet between Erlangen, Germany and Prague, Czech Republic. A (GPS-synchronised) PTP grandmaster was placed in Prague and a PTP slave 500 km away in Erlangen used this Czech grandmaster as a reference signal. When the tests were first started on 21 September 2015, the slave detected the reference signal within 30 seconds and confirmed a sync. Until the end of the tests on 9 November 2015, the slave had lost its reference signal four times and changed its state to uncalibrated (Table 4.1).

Reference disconnected	Reference (re)detected	Time duration	Days between glitches
2015-10-07 18:27:29 UTC	2015-10-07 18:30:47 UTC	0:03:18	22 days
2015-11-02 18:50:55 UTC	2015-11-02 18:52:46 UTC	0:01:51	26 days
2015-11-02 18:59:47 UTC	2015-11-02 19:01:29 UTC	0:01:42	0 days
2015-11-04 17:16:33 UTC	2015-11-04 17:30:51 UTC	0:14:18	2 days

Table 4.1: Slave disconnected and reconnected to reference signal

Path delay values and clock offset values were investigated for three periods: 21–25 September, 28 September – 9 October, and 31 October – 9 November 2015. Path delay values between Erlangen and Prague in these intervals ranged from a minimum of 4.883 ms to a maximum of 26.432 ms. This maximum path delay occurred on 7 October, when the slave lost its reference to the grandmaster (Figure 4.14):

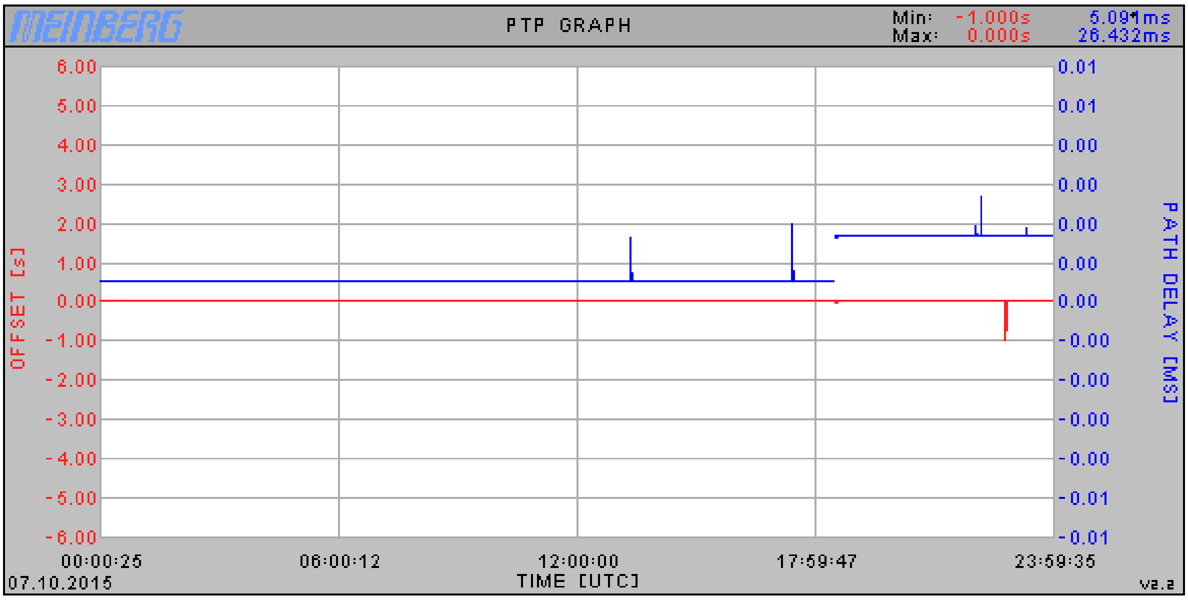


Figure 4.14: Offset and path delay on 7 October 2015 between Erlangen and Prague

Such a jump in delay is indicative of packets suddenly being rerouted over a different path. The reference disconnect happened as a consequence at the same time (18:50:55).

On 2 November 2015 the slave got disconnected from its reference in Prague twice between 18:50:55 and 19:01:29 UTC. The path delay measurements during that time span show an increased elevation with higher variation compared to the hours before and after the reference signal was lost (Figure 4.15):

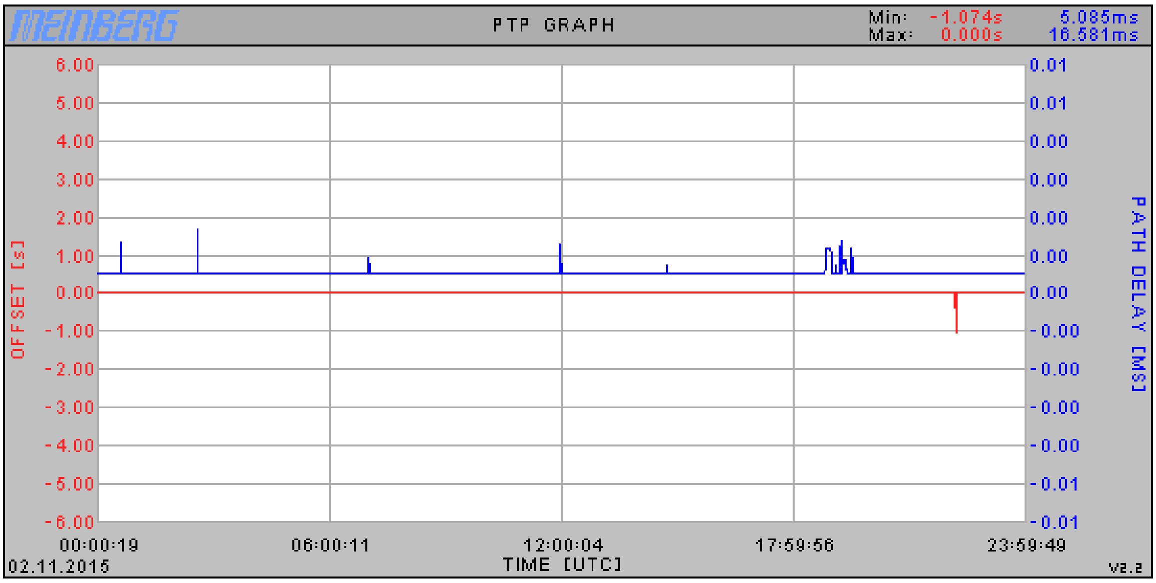


Figure 4.15: Offset and path delay on 2 November 2015 between Erlangen and Prague

On 4 November 2015 the measurements show that at the time of the sync disconnect of the slave from the grandmaster no values were registered, neither for clock offset nor for path delay (Figure 4.16):

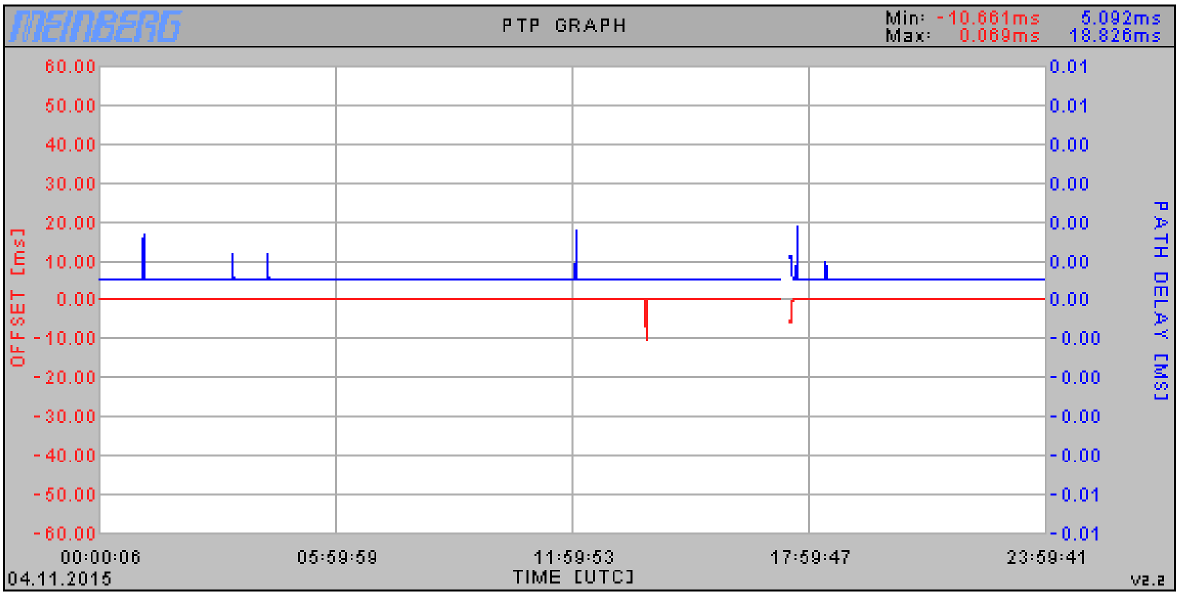


Figure 4.16: Offset and path delay on 4 November 2015 between Erlangen and Prague

At this time it is unclear what caused the interruption of measurements and the loss of the reference signal.

4.2.3 Conclusions and Recommendations

These long-term measurements show that adverse network conditions can lead to a loss of the reference signal that the PTP slave obtains from the grandmaster clock. Clock offsets in a range of milliseconds and even seconds are also quite large. The tests should be repeated, placing grandmaster and slave in closer proximity to each other to see how favourable shorter path delays may be. More investigations need to be done over varying distances, and also longer distances and longer timeframes, in order to be able to determine how far away slaves can be placed from PTP grandmasters and how exactly network conditions such as jitter affect slave calibration to the grandmaster.

In the audio tests AES67 over WAN described above, there was jitter in the MPLS tunnel as low as 50 – 60 us; nevertheless, it was not possible in the tests to have a clear audio without distorting noise. More experiments have to follow to determine if such network jitter values are to be blamed for audio distortions or if different equipment could lead to better results. As existing standards and recommendations do not describe the level of accuracy of PTP needed for provisional audio and video applications, many additional tests are needed in various scenarios to be able to narrow down network jitter or loss requirements.

5 Network Dynamicity

Network dynamicity is the ability of a network to respond and adapt rapidly and optimally to changing demands and/or conditions in terms of resources, traffic, service usage and failures among other aspects. It is key to enabling national resource and education networks to meet new and changing service requirements.

To fully utilise the increased capacity as described in Sections 2 and 3, it should be possible to orchestrate the network resources, optionally combined with orchestration of compute and storage resources. Software-defined networks (SDN) have gained momentum, mainly in the packet layer, as the new paradigm for controlling network resources and to provide programmability of network functions. The concept of SDN is also moving into the transport layer, which enables integrated, layerless approaches for restoration, taking both the transport and the packet layer into consideration.

This section addresses the control and orchestration of transport network resources. First, in Section 5.1, the basics of traditional SDN and how it applies to transport SDN are reviewed and the main trends are reported. The focus is then placed on the extensions to the OpenFlow protocol to support transport networks (Section 5.1.2), before moving up to the orchestration layer where application-based network operations (ABNO) as an orchestration tool is described (Section 5.1.3) and a deployed partner-developed demonstrator is discussed (Section 5.1.4). Second, a special use case to optimise a failure scenario in the NORDUnet network is used to conceptually evaluate the potential benefits of using transport SDN in combination with an open network operating system (ONOS) to provide layerless restoration.

5.1 SDN and Transport SDN Review

The availability of the flexible grid technology facilitates finer spectrum utilisation and the evolution towards elastic optical networks (EON). Deploying elastic optical networks based on the flexible grid technology, different services can be provided by adapting optical connection frequency slot width to the requested bitrate. A provisioning algorithm has to compute a route and find a frequency slot that must be contiguous in the spectrum and the same along the links in its route [48], in the absence of expensive spectrum converters. In addition, the algorithm has to decide from among different modulation formats so as to efficiently use optical resources as a function of the length of the computed route.

Notwithstanding those advances, dynamicity at the optical layer has been kept rather limited so far as a result of the large traffic aggregation performed in the upper network layers. Hence, optical transport networks are currently statically configured and managed. In fact, long planning cycles upgrade and prepare optical transport networks for the next planning period, where spare capacity is usually installed to ensure that traffic forecast and failure scenarios can be supported.

Nevertheless, due to the introduction of new services, such as datacentre interconnection, that NRENs must provide, huge changes in the traffic, not only in volume but also in its distribution and dynamicity, can be anticipated.

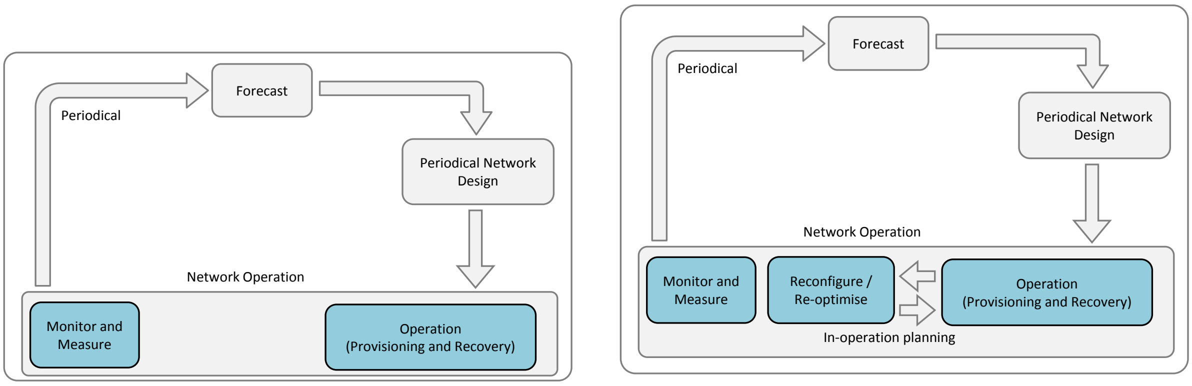


Figure 5.1: Transport networks lifecycle with (a) dynamicity and (b) in-operation planning

The network lifecycle therefore consists of several steps that are performed sequentially. The initial step receives inputs from the service layer and from the state of the resources in the already deployed network and configures the network to be capable of dealing with the forecast traffic, for a period of time. Once the planning phase produces recommendations, the next step is to design, verify and manually implement the network changes. While in operation, the network capacity is continuously monitored and that data is used as input for the next planning cycle (Figure 5.1(a)).

