THE ALCATEL-LUCENT/ NORDUnet PROJECT

TRANSFORMING A LEGACY NETWORK TO AN AGILE OPTICAL NETWORK

TECHNICAL WHITE PAPER

Can transforming a legacy network to an agile optical network meet the needs and budget of a group that supports leading-edge research? Alcatel-Lucent and NORDUnet partnered to provide the Nordic National Research and Education Network (NREN) with a cost-effective, highly scalable and versatile optical network.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 The Alcatel-Lucent/NORDUnet study

The white paper demonstrates how transforming a legacy network to a next-generation, agile, optical network meets Nordic National Research and Education Network (NREN) needs for a cost-effective, highly scalable, versatile and dynamic optical network that attracts and supports leading-edge research. The study validates the value of Optical Transport Network (OTN) services enabled end-to-end (with Operations, Administration and Maintenance [OAM], Generalized Multi-Protocol Label Switching [GMPLS], 100G, etc.) over a legacy network instead of deploying a Greenfield network.

Alcatel-Lucent and NORDUnet tested and deployed the Alcatel-Lucent 1830 Photonic Service Switch (PSS)-based Agile Optical Networking solution over a legacy, photonic Wavelength Division Multiplexing/Reconfigurable Optical Add Drop Multiplexer/Packet-Optical Transport (WDM/ROADM/P-OT) network. The resulting benefits to NORDUnet include improved performance and reduced operational expenses.

1.2 Market drivers for the NREN community

Research is increasingly becoming a global effort. Research projects, teams and communities develop global partnerships and increasingly utilize the resources and capabilities of more than any single country – or even a single region. In this environment, future national research networks need to be dynamic and flexible, and they need to offer high capacity to researchers. At the same time, global market trends such as increased demand for cloud-based services, mobility and virtualization have the same impact on research networks that these trends have on traditional telecom operators: large data flows can be from "anywhere to anywhere."

The challenge for future research networks is to evolve traditional intransigent networks to a more federated way of networking by adopting technologies that are protocol-agnostic and flexible.

2. ALCATEL-LUCENT SOLUTION OVERVIEW

Alcatel-Lucent Agile Optical Networking, based on the Alcatel-Lucent 1830 PSS OTN/WDM platform, enables NRENs such as NORDUnet to conquer these challenges and optimize transport of cloud, mobile broadband and video-intensive services. Agile Optical Networking builds on Alcatel-Lucent's high-performance coherent transport, adding managed agile photonics and multilayer service switching and services to address a wide range of applications on a single platform. Both distributed and centralized network intelligence and virtualization ensure the network can adapt to, or even anticipate, the dynamic nature of the emerging wide range of services.

Agile Optical Networking enables NRENs to realize the untapped potential of their optical network — not just as a resource to transport bits, but as an integral ingredient of the cloud infrastructure that connects end users to their content and applications.

3. ABOUT NORDUnet

3.1 Overview

NORDUnet is a joint collaboration by the five Nordic National Research and Education Networks in Denmark (Forskningsnettet), Finland (Funet), Iceland (RHnet), Norway (Uninett) and Sweden (SUNET) (see Figure 1). NORDUnet operates a world-class Nordic and international network and infrastructure service for the Nordic research and educational community.

NORDUnet is providing the Nordic backbone to the global infrastructure for research and education, thereby interconnecting the Nordic researchers and students to pan-European NRENs. NORDUnet monitors international network research activities and development projects and coordinates Nordic involvement in these projects.

Figure 1. NORDUnet: A collaboration of Nordic NRENs

3.2 Drivers, opportunities and challenges

Looking toward the next-generation network, Nordic NRENs face the challenge of finding the right balance between appropriate network functionality, scalability and cost. Although being somewhat different from traditional telecom operators in terms of service delivery, trends such as cloud computing, mobility and general traffic increase are elements that also impact NRENs. Research networks will also need to support the collaborations and projects ongoing in GEANT, the pan-European research and education community, while still being green, IT-aware and cost-efficient.

It is the vision and strategy of NORDUnet to provide a common world-class network infrastructure that supports these challenges.

The operational aspect of driving an advanced data network, plus delivering state-of-the-art services with a limited resource operations center, is a challenge NORDUnet addresses by selecting highly skilled operators and through the constant pursuit of smarter and more innovative ways of working.