Dealing with traffic dynamicity requires connection provisioning to be automated, which explains the development of centralised architectures based on the software-defined networking (SDN) concept.

SDN decouples the network control and forwarding functions, enabling the network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services. SDN is dynamic, manageable, cost-effective and adaptable, making it ideal for the high-bandwidth, dynamic nature of today's applications.

Operating the network dynamically might bring cost savings, but it also might cause non-optimal network resource utilisation. To solve that, network resources can be made available by applying in-operation network planning [49], i.e. by reconfiguring and/or re-optimising the network on-demand, which leads to an extended network lifecycle (Figure 5.1(b)).

5.1.1 Developments in Transport SDN

The evolution of SDN and its further advancement have played a most significant role in the development of next-generation packet networks to meet the upcoming social needs of the growing population. SDN as a programmable network having “service provisioning on the fly” has induced a keen interest both in the academic world and in industry.

The concept of SDN derives its basis from the computer engineering area, where an abstraction-based architecture has simplified the programming problems of writing and maintaining software. Abstraction is the process by which data and programs are defined with a representation similar in form to its meaning, while hiding away the implementation details. Different levels of abstraction can be defined, providing different amounts of detail (high and low levels) and, in turn, creating different interfaces (instances of abstraction). The objective of the SDN paradigm is realised by redesigning the architecture of networks in order that they operate in a similar way to that of computing architectures.

Figure 5.2 shows a logical view of the SDN architecture. Three layers can be identified in this architecture: an application layer, a control layer, and a data layer. Hence, the SDN paradigm envisions a network architecture where the network devices (routers, switches, optical nodes, etc.) become programmable. This objective is realised by introducing appropriate levels of abstraction that are accessible by applications through the use of control interfaces, specifically, application programming interfaces (APIs). The interface between the application layer and control layer goes under the name of northbound interface (NBI) and is specified by the API, while the interface between control layer and data layer is the southbound interface (SBI) defined by various protocol specifications, OpenFlow being the most popular.

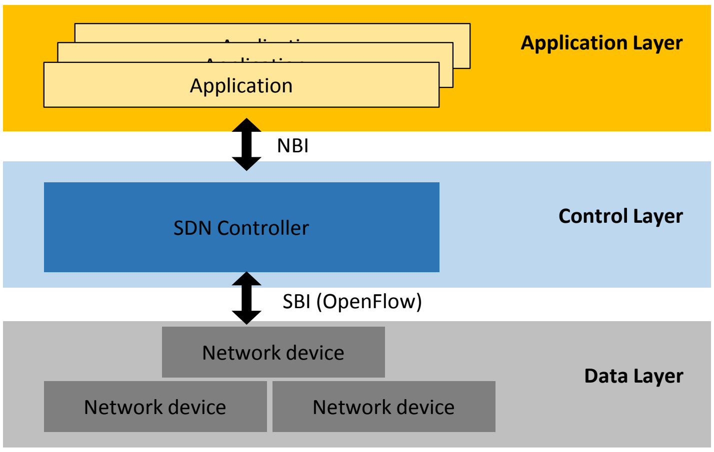


Figure 5.2: SDN architecture

Network intelligence is (logically) centralised in SDN controllers, which maintain a global view of the network. As a result, the network appears to the applications and policy engines as a single, logical switch. With SDN, enterprises and carriers gain vendor-independent control over the entire network from a single logical point, which greatly simplifies the network design and operation. SDN also greatly simplifies the network devices themselves, since they no longer need to understand and process thousands of protocol standards but merely accept instructions from the SDN controllers. A comparison between conventional networking and SDN is shown in Table 5.1.

Characteristics	Conventional Networking	Software Defined Networking
Features	Data and control planes are customised in each node. For each problem a new protocol is proposed with complex network control.	Segregates the data plane from the control plane with a centralised programmable controller that makes the network control simple.
Configuration	When new equipment is added into the existing network, the heterogeneity of the network devices' manufacturers and configuration interfaces requires a certain level of manual configuration procedures, which is tedious and error prone.	Unification of the control plane over all kinds of network devices, including routers, switches and load balancers, permits automated configuration with centralised validation via software controlling. As such, an entire network can be programmatically configured and dynamically optimised based on network status.
Performance	Due to heterogeneity among networking devices and coexistence of various technologies, optimising the performance of the network as a whole is difficult.	Provides an opportunity to improve network performance globally with centralised control and by having a feedback mechanism to exchange information among different tiers of the networking architecture.
Innovation	Difficulties are encountered while implementing new ideas and design due to widely used proprietary hardware, which prevents modification for experimentation and adoption.	Comparatively, SDN encourages implementation of new ideas, applications and new revenue-earning services conveniently and flexibly through the programmable network platform.
Cost	Both data and control planes are embedded on the switches, thereby making the switch more complex and costly.	Data plane and control planes are decoupled from each other which makes the structure of the switches simpler and easier to manufacture, which in turn leads to a lower-cost solution.

Table 5.1: Conventional networking and SDN comparison

The SDN approach has become very natural for store and forward packet networks, especially in the core-metro segments and, more recently, also in the access segment. The extension of the SDN architecture for optical networks poses several challenges. One of the key challenges in designing and operating optical networks is the interaction, control and management between the optical and packet layers.

Multiple standards bodies are currently working on developing SDN standards for the optical network. The two main standards/protocol efforts related to SDN in the optical network are generalised multi-protocol label switching (GMPLS) and OpenFlow:

- GMPLS is often used as the control plane for optical switching; it is a proposed IETF standard to simplify the creation and management of IP services over optical networks, and it is often used as the control plane for optical switching.
- SDN/OpenFlow was designed specifically for packet transport and needs modification to provide SDN-like control to the optical layer.

The Optical Transport working group within the Open Networking Foundation (ONF) is addressing SDN/OpenFlow control capabilities for optical transport networks [50]. The work includes identifying use cases, defining a target reference architecture for controlling optical transport networks incorporating OpenFlow, and creating OpenFlow protocol extensions. The identified use cases are:

- Direct control of optical components in enterprise networks.
- Carrier Ethernet network virtualisation.
- Service provider datacentre interconnection.
- Packet-optical integration.

Nevertheless, services such as content distribution, distributed databases, or inter-datacentre connectivity place a set of new requirements on the operation of networks. They need on-demand and application-specific reservation of network connectivity, reliability and resources (such as bandwidth) in a variety of network applications (such as point-to-point connectivity, network virtualisation or mobile back-haul) and in a range of network technologies from packet down to optical. An environment that operates to meet these types of requirements is said to have application-based network operations (ABNO) [51]. ABNO brings together many existing technologies and may be seen as the use of a toolbox of existing components enhanced with a few new elements. Some identified use cases are:

- Inter-AS connectivity.
- Pseudo-wire operations and management.
- Multi-layer networking.
- Network re-optimisation and adaptive network management.
- Cross-stratum optimisation.
- Virtual network topologies operations and management.

ABNO includes a provisioning manager responsible for the establishment of connections either by giving instructions to a GMPLS control plane running in the networks or by programming individual network devices. In the latter case, the provisioning manager would act as an OpenFlow Controller.

In addition, the current network architecture will need to evolve to include a functional block between the service layer and the network elements to support multi-service provisioning in multi-vendor and multi-technology scenarios. Two standard interfaces are required. First, the northbound interface (NBI), which, among other tasks, gives an abstracted view of the network, enabling a common entry point to provision multiple services and to provision the planned configuration for the network. Moreover, this interface allows coordination of the network and service layer according to service requirements. Second, the southbound interface (SBI), covering provisioning, monitoring and information retrieval.

5.1.2 ONF View on Transport Extensions

The potential of SDN, owing to its separation of control and data layer, is already visible in the packet world, with major vendor and service providers stepping forward to support products and services based on SDN technologies. The advantages of SDN for optical transport over existing control plane solutions, namely GMPLS, have been shown to be substantial with regard to several specific aspects. An SDN-based architecture can simplify the complexities of handling traffic among various networking technologies. It allows the underlying infrastructure to be abstracted and used by applications and network services as a virtual entity. This allows network operators to define and manipulate logical maps of the network, creating multiple co-existing network slices (virtual networks) independent of underlying transport technology and network protocols. Furthermore, the separation of the control plane and data plane makes SDN a suitable candidate for an integrated control plane supporting multiple network domains and multiple transport technologies. The architecture is not only well suited to address the present optical networking problems related to supporting different administrative and technology segments, bridging the gap between packet and optical layers, but it also supports new operations such as virtualisation, cross-layer orchestration, bandwidth on demand (BoD), load balancing and many more.

Due to the unique analogue features of the optical layer, various static and dynamic attributes and properties (e.g. modulation format, capacity, power, impairments) need to be considered in the process of optical resource abstraction. Depending on the type of the optical transmission and networking elements involved and the requirements of the upper layer operations, different levels of abstraction (i.e. the amount of information to be exposed to the upper layer) need to be defined.

One of the key challenges of optimally using the optical infrastructure is to create an abstracted optical resource model and describe it in a way that is simple enough for the higher control layer to utilise it while capturing the true properties of the distributed non-linear, noisy and dispersive analogue optical channel. Existing models are often conservative or over-simplified, and targeted to direct-detection systems, now superseded by digital coherent transmission systems. A key challenge here is to develop simplified models for the optical physical layer, starting from an understanding of the underlying physics of the optical channel and the optical layer analogue characteristics.

Within this technological context, the target of a unified, centralised control plane involves, on the one hand, extending the OpenFlow protocol to support circuit switching (that is, where a dedicated communications channel or circuit is established between end points) and, on the other hand, ensuring that operator use cases and workflows are fully covered. This is of importance since the operation of an optical transport network is significantly different to the operation of a packet switched network. For example, the former usually involves operator intervention before provisioning a new optical connection, and the lifetimes of services are on different timescales.

From a standardisation perspective, extending OpenFlow for optical networks is perceived to be a difficult task, given the intrinsic complexity of the optical technology. One of the reasons is that there is no common, comprehensive, abstract model of optical devices, such as reconfigurable optical cross-connects, nor the associated information and data models. That said, initial efforts are being made by the ONF Optical Transport working group and other standards-developing organisations, as well as in related research initiatives. In fact, the ONF Optical Transport working group has been working internally on preliminary OpenFlow extensions for multi-technology switches with GMPLS label encodings, complementing and adapted to OpenFlow 1.1. It is expected that newer versions will improve the support of optical networks, in order to address, in a more comprehensive way, identified requirements both for fixed- and flexi-grid, notably filter configuration and configuration of cross-connections of media channels in media matrices.

The northbound abstraction is crucial not only for defining application-based services and policies but also for integrating different technology and administrative domains, which are typical of optical-based core networks. The two main aspects to consider for the NBI are the set of functionalities that are exposed to external applications, together with the different interfaces that determine the different mechanisms used to interact with them.

The application abstraction is a common-map abstraction, based on a data abstraction of a network-wide common map manipulated by a network API. The common map has full visibility into both packet and circuit switched networks, allowing creation of network applications that work across multiple layers and multiple optical technologies. Full visibility allows applications to jointly and globally optimise network functions and services across multiple layers and technologies. Implementing network functions as centralised applications is simple and extensible, as the common-map abstraction hides the details of state distribution (including east-west API for multiple controllers) from the applications, allowing unified operation over multiple layers.

One way to represent information to applications is as graphs. A few implementations of transport network controllers, such as the open network operating system (ONOS) [52] and packet and circuit network convergence (PAC.C), use network graphs as the method to define northbound abstraction. These graph abstractions help optical network control and management functions to utilise the wealth of graph computation algorithms that are widely used in the optical world. Another added benefit is to use existing and emerging PCE orchestration architectures to allow applications to seamlessly define network requirements over multiple administrative and technology domains.

See also Appendix B for the latest document about OpenFlow transport extensions from ONF.

5.1.3 ABNO and Its Role as Orchestrator

Standardisation bodies, especially the IETF, have been working to address operators' and NRENs' requirements and, as a result, the application-based network operations (ABNO) architecture is now being proposed as a candidate solution. The ABNO architecture consists of a number of standard components and interfaces which, when combined together, provide a method for controlling and operating the network. A simplified view of the ABNO architecture is represented in Figure 5.3. It includes:

- The **ABNO controller** as the entrance point to the network for NMS/OSS and the service layer for provisioning and advanced network coordination. It acts as a system orchestrator, invoking its inner components according to a specific workflow.
- The **path computation element (PCE)** defined as an entity to serve path computation requests. The PCE protocol (PCEP) might be used to carry path computation requests and PCE responses.
- The **virtual network topology manager (VNTM)** coordinates virtual network topology (VNT) configuration by setting up or tearing down lower-layer connections, and advertising the changes to higher-layer network entities.

- The **provisioning manager** is responsible for the establishment of connections. This can be done by interfacing the control plane using PCEP or by directly programming the data path on individual network nodes using the network configuration protocol (NetConf) or acting as an OpenFlow controller.
- The **operations, administration and maintenance (OAM)** handler is responsible for detecting faults and taking actions to react to problems in the network. It interacts with the nodes to initiate OAM actions such as monitoring and testing new links and services.

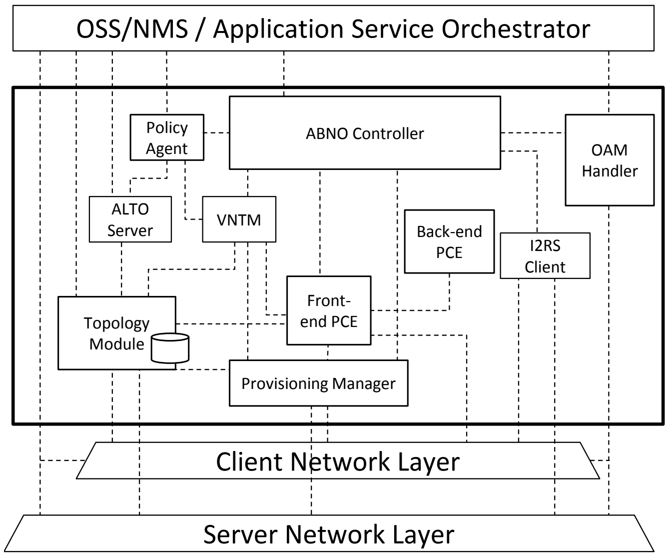


Figure 5.3: ABNO architecture

A multi-domain optical transport network composed of heterogeneous optical transport technologies (e.g. flexi-/fixed-grid optical circuit switching and optical packet switching) and control plane technologies (e.g. centralised OpenFlow or distributed GMPLS) does not naturally interoperate, and a network orchestration mechanism is required. A network orchestrator allows the composition of end-to-end network service provisioning across multi-domain optical networks comprising different transport and control plane technologies. SDN is a key technology to address this requirement, since the separation of control and data planes makes the SDN a suitable candidate for end-to-end provisioning service orchestration across multiple domains with heterogeneous control and transport technologies.

The ABNO architecture is the ideal element for such orchestration. Figure 5.4 presents the building blocks of the ABNO architecture that are required to support the multi-domain and multi-layer network orchestration. The orchestration controller runs the different workflows and can interwork with the different blocks. The topology module gathers the domain topology of each SDN/OpenFlow domain controller exposed by the NBI and/or the GMPLS/PCE domain through new protocols such as BGP-LS to obtain the traffic engineering database (TED) by BGP peering. The TED stores the global network topology, which is composed of the intra-domain topologies with the inter-domain links connecting them. The PCE handles the path computation across the network graph provided by the topology module and needs to be extended to deal with OpenFlow datapath identifiers. The provisioning manager is responsible for the actual flow-establishment requests to the OpenFlow domain controllers through each specific controller's NBI, and to the AS-PCE of the GMPLS domains.

The flow server is responsible for storing the state of the provisioned flows in the label switch path database (LSPDB). Finally, the VNTM is responsible for coordinating the path provisioning in multi-layer networks by performing the layered establishment of connections in the server layer (e.g. optical connections) and its promotion as a logical link in the client layer (e.g. IP). It is worth mentioning that the NBI of the SDN/OpenFlow or GMPLS/PCE controllers is typically technology and vendor dependent. Thus, the network orchestrator shall implement different plugins for each of the controllers' NBIs.

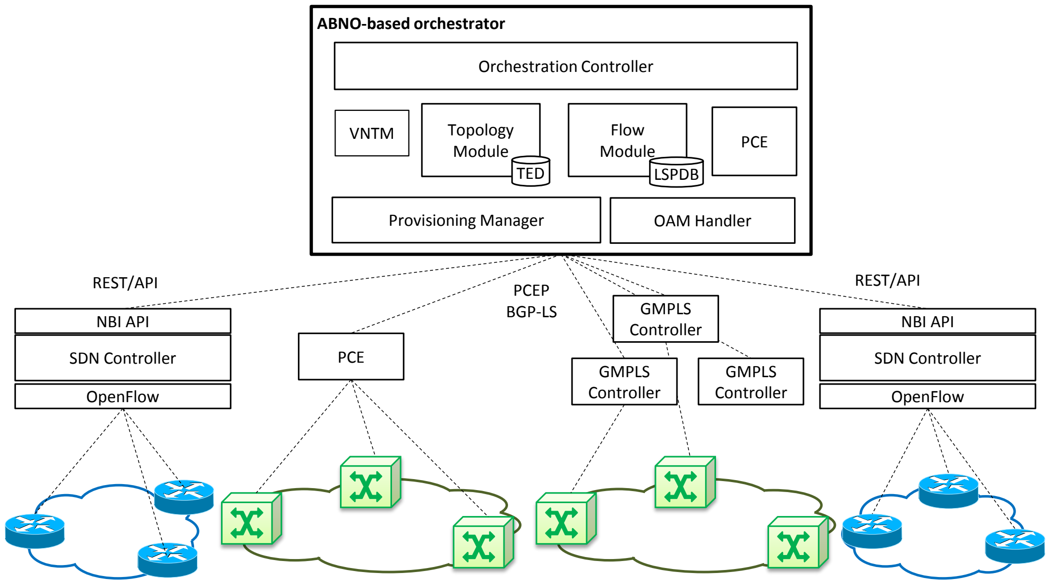


Figure 5.4: ABNO-based network orchestrator

5.1.4 ABNO-Based Integrated Demonstrator

An emulated environment is being developed within JRA1 Task 1. Figure 5.5 shows the optical domain architecture where an SDN controller has been deployed and is being studied. The SDN controller has a database storing the network topology, the state of the network resources, and the already established connections (label switched paths (LSPs)).

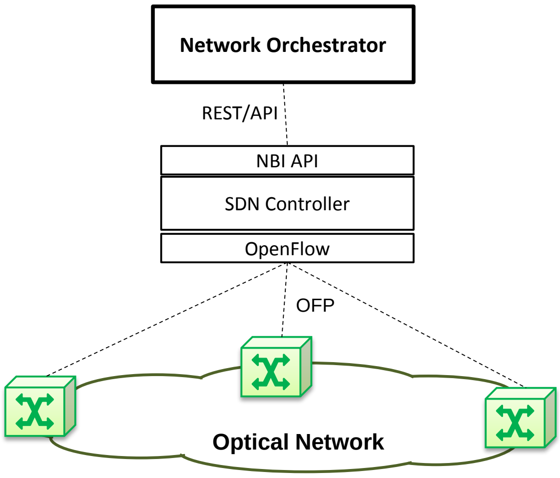


Figure 5.5: Optical domain demonstrator architecture

To control the network elements from the SDN controller, the OpenFlow protocol (OFP) has been used. Since OFP v1.4, new properties in support of optical ports have been added, allowing configuration and monitoring of the laser in the transmitter, and of frequency and power in the receiver. These properties support optical ports in optical cross-connects (OXC). However, they do not include modulation format support for the transmitters. In view of that, the Task has implemented extensions to OFP v1.4 to support modulation formats in the form of EXPERIMENTER properties. The following sub-sections define the extensions implemented in OFP v1.4.

5.1.4.1 *Port Description*

Regarding the port description, the standard `ofp_port_desc_prop_optical` currently retrieves the port features (RX tunable, TX tunable, TX power adjustable, values specified in frequency or wavelength units), minimum and maximum TX and RX frequency/wavelength, TX and RX grid spacing in frequency or wavelength units, and minimum and maximum TX power. To extend those, Task 1 has implemented a new experimental property to obtain the modulation formats supported by the port. The property is named `ofp_port_desc_prop_experimenter_modulation_formats` and its structure is as follows:

```
  struct ofp_port_desc_prop_experimenter_modulation_formats {
      uint16_t type;               /* OFPPDPT_EXPERIMENTER. */
      uint16_t length;             /* Length in bytes of this property. */
      uint32_t experimenter;       /* Experimenter ID. */
      uint32_t exp_type;           /* Type=1 Modulation Formats Description. */
      uint8_t num_mod_formats;     /* Number of modulation formats supported. */
      uint32_t mod_formats[0];      /* List of modulation formats supported. Each following
structure
                                      ofp_port_desc_prop_experimenter_modulation_format. */
      uint32_t pad[0];             /* 64-bit alignment */
  };

  struct ofp_port_desc_prop_experimenter_modulation_format {
      uint16_t id;                 /* Identifier of the modulation format. */
      uint16_t bits_per_symbol;    /* Spectral efficiency in bits per baud. */
  };
```

5.1.4.2 *Port Configuration*

Port configuration messages currently support the definition of configuration flags, central frequency, offset, slot width and transmission power of the port, but not the desired modulation format configuration. The Task has implemented a new experimental property to set the desired modulation format of the port. The property is named `ofp_port_mod_prop_experimenter_modulation_format` and its structure is as follows:

```
struct ofp_port_mod_prop_experimenter_modulation_format {
    uint16_t type;                  /* OFPPMPT_EXPERIMENTER. */
    uint16_t length;                /* Length in bytes of this property. */
    uint32_t experimenter;          /* Experimenter ID. */
    uint32_t exp_type;              /* Type=1 ModulationFormatConfiguration. */
    uint16_t  mod_format_id;           /* Modulation format id. One from Modulation Formats
Description. */
    float_t symbol_rate;              /* Symbol rate in bauds/s formatted as an IEEE 32 bit
float */
    uint16_t num_subcarriers;       /* Number of subcarriers used. */
    uint16_t  bits_per_symbol;        /* Bits per symbol as reported in Modulation Formats
Description. */
    uint32_t pad[0];                /* 64-bit alignment */
};
```

5.1.4.3 *Optical Frequency Slot Matching*

The optical label for WDM specifies the grid identifier, the channel spacing and the nominal central frequency index, as defined in IETF RFC6205 [53]. In the case of the flexible grid technology, an extra field defining the slot width has to be included, as defined in [54].

In the demonstrator, the Task has used a 20-bit MPLS-like label, the structure of which actually depends on the technology used.

```
 0                   1
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|GR | CS  |         n         | t  | RES |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

WDM label format

```
 0                   1
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|GR |         n         |      m     | t  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Flexible grid label format

The fields in the label are as follows:

- **Grid** (GR, 2 bit): Supported values are 01 for ITU-T DWDM, 10 for ITU-T CWDM, 11 for flexible grid and 00 is a reserved value.
- **Channel Spacing** (CS, 3 bits): Supported values are 001 for 100 GHz, 010 for 50 GHz, 011 for 25 GHz, 100 for 12.5 GHz, 101 for 6.25 GHz, and 000 is a reserved value. For flexible grid technology, this field is assumed to be 6.25 GHz.

- **Nominal Central Frequency** index (n, 9 bits): The maximum spectrum width is 4 THz; when using 6.25 GHz slices, 640 possible indexes need to be representable. The reference central frequency, e.g. 193.1 THz, corresponds to n=0; n is a signed integer in two-complement notation, thus requiring 9 bits for its representation. The nominal central frequency is computed as 193.1 THz + n x CS / 1000.
- **Slot Width** (m, 6 bits): This field is used only in flexible grid technology. The field size for m has been computed to allow encoding a 1 Tb/s connection that, using the worst modulation format, e.g. QPSK, requires 20 frequency slices of 12.5 GHz.
- **Ethernet Type** (t, 3 bits): This field is not required by the IETF label format, but it is required in Task 1's integrated demonstrator since, when enveloping an Ethernet frame in an MPLS frame, its Ethernet type, e.g. ARP, IP, IPv6, IGMP, MPLS, etc. field is substituted by MPLS, thus preventing the reconstruction of the original frame at the receptor. For this reason, a field used to encode the original frame protocol was added. Supported values are: 0000 for ARP, 0001 for IP, 0010 for IPv6, 0011 for IGMP and 0100 for MPLS. Remaining values are reserved for future use.

5.1.4.4 *End-to-End Management*

In the case of a multi-domain/-layer network, a network orchestrator needs to be configured on top of the set of single-layer/-domain SDN controllers. To that end, the SDN controllers must export the underlying network topology and resources to the controller, so that an end-to-end view of the network can be created. The IETF is currently working on defining data models to specify optical networks based on YANG. Since YANG model definitions are still not defined, the Task decided to implement a REST/API in the demonstrator, so that the SDN controllers can export their topology and resources.

A different REST/API needs to be developed to set up, update or tear down an LSP. For the set-up operation an LSP identifier (symbolic path name) the end-points of the LSP and the explicit route object (ERO) needs to be provided. For the update operation, the LSP's symbolic path name and the new ERO are enough. For the tear-down operation, the LSP's symbolic path name is enough.

5.1.4.5 *Demonstrator Deployment*

The demonstrator to test the single-layer/-domain functionality described above has been experimentally implemented using Ryu SDN controller v3.25, since it supports all available OFP versions as well as the standardised optical port extensions. Controller applications developed for the Ryu controller use the cookie field in each flow configured in the network elements to identify the LSP for which that rule is being configured. The controller application has been implemented in Python and was configured with a northbound interface in the form of a REST API used to receive requests from an orchestrator. In addition, a southbound interface to control the underlying network elements has been configured to use OFP v1.4 with extensions to support WDM and flexible grid technologies.

Mininet v2.1.0 has been used to orchestrate the deployment and configuration of each network element in the topology. Each network element has been deployed using an OpenVSwitch v2.4.0 bridge with the optical extensions for WDM and flexible grid technology emulation. The Task emulated the transmission of an optical signal by encapsulating each Ethernet frame being converted from electrical to optical into an MPLS-like frame where the MPLS label encoded the optical spectrum label. Intermediate OXCs switched the frame according to that MPLS label and, at the receiver, the MPLS label is removed to restore the original Ethernet frame.