As an example, NORDUnet has adopted the Nagios® alarm system, a service-oriented IT infrastructure monitoring system. Nagios collects alarms from different elements in the network, ranging from cooling systems to router interfaces, and presents the alarms from these elements in a clear manner to the operator.

NORDUnet foresees that by adding an OTN switching layer on top of, or integrated with, a photonic layer, service operations can be simplified. Similar advantages can also be achieved by adding a control plane.

The primary advantage of adding a control plane to the photonic layer, the OTN layer, or even both, is the added service restoration capabilities of the network. However, the operator's tasks also become easier because services can be delivered throughout the network with minimal field interventions and operator efforts. Furthermore, control plane technologies such as GMPLS can be used for auto-provisioning systems to support bandwidth-on-demand services.

Finally, the end-to-end monitoring capabilities of the OTN technology adds the benefit of delivering robust and quality services to end users in both single- and multi-domain environments.

3.3 Overview of the tests

Based on these considerations, NORDUnet conducted tests on the Alcatel-Lucent 1830 PSS-36 platform, which was easily integrated into the existing Dense Wave Division Multiplexing (DWDM) platform, the Alcatel-Lucent 1626 Light Manager (LM]). This integration enabled flexible testing of new technologies, such as control plane-enabled bandwidth-on-demand and inter-domain monitored service delivery, that support existing NREN research. However, the testing focused primarily on future service capabilities that NORDUnet intends to offer.

The trial was an experiment to exploit OTN technology and also to investigate whether OTN can help fulfill some of the future network needs of NORDUnet.

The installation and commissioning of the 1830 PSS was fairly effortless, and the photonic integration with the existing DWDM platform was completed without problems. The only real challenge was encountered during the integration of the network element management, during which the Data Communication Network (DCN) design had to be revisited.

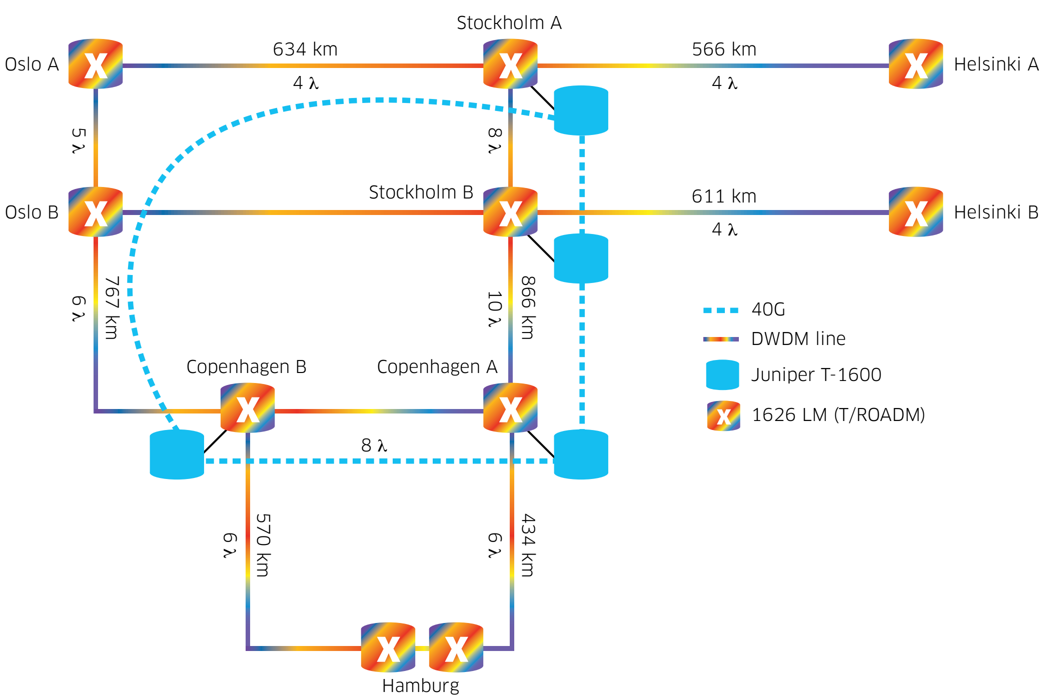
3.4 The NORDUnet network

The NORDUnet optical network spans all the Nordic countries, with 10 main sites and up to about 2,000 km. Network traffic is about 0.2 Tbs but is expected to reach approximately 0.8 Tbs by the beginning of 2015.