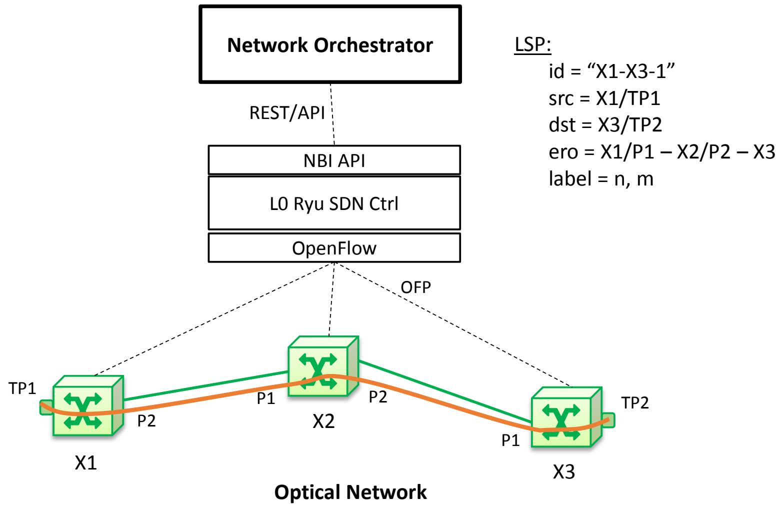


Figure 5.6: Example of LSP setup

When the network orchestrator needs to set up an LSP, it computes the LSP’s explicit route object (ERO), containing the resource assignment for that LSP along a route. For instance, in Figure 5.6, the LSP to be set up is between X1/TP1 and X3/TP2. Upon the reception of an ERO in the SDN controller, the ERO is used to configure the transmitter and receiver transponders and contains the source and destination end points specifying the node and its port. In the example in Figure 5.6, the source port is transponder TP1 in X1 and the destination port is transponder TP2 in X3. The ERO defines the set of individual connections to be set up in every OXC along the route and includes a label defining the frequency slot that must be used for the LSP along the route.

5.2 The NORDUnet UNINETT Use Case

This use case was selected for investigation because it represents a typical situation in a packet-optical network, where routing might not be optimal because of lack of coordination between the path calculation elements of different network layers.

5.2.1 The Problem

NORDUnet use three routers (R-USI, R-OSC, and R-TUG) for providing IP connectivity to UNINETT (Figure 5.7)[2].

[2] The case description was provided by Alberto Colmenero and Rasmus Lund from NORDUnet.

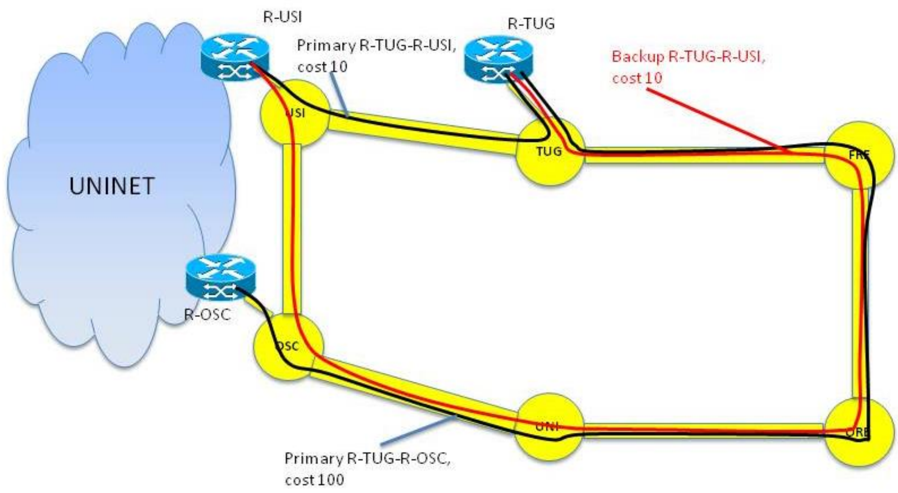


Figure 5.7: Packet and optical layers of NORDUnet

IP-traffic from NORDUnet to UNINETT is aggregated by R-TUG and sent to a UNINETT destination either through the R-TUG–R-USI primary connection (cost 10) or the R-TUG–R-OSC primary connection (cost 100). Both connections use the OTN/DWDM infrastructure circuits and have 10G capacity. The R-TUG–R-USI connection uses the direct TUG–USI circuit while the R-TUG–R-OSC connection uses the compound circuit TUG–FRE–ORE–UNI–OSC. The cost of the connections reflects the characteristics of the circuits they use, such as distance, number of spans, delays; that is why the cost of the R-TUG–R-OSC connection is 10 while the cost of the R-TUG–R-OSC connection is 100.

Optical boxes (TUG, USI, OSC and others) have 10GE tributary ports to provide connections with IP routers and 100G line ports with ODU4 framing for inter-connections. Within optical boxes, IP traffic maps onto ODU2e frames that are then multiplexed into the respective time slots of the ODU4 signal.

Under normal conditions, router R-TUG sends IP packets to UNINETT through router R-USI, as the cost of this route (10) is less than the cost of the alternative route through router R-OSC (100).

The problem with a non-optimal routing arises when an outage in the fibre between USI and TUG takes place. The OTN layer of the NORDUnet optical network has a GMPLS control plane, which is used for rerouting OTN circuits in the event of fibre and wavelength faults. So, when the OSPF protocol detects a loss of connectivity along the TUG–OSC OTN circuit, it recalculates a route and sets up a backup one. In this example case, the backup circuit goes around the fibre ring along the TUG–FRE–ORE–UNI–OSC–USI route.

For the IP routers, the rerouting happening at the OTN layer remains invisible and router R-TUG keeps sending IP packets towards UNINETT through router R-USI, as this route still has a cost of 10. In fact, after the rererouting, router R-TUG should have sent traffic to UNINETT through router R-OSC, as this route at the OTN layer has better characteristics (hop number, distance, delay) than the route through R-USI. However, to do so, the routers would have to have known the corrected costs of the OTN circuits, but such an information exchange in automatic mode between the IP and OTN layers is not supported by NORDUnet network equipment (Juniper routers and Ciena OTN/DWDM boxes at the moment. As a result the **route from R-TUG towards UNINETT destinations remains non-optimal, one optical hop longer than an alternative route through R-OSC and hence resulting in longer delays of signal propagation along a route.** Such a situation takes place until the manual intervention of an IP administrator who corrects the route costs according to the information passed to him or her by an ONP/DWDM network administrator – an informal procedure, which might take too much time and involve mistakes.

5.2.2 The SDN Solution

The problem described above is not specific to NORDUnet, as historically the IP control plane worked on its own, without any interaction with the optical layers. The following sub-sections summarise the current situation and developments with regard to layer interaction to establish the context for then considering SDN as a natural way to effective routing in multi-layer packet-optical networks.

5.2.2.1 *Manual Interaction of Layers*

Usually, the packet and optical networks of a network provider (if it owns both) are managed by two different teams of network administrators (sometimes by two different Network Operations Centres (NOCs)). The optical network administrators establish circuit-based connections for IP routers according to requests from the packet network administrators, who specify the end points and bandwidth of a connection. If the packet network administrator who makes such a request takes into account the topology of the optical network, the resulting route might be optimal or close to optimal. However, if such a request is made in "blind" mode, i.e. without knowledge of the optical network topology, the result could be quite far from optimal.

5.2.2.2 *GMPLS-Based Layer Interaction*

The introduction of GMPLS brought an automatic interaction between the control planes of packet and optical networks. However, the main model of the IP-GMPLS interaction functionality, called the overlay model, is very close to the manual blind mode described above. In the overlay model, the IP control plane has a limited view of the optical network topology, seeing only the entry points of the optical network, to which routers are connected, and makes a request to the optical GMPLS control plane to set up a circuit between two of those entry points. The effectiveness of the resulting combined route going through IP-OTN-DWDM layers as in the manual blind mode depends to some extent on luck.

Another GMPLS model – the peer model – assumes that all the nodes of both networks have full knowledge about the layerless topology of the combined packet-optical network. In such a case the routing might be optimal; it depends on the routing protocol used but, in principle, having the full topology information available at each network node potentially allows effective routing to be achieved. The implementation of the peer GMPLS model faces several challenges:

- The IP and underlying optical network can be under different administrative control – such a situation was very typical in the past; now more and more providers own and control both types of networks.

- All network nodes – IP routers and OTN/DWDM switches – have to support GMPLS protocols; for routers this is not common, as GMPLS protocols differ from the standard IP control plane protocols.
- The complexity of the path calculation task grows significantly with the addition of extra nodes and links to the combined network topology graph; this could be too heavy a task for network nodes.

Because of these challenges, development of the GMPLS technology and its applications mostly stuck to the overlay model and hence cannot make use of the potential benefits of routing based on a global view of the packet-optical network topology.

5.2.2.3 *SDN-Based Layer Interaction*

The SDN paradigm assumes the logically centralised control of a network. One of the consequences of this paradigm is that it provides a natural way to control all network layers from a single point (the SDN controller) that has a global view of the network as a whole and optimises its behaviour accordingly.

The global view of a packet-optical network can be achieved through two kinds of generalisation [55]:

- A common-flow abstraction that generalises packet flows and circuit flows.
- A common-map abstraction that allows a packet-optical topology to be presented as a flat layerless map.

The benefits of a global view of a packet-optical network are multi-faceted as such a view allows different aspects of network behaviour to be optimised, including establishing optimal routes for compound (packet-circuit-packet) flows on an end-to-end basis.

SDN control of a packet-optical network based on a generalised layerless topology is similar to the GMPLS peer model approach but it copes better with the challenges described above:

- Network nodes do not need to run complex GMPLS protocols. Instead, they need only comply with an SDN switch specification (e.g. from ONF) and support an SDN controller-switch protocol (e.g. OF).
- The increased complexity of the path calculation due to the increased dimension of the combined network graph is not a big problem for the centralised computational power of an SDN controller: to deploy one or several very powerful computers running a path computation element (PCE) application is much simpler than increasing the computational power of each network node.

Of course, as with a GMPLS peer model, an SDN layerless global approach cannot help if the packet and optical networks are under different administrative control.

SDN-based control of a packet-optical network can use an overlay approach too. In such a case there are two separate topology databases, one for the packet network and one for the optical network [51]. Two different SDN controllers control their respective networks separately but coordinate their work if necessary. For example, when an IP SDN controller needs to set up a new link between routers, it makes a request to an optical SDN controller specifying the end points and bandwidth of a connection.

5.2.2.4 *Taking an SDN Layerless Approach to the NORDUnet Use Case*

Taking an SDN layerless approach to the NORDUnet use case results in the topology shown in Figure 5.8. The topology includes both physical and virtual elements of the combined network. The physical elements are represented by physical ports and links – fibres between routers and tributary 10GE ports of the optical nodes. Virtual elements are wavelengths of the DWDM and time-slots of the OTN layers and virtual ports.

A virtual port maps data between layers. For example, virtual port 1 of the TUG optical node maps incoming packets of a packet flow onto ODU2e frames. Virtual port 2 of TUG maps ODU2e data onto time-slots of an ODU4 frame of one of the wavelengths outgoing from one of the TUG 100G ports.

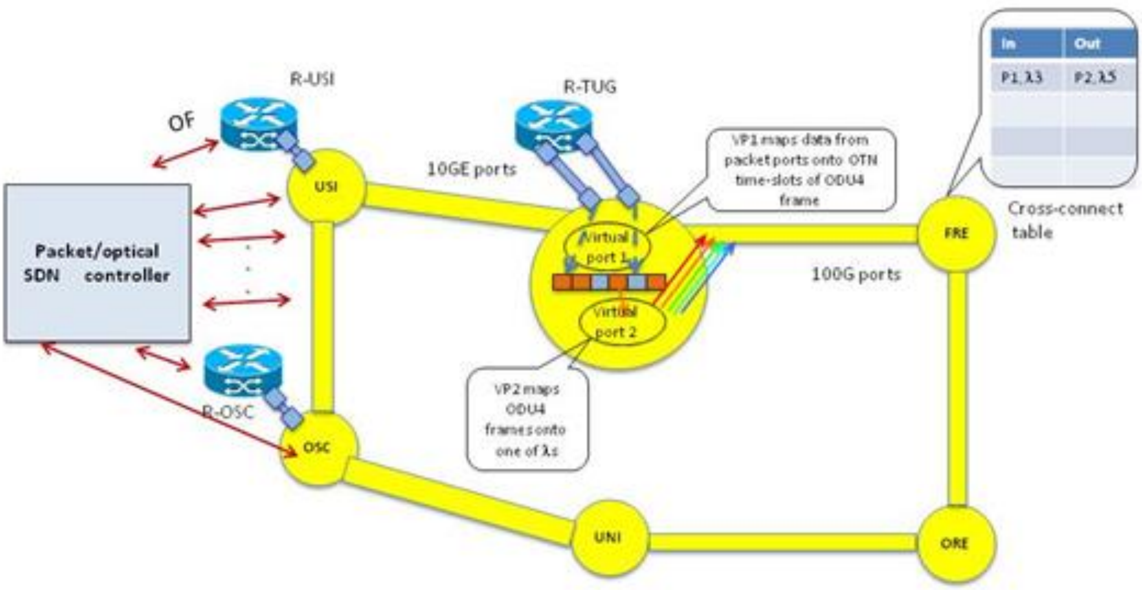


Figure 5.8: A global view of the NORDUnet layerless topology

An example of several first hops of a path of flow 3 going through R-TUG packet port 2 and then through TUG and FRE towards R-USI might look like this:

R-TUG {$Flow_3$, $Port_2$} -> TUG {$Port_2$->VP_1} -> TUG{VP_1-mapping->ODU2e} -> TUG{ VP_1->VP_2} ->TUG{VP2-multiplexing-> (ODU4, time-slots k, …, j)} -> TUG{VP_2-mapping ->(λ_3,$Port_2$)} -> FRE{($Port_1$, l_3)-> ($Port_2$, l_5) -> …

This example shows that the dimension of the combined layerless graph of a network topology grows not only because the combined topology includes more physical nodes and links than each separate topology (packet or optical) on its own. This growth is also the result of multiple choices, which produce some mapping and multiplexing operations. For example, an ODU2e frame can be mapped onto different wavelengths of output port 2 and the number of choices depends on the availability of eighty time-slots in an ODU4 frame of each wavelength.

The global view of a combined packet-optical NORDUnet topology gives the PCE element of an SDN controller the possibility to find an optimal route from R-TUG towards UNINETT in accordance with a metric, which can be either quite traditional, such as the number of physical hops, or more sophisticated, taking into account signal delays, BER, etc.

If the number of hops is used as a metric, then it is not difficult to see that the fibre outage in question (i.e. between USI and TUG) should cause a rerouting of flows going from R-TUG towards UNINETT through R-OSC and not through R-USI as happened in reality, because the former route has one hop fewer.

5.2.3 Simulation of the NORDUnet Use Case in the ONOS/Mininet Environment

The purpose of this simulation was to find out how effectively existing SDN controllers can make routing decisions for packet-optical networks using the NORDUnet use case as a reference topology.

The open network operating system (ONOS) [52] was chosen for this simulation because:

- It is a very popular open SDN controller from the Open Networking Lab (ON.Lab) – a non-profit organisation founded by SDN inventors and leaders from Stanford University and the University of California, Berkeley.
- The ONOS distribution includes a packet-optical tutorial application that supports layerless routing.
- It is integrated with Mininet [56] and LINC Open Extension (LINC-OE) switch [57], which simulates a DWDM multiplexor and OF v.1.3 protocol.

Unfortunately, Task 1 failed to find a software implementation that simulates a switch with OTN capabilities as is required for the NORDUnet use case. LINC-OE software turned out to be the most suitable to our purpose as it supports multiplexing and cross-connecting wavelengths in the fixed grid environment (80 wavelengths per port). LINC-OE software was written before the ONF published its Optical Transport Protocol Extensions v.1.0, so it uses its own version of the extensions 10 OF 1.3 that are supported by the ONOS SDN controller.

However, despite the lack of OTN functionality, the two-layer topology (IP and DWDM) allows (to some extent) simulation of the routing decisions taking place in the three-layer NORDUnet network.

If it is assumed that ODU4 frames of all 80 wavelengths of each optical 100G port of the NORDUnet network always have 8 spare time-slots required for multiplexing a tributary ODU2e frame then the selection of an optimal route will not depend on the OTN layer details and will depend only on the wavelengths routes. The NORDUnet OTN and DWDM infrastructures were not heavily used at the time of this simulation, so the assumption is very likely to be reasonable and the simulation of the two-layer network should have given some plausible results.

Figure 5.9 below shows the ONOS topology view of the simulated NORDUnet case. The topology includes three routers (R-TUG, R-USI, and R-UNI) that are simulated by the standard Mininet switch software. Six NORDUnet optical nodes (TUG, FRE, ORE, UNI, OSC and USC) are simulated by LINC-OE software. Router R-UNI was added to the topology to represent an IP destination in UNINETT so that the ONOS PCE could make end-to-end routing decisions. R-UNI is connected by two packet links to the NORDUnet routers R-USI and R-OSC to provide diverse routes from NORDUnet to UNINETT. Router R-UNI does not correspond to any real UNINETT router (in contrast to the other topology nodes); it was introduced just to have some sink point in UNINETT.

Several Mininet hosts were also added to the topology to simulate end-to-end flows, which trigger the ONOS intent mechanism which in its turn evokes the ONOS PCE.

The topology view reflects the fact that ONOS treats a packet-optical network as layerless, putting the nodes of different types at the same level.

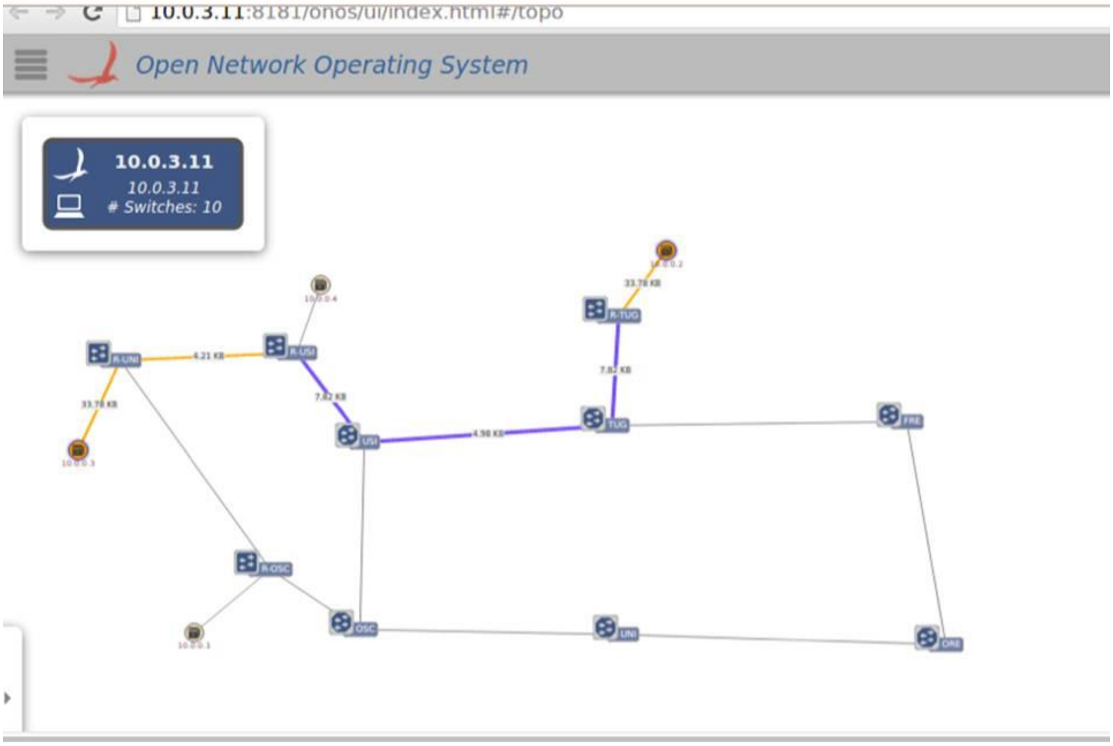


Figure 5.9: The primary route between R-TUG and a UNINETT router

The route found by the ONOS PCE for a situation where there is no outage in the network is shown in Figure 5.9 by the yellow-purple line. The yellow hops correspond to packet flows while purple ones are optical flows. The route has a minimal number of hops between end hosts among all possible routes between R-TUG and R-UNI.

The result of rerouting flows between R-TUG and R-UNI after the outage is shown in Figure 5.10. The outage was simulated by changing the state of the TUG 100G port facing USC to “down” in the system config files of the respective LINC-OE switch. The ONOS PCE found the new route that goes through R-OSC and not through R-USI as happened in reality. In other words, the ONOS PCE found (taking into account the combined layerless topology) the route that was one hop better than the route that was found by the isolated OSPF protocol, which saw only the OTN layer topology.

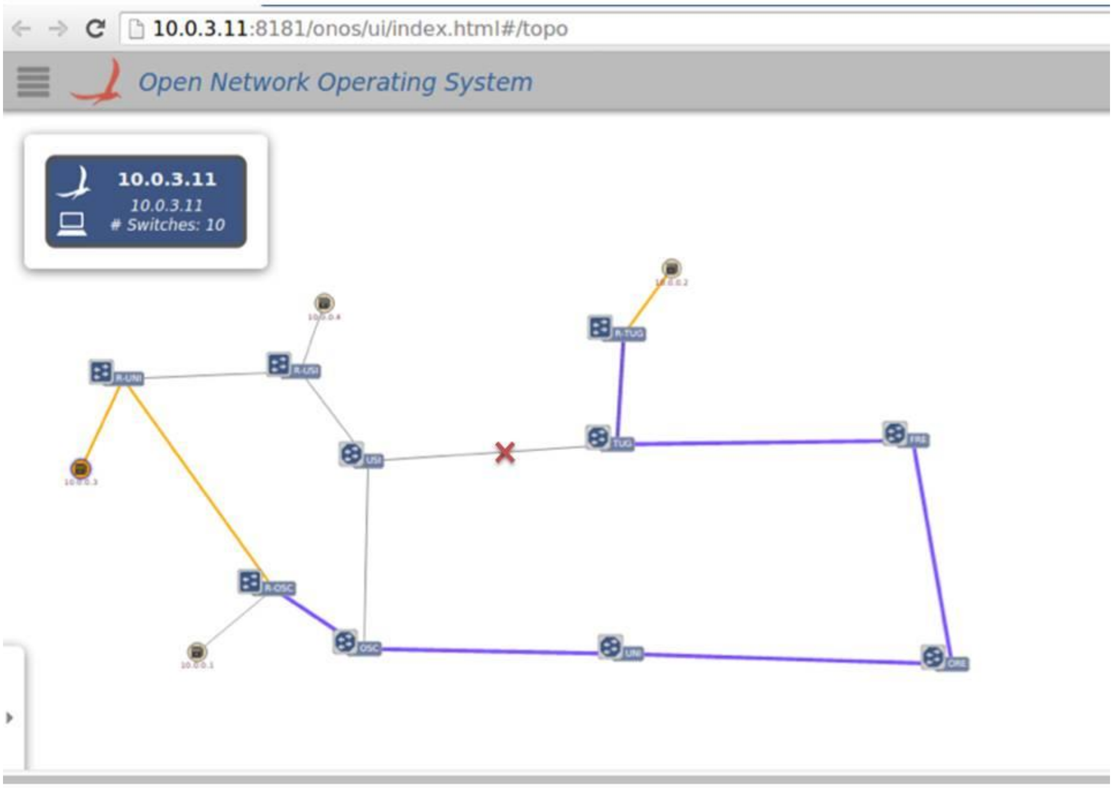


Figure 5.10: The backup route between R-TUG and a UNINETT router

The results of the simulation look quite encouraging, as they show that the modern SDN controller – ONOS in this case – can work effectively in a packet-optical environment using a global view of the combined network. At the same time it is quite obvious that further developments in this direction are needed, such as the ability to work with OTN switches, and the ability to specify more sophisticated metrics than just hop numbers and some others.

5.3 Conclusions

Software-defined networking, now that it has moved to the transport layer as well as the packet layer, is a promising candidate concept for providing the network dynamicity required to fully utilise the increased capacity delivered by the approaches discussed in Sections 2 and 3. It can simplify the complexities of handling traffic among various networking technologies, offering a central, integrated multi-layer view and allowing the underlying infrastructure to be abstracted (in the forms of maps and graphs) and used by applications and network services as a virtual entity. The architecture is not only well suited to address the present optical networking problems related to supporting different administrative and technology segments, bridging the gap between packet and optical layers, but it also supports new operations such as virtualisation, cross-layer orchestration, bandwidth on demand (BoD), load balancing and many more. The OpenFlow protocol extensions developed by the ONF are further increasing SDN's potential within optical networks.

Similarly, an application-based network operations (ABNO) environment is being increasingly favoured as an orchestration mechanism to meet new requirements (such as on-demand and application-specific reservation of network connectivity, reliability and resources across multiple network applications and technologies) of new services. JRA1 T1 has built an ABNO-based integrated demonstrator, which provides an emulated environment for evaluating the ability of SDN to control network resources and provide programmability of network function. It uses the OpenFlow Protocol extensions, in the form of EXPERIMENTER properties, to provide modulation format support for the transmitters.

A use case to optimise a failure scenario has demonstrated the ability of transport SDN, combined with an open network operating system (ONOS), to work effectively in a packet-optical environment using a global view of the combined network, making optimal routing decisions to provide layerless restoration. At the same time it is clear that further developments in this direction are needed, such as the ability to work with OTN switches, and the ability to specify more sophisticated metrics than just hop numbers and some others.

6 Conclusions

In this deliverable the concept of zero-touch connectivity is cited as a way to satisfy the requirements from the NRENs' user base, whether these are university students or high-demanding research projects. The vision is to provide the needed bandwidth to the user wherever the user is located and whenever the user requests it. The deliverable addresses the underlying processes and requirements needed in order to fulfil or partly fulfil this vision. These include a high-capacity flexible network infrastructure and key functionalities. The deliverable therefore addresses the flexibility and capacity development of the photonic layer, the flexible deployment of infrastructures using alien wavelengths, functionalities for time and frequency synchronisation, and overall resource management and orchestration.

Growing Capacity Trends

A number of new formats and modulations currently offer the ability to increase the capacity of the fibre, though none is completely problem free. Client-side higher-order modulation techniques have started to emerge, of which the simplest, and thus most cost-effective, form at this stage is PAM-4. The SDM technologies of FMF and MCF are promising, but not without problems, including constraints imposed by the available amplification techniques.

In parallel with the important progress in high-bitrate standardisation being delivered by three standardisation bodies, GÉANT partners PSNC and CESNET have conducted successful 400G transmission experiments, including the use of software-defined optics to deliver flexible data rates and modulation. As a result, PSNC has established and configured two operational 400G links and the CESNET tests demonstrated the successful extension of all-optical reach to 2,000 km and with high-bitrate traffic that can easily be transported as alien wavelengths over CESNET's production network. These deployments are direct results of the experiments conducted within GN4-1 and show the viability of high bitrate transmission for NRENs.

With regard to enabling effective, optimal use of the availability capacity through flexible optical networks (FON), the GN3plus Open Call project REACTION introduced significant innovations in the context of data plane (support for sliceability), control plane (novel PCE architecture), and routing and spectrum allocation strategies (novel RSA algorithms). Developments since REACTION have further enhanced FON's ability to maximise spectral efficiency and reach by minimising the negative penalties. For the future, there is increasing need for vendor interoperability for network subsystems, or even elements, and hence for a common network management platform.

A survey of BVT vendors showed a subset of common functionalities, though with implementations – particularly of spectral occupancy and Baud rate – varying from vendor to vendor. Further, the interoperability of two S-BVT implementations has been recently demonstrated on a pan-European multi-domain multi-vendor elastic optical network (EON) testbed within the IDEALIST project. Experiments proved the need for a new soft-decision FEC standard which would significantly increase reach in single- and cross-vendor transmission.

Spectral Sharing and Alien Waves

Alien waves and spectral sharing are gaining momentum among NRENs as one way of providing a more dynamic, flexible and cost efficient infrastructure. The reliability and integrity of alien waves have been sufficiently proven for SURFnet and NORDUnet to have transitioned AW services into production for both client and own use. Valuable results have been obtained on defining important physical transmission parameters for the native and alien signals' interaction. The multi-domain optical modelling tool (MOMoT), originally developed during a GN3plus Open Call project and further developed during GN4-1, helps determine these and other design parameters needed for AW adoption. Verification tests in NORDUnet's live production network, with BER vs. launch power as a criterion, showed a reasonable correlation between MOMoT's predictions and actual measurements. This is very useful for future AW deployments, as NRENs using the extended MOMoT tool can safely estimate the impact on the alien and the host waves. This potentially improves the setup time of alien waves.

Frequency and Time Distribution

The transmission of accurate time and stable frequency over alien lambdas is possible and is already in operation or has been tested.

When higher time or frequency stability is required, bi-directional transmission using single bi-directional all-optical channel needs to be established. The use of non-standard telecom devices (mainly amplifiers) opens up some issues to be solved, especially monitoring of bi-directional signals at the optical layer and identifying best engineering practices (amplifier gains, optical powers to achieve the best performance without disturbing NREN traffic).

The techniques investigated are very promising, because they provide sufficient accuracy for very high-demanding applications such as remotely compared atomic clocks.

The suitability of precision time protocol (PTP) for providing clock synchronisation over layer 3 networks was investigated. In particular, MPLS tunnels were used and an audio stream selected as a time-sensitive data application. The transfer was measured and compared to LAN environments. These long-term measurements show that adverse network conditions can lead to a loss of the reference signal that the PTP slave obtains from the grandmaster clock. More investigations need to be done over varying distances, and also longer distances and longer timeframes, in order to be able to determine how far away slaves can be placed from PTP grandmasters and how exactly network conditions such as jitter affect slave calibration to the grandmaster. In the audio tests, there was jitter in the MPLS tunnel as low as 50 – 60 us; nevertheless, it was not possible in the tests to have a clear audio without distorting noise. As existing standards and recommendations do not describe the level of accuracy of PTP needed for provisional audio and video applications, many additional tests are needed in various scenarios to be able to narrow down network jitter or loss requirements.

Network Dynamicity

Software-defined networking, now that it has moved to the transport layer as well as the packet layer, is a promising candidate concept for providing the network dynamicity required to fully utilise the increased capacity and flexibility of optical networks. The approach is not only well suited to address the present optical networking problems related to supporting different administrative and technology segments, bridging the gap between packet and optical layers, but it also supports new operations such as virtualisation, cross-layer orchestration, bandwidth on demand (BoD), load balancing and many more. The OpenFlow protocol extensions developed by the ONF are further increasing SDN's potential within optical networks.

The application-based network operations (ABNO) environment is being increasingly favoured as an SDN-aware orchestration mechanism to meet new requirements (such as on-demand and application-specific reservation of network connectivity, reliability and resources across multiple network applications and technologies) of new services. JRA1 T1 has built an ABNO-based integrated demonstrator, which provides an emulated environment for evaluating the ability of SDN to control network resources and provide programmability of network function. It uses the OpenFlow Protocol extensions, in the form of EXPERIMENTER properties, to provide modulation format support for the transmitters.

A use case to optimise a failure scenario has demonstrated the ability of transport SDN, combined with an open network operating system (ONOS), to work effectively in a packet-optical environment using a global view of the combined network, making optimal routing decisions to provide layerless restoration. At the same time it is clear that further developments in this direction are needed, such as the ability to work with OTN switches, and the ability to specify more sophisticated metrics than just hop numbers and some others.

Summary Evaluation

This deliverable presents the results of comprehensive research and experimentation by JRA1 T1 into the current trends and technologies in the physical and logical domains of optical transport networks, with the aim of supporting the ZTC vision that will help NRENs to meet the high-demanding requirements they face from user, technology, cost and management perspectives. While challenges and the need for further testing exist in many of the areas analysed, the work has identified several promising solutions and, of particular importance, has assessed these in the NREN environment. This has led to the deployment of enhanced operational services in some NRENs, and it is hoped that the findings will similarly guide other NRENs in the development of their next-generation infrastructure.

Appendix A MOMoT Modelling Tool

The multi-domain optical modelling tool is software (.exe) providing a user-friendly interface where link, native and alien wavelength parameters can be set. Based on the provided input parameters, the software outputs bit error rate (BER) estimation. Figure A.1 below shows the interface of the modelling tool, where input parameters can be set and outputs are visualised.

A.1 Inputs

The user can set the following parameters through the interface:

- The bitrate of the native or alien wavelength in Gb/s (Native).
- The defined channel spacing in the transmission link (Native).
- The bitrate of the alien wavelength in Gb/s (Bitrate).
- The modulation format of the alien wavelength in Gb/s (Modulation format).
- The noise figure of the amplifiers in dB (Noise Figure).
- The launch power of the native and alien wavelengths at the transmitter, in dBm (TX power).
- The number of spans (integer number #).
- The residual chromatic dispersion of each span when dispersion compensating fibres (DCFs) are installed in the network.
- Whether DCFs are installed or not.
- The worst-case margins (in dB) to account for non-modelled impairments (such as fibre ageing).
- The parameters related to each span:
  - Length in km (Length).
  - Attenuation in dB (Attenuation).
  - Chromatic dispersion in ps/nm (chromatic dispersion).

A.2 Outputs

When the button “Compute” is pressed, the software will run and the following output will be presented:

- Evaluated BER pre-FEC: in this field the estimated BER of the (alien) wavelength will be reported.
- Output messages: in this field, possible messages will be displayed. For example, if the power of the alien wavelength exceeds the threshold of 2 dBm, the following message is displayed: “Warning: new channel may be disruptive for adjacent channels”. This has been introduced since the level of power may be too high and it may induce excessive cross-phase modulation (XPM) on active wavelengths. If there is no warning, nothing is visualised in this field. In the case of injecting a PM-QPSK alien wave into an OOK native network, output messages will report the BER of the alien wave at varying guard band between the alien and a native OOK, as shown in Figure A.2. Indeed, the BER of a PM-QPSK is strongly affected by the presence of OOK neighbours because of XPM. Thus, by spacing out PM-QPSK and OOK, the performance of the PM-QPSK improves. Guard band is defined as the number of free channels between a PM-QPSK and an OOK. Another kind of output message is reported if the performance is strongly affected by the PMD.

A.3 Buttons

The following buttons are present in the user interface:

- Compute: when this button is pressed, the model is run to evaluate the BER pre-FEC.
- Reset: when this button is pressed, the output only is reset, while the last input parameters are kept in memory and can be changed one by one if necessary. This button is particularly useful when varying just one or a few parameters (e.g. TX power). Thus, only one or a few parameters have to be changed manually.
- Reset all: when this button is pressed, all inputs and outputs are reset.
- Save file: a file including the configuration of all the input parameters can be saved (“configuration file”).
- Browse file: once a “configuration file” has been saved, this button enables the identification of the directory where the file is placed.
- Load file: when this button is pressed, the configuration parameters saved are loaded into the “configuration file”.

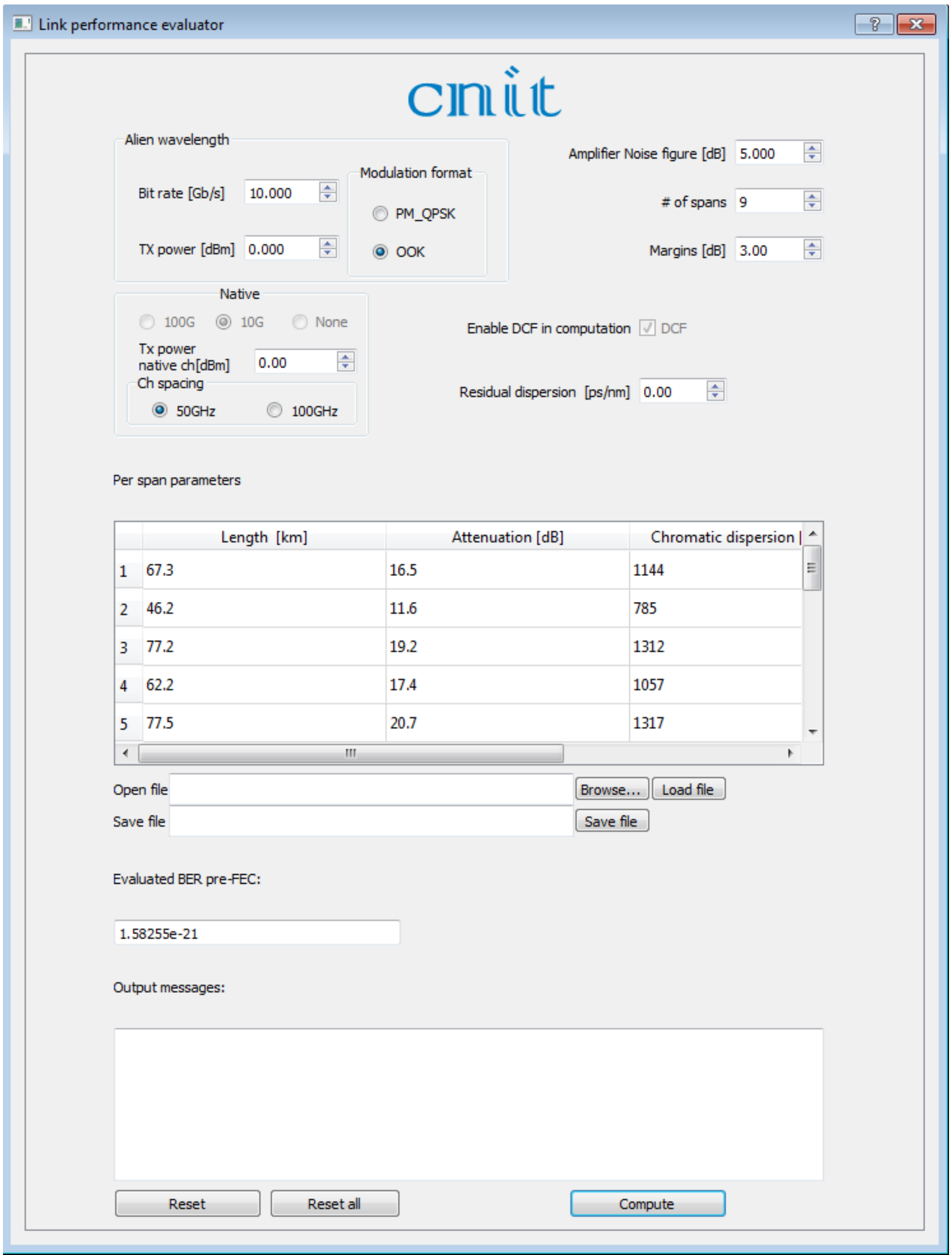


Figure A.1: Modelling tool interface

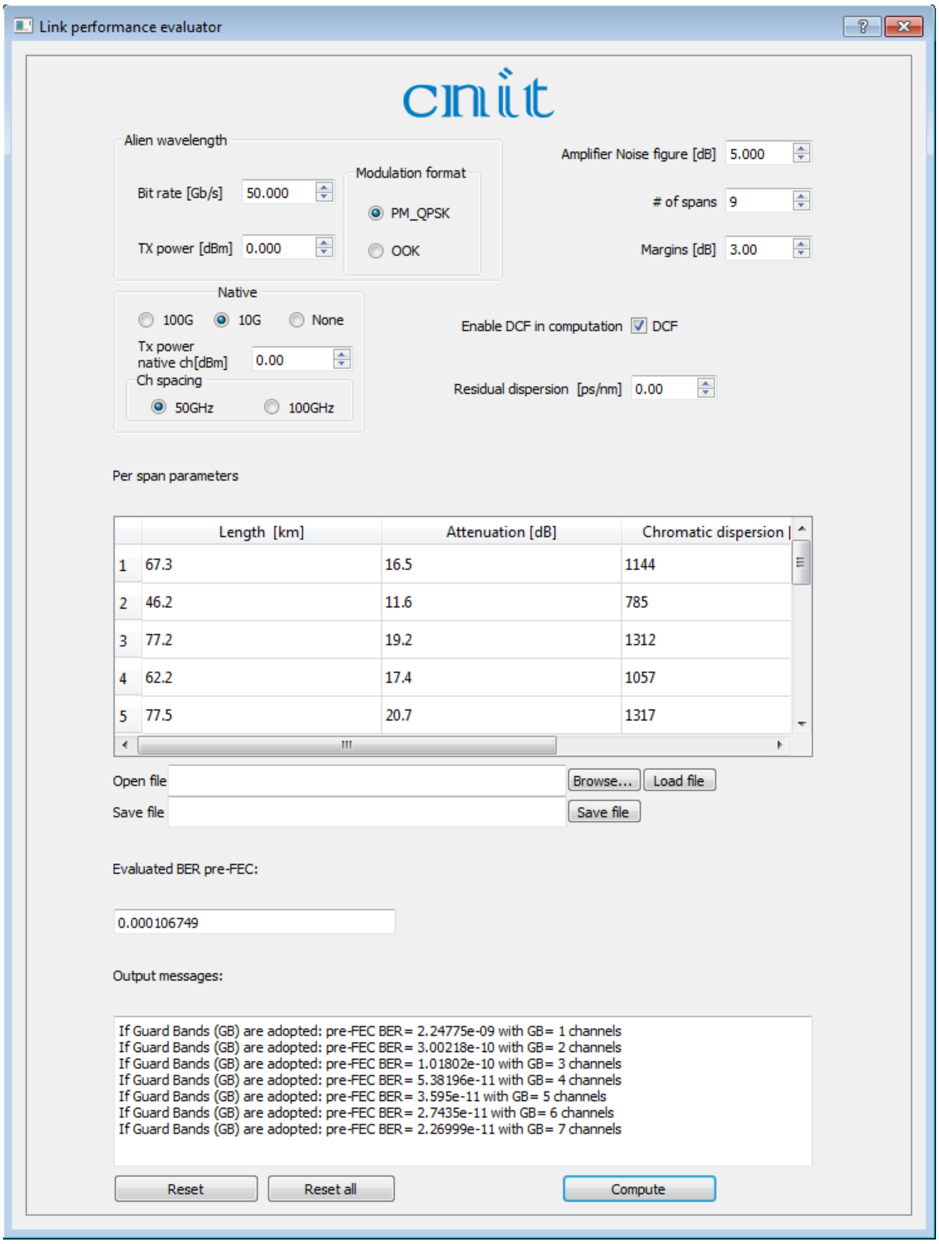


Figure A.2: Modelling tool interface and output messages including guard band information

Appendix B Transport Extensions in the ONF OpenFlow Protocol

B.1 Background

The initial version 1.0 of the OpenFlow protocol was designed to control packet switches and routers; accordingly, the main elements of OF v1.0 (such as flow and port descriptions) were packet-oriented only. However, it became clear that optical transport equipment and networks (based on OTN, SDH and DWDM technologies) that had been an integral part of modern telecommunication networks for years also have to be included in the SDN realm in a consistent way, allowing smooth control of combined packet-optical networks.

Since standardisation of OF v1.0 in 2009, the SDN community has been actively working on extending the OF protocol with an ability to operate with switched units of optical transport networks – time-slots, wavelengths and fibres. Until recently, these extensions were mostly proprietary, suggested both by researchers and vendors. One of the most popular documents describing such extensions was *Extensions to the OpenFlow Protocol in support of Circuit Switching. Addendum to OpenFlow Protocol Specification (v1.0) – Circuit Switch Addendum v0.3* [58], developed by the OpenFlow Switch Consortium in 2010.

The ONF took over from the OpenFlow Switch Consortium in the development of the OF protocol in 2011 and started introducing more flexibility in the protocol functionality by adding so-called EXPERIMENTER elements to its constructions. Initially this was done to the protocol messages only (since OF v1.1), and then extended to flow match and action fields, queue and statistics properties (since of v1.2) and port description properties (since OF v1.4).

The EXPERIMENTER type of OF protocol element allows a researcher or vendor to define a new structure for those elements, for example, a new structure for a protocol message, and implement it in the network equipment and SDN controllers to achieve some specific functionality. The EXPERIMENTER type of protocol element can be either proprietary or standard, i.e. defined by a standards body. The OF optical transport extensions described in Sections 5.1.4.1 and 5.1.4.2 of this document are examples of proprietary extensions.

A specification *Optical Transport Protocol Extensions v.1.0* [59] developed by the ONF describes the OpenFlow standard extensions based on the EXPERIMENTER protocol elements. The specification is seen by the ONF as an initial document that systematises the OF optical transport extensions in three areas:

- Flow match fields and actions.
- Port description extensions for OTN ports.
- Port extensions for adjacency discovery.

The ONF assumes that the extensions described in the separate specification will gradually become parts of the main OF protocol specification.

The ONF is also going to develop optical transport extensions for other areas such as:

- OAM/monitoring of optical network links.
- Support of protection switching mechanisms.
- Support of multilayer connections (reflecting the adaptation of a client signal into a server one).
- Support of OF protocol use for vertical controller-to-controller communications.

The following sections consider the OF transport extensions in the three initial areas.

B.2 Flow Match Fields and Actions

The proposed extensions allow the selection of circuit-switched flows based on signals of two types:

- Wavelength signals (optical channel (OCh)).
- OTN signals (ODUj/k frames).

In both cases the match fields are the OF Extensible Match EXPERIMENTER type (0xFFFF) and include EXPERIMENTER_ID 0xFF000007 assigned to the Optical Transport Working Group of ONF.

Two match fields are used to select a particular signal:

- `OFPXMT_EXP_OCH_SIGTYPE` and `OFPXMT_EXP_OCH_SIGID` for wavelength signals.
- `OFPXMT_EXP_ODU_SIGTYPE` and `OFPXMT_EXP_ODU_SIGID` for OTU signals.

A xxx_SIGTYPE field is used for a broad description of the signal type, while a xxx_SIGID field specifies the signal more precisely.

Wavelength Signals

In the case of wavelength signals, the `OFPXMT_EXP_OCH_SIGTYPE` field can have one of two values:

- `OFPOCHT_FIX_GRID` if a signal uses a fixed grid.
- `OFPOCHT_FLEX_GRID` if a signal uses a flex grid.

The second field `OFPXMT_EXP_OCH_SIGID` describes the precise position of the signal on the grid using the following structure:

```
/* OFPXMT_EXP_OCH_SIGID Payload format */
```

```
struct ofp_oxm_exp_OCH_sigid {
uint32_t oxm_header; /* oxm_class = OFPXMC_EXPERIMENTER */
uint32_t experimenter; /* Experimenter ID = 0xFF000007 */
uint8_t grid_type; /* Grid Type */
uint8_t chl_spacing; /* Channel spacing */
uint16_t n;  /* n is used to calculate the frequency as in [ITU
G.694.1]
                     * Frequency(THz)= 193.1 THz + n*chl_spacing
(THz)*/
uint16_t m;  /* m is used to identify the slot width as defined
in [ITU G.694.1],
                    * Slot Width (GHz) = m*12.5 (GHz)
                     * For fix grid networks, m=1 */   }
```

In this structure the `grid_type` parameter gives more information about the grid type than the `OFPXMT_EXP_OCH_SIGTYPE` field as it can differentiate between DWDM, CWDM and flex grids; however, the flex grid case is left for further discussion in the current version 1.0 of the specification.

OTU Signals

For OTU signals the `OFPXMT_EXP_ODU_SIGTYPE` field gives information about the high order (HO) ODU frame type of the signal, including ODU flex frames:

```
enum ofp_odu_signal_type {
OFPODUT_ODU1 = 1,
OFPODUT_ODU2 = 2,
OFPODUT_ODU3 = 3,
OFPODUT_ODU4 = 4,
OFPODUT_ODU0 = 10,
OFPODUT_ODU2E = 11,
OFPODUT_ODUfCBR = 20,
OFPODUT_ODUfGFPfHAO = 21,
OFPODUT_ODUfGFPf = 22,
};
```

If an HO OTN switching takes place, a signal is fully defined by the `OFPXMT_EXP_ODU_SIGTYPE` field and together with an input port number (described by the `OFPXMT_OFB_IN_PORT` field) a circuit-switched flow is fully defined too.

However, for a low order (LO) OTN switching that operates with an ODU frame multiplexed into a higher order ODU frame, the second flow match field `OFPXMT_EXP_ODU_SIGID` that describes the positions of the LO frame time-slots within a multiplexed HO ODU structure:

```
/* OFPXMT_EXP_ODU_SIGID Payload format */
struct ofp_oxm_exp_ODU_sigid {
  uint32_t oxm_header; /* oxm_class = OFPXMC_EXPERIMENTER */
  uint32_t experimenter; /* Experimenter ID ID = 0xFF000007 */
  uint16_t tpn; /* Tributary Port Number */
```

```
  uint16_t tslen; /* Number of Tributary Slots included in tsmap,
based on the Server ODU type and TS
                           * Granularity. */
 uint8_t tsmap[0]; /* Tributary slot bitmap */
};
```

The ONF approach to defining LO ODU data within a multiplexed HO ODU frame is similar to the one taken by the IETF in defining GMPLS labels for OTN data [60]. In both cases the bitmap bits indicate which tributary slots in the HO ODUk the LO ODUj will be multiplexed into. Each bit in the bitmap represents the corresponding tributary slot in the HO ODUk, with a value of 1 or 0 indicating whether the tributary slot will be used by the LO ODUj or not.

Specific actions extensions for the optical transport are not defined by the specification. Instead the specification suggests using the standard OF `SET_FIELD` action with the new flow match field types, described above.

B.2.1 Examples

This section presents three examples of how operations with circuit flows can be defined by the use of the new flow match extensions:

- ODU2 HO – ODU2 HO flow.
- ODU0 LO (ODU2) to ODU0 LO (ODU2) flow.
- 1GE to ODU0 LO-ODU flow.

B.2.1.1 *Example 1: ODU2 HO – ODU2 HO flow*

This is a simple case, as a switch just needs to transmit ODU2 frames from one port 2 to port 7 without looking inside the frame header fields. Only the `OFPXMT_EXP_ODU_SIGTYPE` match flow field is needed for this:

Match:

```
ofp_match_type = OFPMT_OXM
ofp_oxm_class = OFPXMC_OPENFLOW_BASIC
ofp_oxm_field = OFPXMT_OFB_IN_PORT
data = 2 (input port number)
ofp_oxm_class = OFPXMC_EXPERIMENTER
ofp-oxm_field = OFPXMT_EXP_ODU_SIGTYPE
experimenter = 0xFF000007
sigtype = OFPODUT_ODU2
```

Instruction:

```
type = OFPIT_APPLY_ACTIONS
```

Actions:

```
type = OFPAT_OUTPUT
port = 7 (output port number)
```

B.2.1.2 *Example 2: ODU0 LO (ODU2) to ODU0 LO (ODU2) flow*

This example shows the creation of a flow of a signal contained in ODU0 frames multiplexed into ODU2 frames. To specify a signal both SIGTYPE and SIGID match fields are needed. The flow input port is 3, the output port is 8, and both are ODU2 type.

Match:

```
ofp_match_type = OFPMT_OXM
ofp_oxm_class = OFPXMC_OPENFLOW_BASIC
ofp_oxm_field = OFPXMT_OFB_IN_PORT
data = 3 (input port number)
ofp_oxm_class = OFPXMC_EXPERIMENTER
ofp-oxm_field = OFPXMT_EXP_ODU_SIGTYPE
experimenter = 0xFF000007
sigtype = OFPODUT_ODU0
ofp_oxm_class = OFPXMC_EXPERIMENTER
ofp-oxm_field = OFPXMT_EXP_ODU_SIGID
experimenter = 0xFF000007
tpn = 1 (tributary port number)
tslen = 8 (ODU2 frame has 8 time-slots with 1.25 Gbps
granularity)
tsmap = 00100000 (tributary slot bitmap)
```

Instruction:

```
type = OFPIT_APPLY_ACTIONS
```

Actions:

```
type = OFPAT_SET_FIELD
ofp_oxm_class = OFPXMC_EXPERIMENTER
ofp-oxm_field = OFPXMT_EXP_ODU_SIGID
experimenter = 0xFF000007
tpn = 1 (tributary port number)
tslen = 8
tsmap = 00001000 (tributary slot bitmap)
type = OFPAT_OUTPUT
port = 8 (output port number)
```

The tributary slot bitmap field values define the cross-connect action required from a switch, taking a signal from the 3rd time-slot of the input ODU2 frame and placing it into the 5th time-slot of the output ODU2 frame.

B.2.1.3 *Example 3: 1GE to ODU0 LO-ODU flow*

This example shows that hybrid packet-optical flows can also be defined by using the new flow match fields. The flow in this example is between packets of input 1GE port number 2 and the ODU0 time-slot of the ODU2 output port 5.

Match:

```
ofp_match_type = OFPMT_OXM
ofp_oxm_class = OFPXMC_OPENFLOW_BASIC
ofp_oxm_field = OFPXMT_OFB_IN_PORT
data = 2 (input 1GE port number )
ofp_oxm_class = OFPXMC_EXPERIMENTER
ofp-oxm_field = OFPXMT_EXP_ODU_SIGTYPE
experimenter = 0xFF000007
sigtype = OFPODUT_ODU0
```

Instruction:

```
type = OFPIT_APPLY_ACTIONS
```

Actions:

```
type = OFPAT_SET_FIELD
ofp_oxm_class = OFPXMC_EXPERIMENTER
ofp-oxm_field = OFPXMT_EXP_ODU_SIGID
experimenter = 0xFF000007
tpn = 1 (tributary port number)
tslen = 8
tsmap = 01000000 (tributary slot bitmap)
type = OFPAT_OUTPUT
port = 5 (output ODU2 port number )
```

B.3 Port Description Extensions

The extension specification defines properties of the OTN port only, as those of the optical (xWDM) port are defined in the main OF specification since version 1.4. The main OF specification v.1.4 (and higher) introduces three types of physical ports properties:

```
/* Port description property types. */
enum ofp_port_desc_prop_type {
OFPPDPT_ETHERNET = 0, /* Ethernet property. */
OFPPDPT_OPTICAL = 1, /* Optical property. */
OFPPDPT_EXPERIMENTER = 0xFFFF, /* Experimenter property. */
};
```

(Note that OF versions lower than 1.4 define only the `OFPPDPT_ETHERNET` type of port properties).

For convenience, the definition of the optical port properties from the OF v.1.4 specification are given here:

```
/* Optical port description property. */
struct ofp_port_desc_prop_optical {
uint16_t type; /* OFPPDPT_3OPTICAL. */
uint16_t length; /* Length in bytes of this property. */
uint8_t pad[4]; /* Align to 64 bits. */
uint32_t supported; /* Features supported by the port. */
uint32_t tx_min_freq_lmda; /* Minimum TX Frequency/Wavelength *
uint32_t tx_max_freq_lmda; /* Maximum TX Frequency/Wavelength */
uint32_t tx_grid_freq_lmda; /* TX Grid Spacing
Frequency/Wavelength */
uint32_t rx_min_freq_lmda; /* Minimum RX Frequency/Wavelength */
uint32_t rx_max_freq_lmda; /* Maximum RX Frequency/Wavelength */
uint32_t rx_grid_freq_lmda; /* RX Grid Spacing
Frequency/Wavelength */
uint16_t tx_pwr_min; /* Minimum TX power */
uint16_t tx_pwr_max; /* Maximum TX power */
};
OFP_ASSERT(sizeof(struct ofp_port_desc_prop_optical) == 40);
```

The features of the optical port are defined by the `supported` parameter:

```
/* Features of optical ports available in switch. */
enum ofp_optical_port_features {
OFPOPF_RX_TUNE = 1 << 0, /* Receiver is tunable */
OFPOPF_TX_TUNE = 1 << 1, /* Transmit is tunable */
OFPOPF_TX_PWR = 1 << 2, /* Power is configurable */
OFPOPF_USE_FREQ = 1 << 3, /* Use Frequency, not wavelength */
};
```

The transport extensions specification uses the `OFPPDPT_EXPERIMENTER` properties type with the EXPERIMENTER ID assigned to OTWG (0xFF000007) to define the OTN port properties.

The most informative data structure describing the OTN port properties (among others) is the following:

```
/* OTN Layer Stack Entry Encoding */
struct ofp_port_optical_transport_layer_entry {
uint8_t layer_class; /* OFPOTPL_* */
uint8_t signal_type; /* OFP(OTP/OCH/ODU/ODUCL)T_*/
uint8_t adaptation; /* OFPADAPT_*/
```

The three enum variables of this structure allow the major parameters of the OTN port to be described:

- The variable `layer_class` defines the type of port, either ODU or ODUCLT (a client port).

- The variable `signal_port` specifies the type of the port signal type:
  - For the ODU port it can be one of the following:

```
OFPODUT_ODU1 = 1,
OFPODUT_ODU2 = 2,
OFPODUT_ODU3 = 3,
OFPODUT_ODU4 = 4,
OFPODUT_ODU0 = 10,
OFPODUT_ODU2E = 11,
OFPODUT_ODUfCBR = 20,
OFPODUT_ODUfGFPfHAO = 21,
OFPODUT_ODUfGFPf = 22
```

  - For the ODUCLT port it can be one of the following:

```
OFPODUCLT_STM16 = 1,
OFPODUCLT_STM64 = 2,
OFPODUCLT_STM256 = 3,
OFPODUCLT_STM1 = 4,
OFPODUCLT_STM4 = 5,
OFPODUCLT_1GBE = 6,
OFPODUCLT_10GBE = 7,
OFPODUCLT_40GBE = 8,
OFPODUCLT_100GBE = 9,
OFPODUCLT_FC100 = 10,
OFPODUCLT_FC200 = 11,
OFPODUCLT_FC400 = 12,
OFPODUCLT_FC800 = 13,
OFPODUCLT_FC1200 = 14,
OFPODUCLT_GPON = 15,
OFPODUCLT_XGPON = 16,
OFPODUCLT_IB_SDR = 17,
OFPODUCLT_IB_DDR = 18,
OFPODUCLT_IB_QDR = 19,
OFPODUCLT_SBCON_ESCON = 20,
OFPODUCLT_DVB-ASI = 21,
OFPODUCLT_SDI = 22,
OFPODUCLT_SDI1G5 = 23,
OFPODUCLT_SDI3G = 24,
OFPODUCLT_ATM = 25,
OFPODUCLT_ETH = 26,
OFPODUCLT_MPLS = 27,
OFPODUCLT_IP = 28
```

- Finally, the variable `adaptation` shows what type of adaptation the port supports:

```
OFPADAPT_OTS_OMS = 1,
OFPADAPT_OMS_OCH = 2,
```

```
    OFPADAPT_OPS_OCHr = 3,
    OFPADAPT_OPSM_OTUk = 4,
    OFPADAPT_OCH_OTUk = 5,
    OFPADAPT_ODUk_ODUij = 6,
    OFPADAPT_ODUk_ODUj21 = 7,
    OFPADAPT_ODUkh_ODUj21 = 8,
    OFPADAPT_ODU0_CBRx = 9,
    OFPADAPT_ODUk_CBRx = 10,
    OFPADAPT_ODUk_CBRxg = 11,
    OFPADAPT_ODUk_RSn = 12,
    OFPADAPT_ODUk_ATM = 13,
    OFPADAPT_ODUk_ETH = 14,
    OFPADAPT_ODUkh_ETH = 15,
    OFPADAPT_ODUk_ETHPPOS = 16
```

In OF v.1.3 protocol the OTN port information is passed to a controller by using a multi-part message; the structures that are used in this message for describing port properties are the same as for OF 1.4.

B.4 Port Extensions for Adjacency Discovery

The transport extensions specification also introduces port extensions for adjacency discovery of OTN boxes. These extensions suggest that the OTN boxes use *Protocol for automatic discovery in transport networks* (Recommendation ITU-T G.7714.1/Y.1705.1) [61]. According to this protocol, the OTN boxes exchange identity information (such as an E.164 name or an arbitrary number), which allows neighbours to be identified and a network topology to be built. The exchange happens in-service as the box ID is placed into the Trial Termination Identifier (TTI) field of an ODU header. By default, the ODU tandem connection monitoring (TCM) sub-layer 6 (TCM6) is used for discovery.

The port extensions for adjacency discovery define the new port properties structures, which can store three TTI values:

- To be sent by the port.
- Expected to be received on the port.
- Actually received on the port.

A controller can obtain the TTI values stored by the port and modify them using the OF messages. Having knowledge of these values from all the ports, a controller is able to build a network topology map.

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Glossary

1PPS	Pulse Per Second
2D	Two-dimensional
ABNO	Application-Based Network Operations
AC	Application Code
ACES	Atomic Clock Ensemble in Space
ADC	Analog to Digital Converter
AES	Audio Engineering Society
API	Application Programming Interface
ARP	Address Resolution Protocol
AS	Autonomous System
ASE	Amplified Spontaneous Emission
ASK	Amplitude-Shift Keying
AUI	Attachment Unit Interface
AW	Alien Wave (or Wavelength)
B100G	Beyond 100G
BER	Bit Error Rate (or Ratio)
BGP	Border Gateway Protocol
BL	Black Link
BoD	Bandwidth on Demand
bPCE	Back-End PCE
BPSK	Pinary PSK
BVT	Bandwidth Variable Transponders
C band	Conventional band
CD	Chromatic Dispersion
CFP	C Form-factor Pluggable
CNIT	Inter-University National Consortium for Telecommunications
CV	Common View
CV	Cross Vendor
CWDM	Coarse Wavelength Division Multiplexing
dB	Decibel
dBm	the power ratio in decibels of the measured power referenced to one milliwatt
DCF	Dispersion Compensating Fibre
DCM	Dispersion Compensating Module
DEMUX	Demultiplexer
DFA	Doped-Fibre Amplification
DMG	Differential Modal Gain
DP-QPSK	Dual Polarisation-QPSK

DPSK	Differential Phase-Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
ECOC	European Conference on Optical Communications
EDFA	Erbium-Doped Fibre Amplifiers
EDWA	Erbium-Doped Waveguide Amplifiers
E-FEC	Enhanced Forward Error Correction
EON	Elastic Optical Network
Er	Erbium
ERO	Explicit Route Object
ESA	European Space Agency
ETSI	European Telecommunications Standards Institute
EVM	Error Vector Magnitude
FBA	Fibre Brillouin Amplification
FEC	Forward Error Correction
FMF	Few-Mode Fibres
FON	Flexible Optical Network
FTTx	Fibre To The x
FWM	Four-Wave Mixing
Gb	Gigabit
Gb/s	Gigabit per second
GE	Gigabit Ethernet
G-FEC	Generic Forward Error Correction
GFP	Generic Framing Procedure
GHz	Gigahertz
GMPLS	Generalised Multi-Protocol Label Switching
GNSS	Global Navigation Satellite System
GPIB	General Purpose Interface Bus
GPS	Global Positioning System
HD	Hard Decision
HDFA	Holmium-Doped Fibre Amplifiers
HG-FEC	High-Grain Forward Error Correction
HO	High Order
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
IEEE-SA	IEEE Standards Association
IETF	Internet Engineering Task Force
IGMP	Internet Group Management Protocol
IL	Insertion Loss
ILA	In-Line Amplifier
I/O	Input and Output
IP	Internet Protocol
IRU	Indefeasible Right of Use
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardisation Sector
JRA	Joint Research Activity

JRA1	GN4-1 Joint Research Activity 1 Future Network Topologies
kHz	Kilohertz
km	Kilometre
L*n*	Layer *n*
LAG	Link Aggregation Group
LAN	Local Area Network
L-band	Long band
LINC	A pure OpenFlow software switch written in Erlang
LO	Low Order
LS	Link State
LSP	Label Switched Path
LSPDB	Label Switch Path Database
MAC	Media Access Control
MCF	Multi-Core Fibres
MIB	Management Information Base
MIMO	Multiple Input Multiple Output
MMF	Multi-Mode Fibres
MOMoT	Multi-Domain Optical Modelling Tool
MP-AFRO	Multi-Path After-Failure Repair Optimisation
MPLS	Multi-Protocol Label Switching
ms	milliseconds
NBI	Northbound Interface
NE	Network Element
NetConf	Network Configuration Protocol
NG	Next Generation
nm	Nanometre
NMI	National Metrology Institute
NMS	Network Management System
NOC	Network Operations Centre
NREN	National Research and Education Network
NRZ	Non Return to Zero
ns	nanoseconds
NTP	Network Time Protocol
OADM	Optical Add/Drop Multiplexers
OAM	Operations, Administration and Maintenance
O-band	Original band
OCh	Optical Channel
ODTUG	Optical channel Data Tributary Unit Group
ODTUjk	Optical channel Data Tributary Unit j into k
ODU	Optical Channel Data Unit
ODUk	Optical Channel Data Unit-k
OE	Open Extension
OF	OpenFlow
OFC	Optical Fibre Communication Conference and Exposition
OFP	OpenFlow Protocol
OIF	Optical Internetworking Forum
OMU	Optical Multiplex Unit

ONF	Open Networking Foundation
ON.Lab	Open Networking Lab
ONOS	Open Network Operating System
ONP	Open Network Platform
OOK	On-Off Keying
OPTIME	High precision dissemination of time and frequency reference signals project
OPU	Optical Channel Payload Unit
OPUk	Optical Channel Payload Unit-k
OSNR	Optical Signal-to-Noise Ratio
OSPF	Open Shortest Path First
OSS	Operations Support System
OTN	Optical Transport Network
OTU	Optical Channel Transport Unit
OTWG	Optical Transport Working Group
OXC	Optical Cross-Connects
P2P	Point to Point
PAC.C	Packet and Circuit Network Convergence
PAM	Pulse-Amplitude Modulation
PCE	Path Computation Element
PHARAO	Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite
PHYs	Physical Layer
PMD	Polarisation Mode Dispersion
PM-QPSK	Polarisation Multiplexing-QPSK
PoP	Point of Presence
PoSK	Polarisation-Shift Keying
PPP	Precise Point Positioning
PSK	Phase-Shift Keying
PTB	National Metrology Institute, Germany (Physikalisch-Technische Bundesanstalt)
PTP	Precision Time Protocol
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
R	Receiver
REACTION	Research and Experimental Assessment of Control plane archiTectures for In-Operation flexgrid Network re-optimisation
REFIMEVE+	Metrological Fibre Network with European Vocation + (REseau FIbré MEtrologique à Vocation Européenne+)
REST	REpresentational State Transfer
RFC	Request for Comments
RFQ	Request for Quotation
RLS	Repeater Laser Stations
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RSA	Routing and Spectrum Allocation
S-band	Short band
SBI	Southbound Interface
SBS	Stimulated Bouillon Scattering
S-BVT	Sliceable Bandwidth Variable Transponders
SC	Super-Channel

SD	Soft Decision
SD-FEC	Soft-Decision Forward Error Correction
SDH	Synchronous Digital Hierarchy
SDM	Space-Division Multiplexing
SDN	Software-Defined Networks [or Networking]
SMF	Single-Mode Fibre
SNMP	Simple Network Management Protocol
SNR	Signal-to-Noise Ratio
SOI	Silicon On Insulator
SPM	Self-Phase Modulation
SCPP	**Sub-Carrier Power Pre-emphasis**
SRS	Stimulated Raman Scattering
SSS	Spectrum Selective Switch
SV	Single Vendor
T	Transmitter
T1	JRA1 Current and Future Network Technologies
Tb	Terabit
Tb/s	Terabit per second
TC	Transponder Class
TCM	Tandem Connection Monitoring
TDEV	Time Deviation
TDFA	Thulium-Doped Fibre Amplifiers
TE	Traffic Engineering
TED	Traffic Engineering Database
TTI	Trial Termination Identifier
U-FEC	Universal Forward Error Correction
USB	Universal Serial Bus
UTC	Coordinated Universal Time
VNT	Virtual Network Topology
VNTM	Virtual Network Topology Manager
VOA	Variable Optical Attenuator
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch
XPM	Cross-Phase Modulation
YANG	**A** data modelling language used to model configuration and state data manipulated by the network configuration protocol (NETCONF), NETCONF remote procedure calls, and NETCONF notifications
ZBLAN	ZrF_4-BaF_2-LaF_3-AlF_3-NaF glass
ZTC	Zero-Touch Connectivity