The network supports international science projects in multiple fields, including medicine, high-energy physics, environmental research and astronomy.

Operations are managed by Nordic University NOC (NUNOC) in Stockholm, which provides around-the-clock support for the optical and IP network infrastructure (see Figure 2).

Figure 2 . NORDUnet optical and IP network infrastructure



4. OTN OVERVIEW

Standardized by the ITU-T, the OTN capitalizes on past transport experience and extends capabilities to higher bit rates and multicarrier domains. The OTN is an integrated approach to providing switching and multiplexing in electronic or photonic domains, or in both.

The OTN was designed and has been updated to keep pace with the diversity of traffic types – with special attention paid to packet clients – whether IP/MPLS, Ethernet or packet optical. OTN defines adaptation and multiplexing to carry these clients transparently. Client data rates can vary from 1 to 100 Gb/s.

OTN integrates these capabilities with WDM networking functions in a single consistent framework to provide a high-capacity foundation for next-generation networks.

4.1 Switching capabilities

The photonic and electronic switching capabilities play complementary roles for maximum network efficiency.

4.1.1 Photonic switching domain

Optical signals transiting a network node are switched at the wavelength level. This is best suited for cases in which the granularity of the transported service is close to the wavelength capacity. Photonic switching is used primarily to provision and restore wavelength services.

4.1.2 Electronic switching domain

Each optical signal is terminated, and the entire signal — or its service-specific traffic contributions — can be individually switched. Electronic switching is used primarily to provision and restore sub-wavelength services that consume less than a wavelength of bandwidth.

4.2 Standardization

OTN technology originated in the 1990s when DWDM systems were being standardized. Initially, the OTN defined client signal types that mostly aligned with SDH/SONET, and although the OTN covered rates up to 40G, it was used mainly for wavelength management at 2.5G and 10G.

ITU-T Recommendation G.709 was recently updated to align with Ethernet clients from 1 to 100 Gb/s and has gained widespread market acceptance in the last few years. As a result, work continues on a number of complementary technologies, including the GMPLS control plane, variable size transport containers and data rates higher than 100G.

4.3 Optical Transport Hierarchy

The OTN integrates a new, expanded hierarchy for sub-wavelength bandwidth management in the electronic domain. The Optical Transport Hierarchy (OTH) offers a powerful networking tool capable of managing 1 Gb/s, 2.5 Gb/s, 10 Gb/s, 40 Gb/s and 100 Gb/s bandwidth pipes, including increments of multiple 1 Gb/s for maximum flexibility.

The OTH leverages the familiar Time Division Multiplexing (TDM) technique, allocating any type of traffic flow into fixed-size bit frames (time slots) that are then switched by bufferless network nodes and transmitted over the digital signal.

The OTH provides unique, well-proven capabilities for transport networking, such as cost-effectiveness and minimized complexity, offering the best trade-offs among networking flexibility, hardware design simplicity and network efficiency. These OTN characteristics offer key advantages.

4.3.1 Transparency and multiservice

Regardless of the nature of the transported service, in the OTH any type of client traffic, including IP packets, is encapsulated in frames that are switched in bufferless network nodes and transported through logical pipes at a constant bit rate and guaranteed quality and with deterministic performance. This technique avoids the sophisticated traffic processing that is typical of packet technologies, such as classification, metering, queuing, Quality of Service (QoS) and congestion avoidance.

Particularly advantageous in regional or backbone networks, where traffic of multiple services from multiple access and metro locations is already well consolidated, this approach is a simple, efficient method for transparent, reliable transport over long distances.

4.3.2 Security

In the electronic domain, OTH ensures that the networking technology used by the transport layer is fully independent from that used by the transported client service layer. This feature guarantees full client traffic segregation, paving the way for an efficient shared network infrastructure among multiple service providers.

4.4 Hierarchical transport layers

The OTN architecture encompasses three hierarchical transport layers (see Figure 3).

4.4.1 Optical Transport Section

The Optical Transport Section (OTS) layer is devoted to the management of line optical amplifiers and related links. The OTS represents a managed multi-wavelength signal over a single optical span (for example, between line amplifiers).

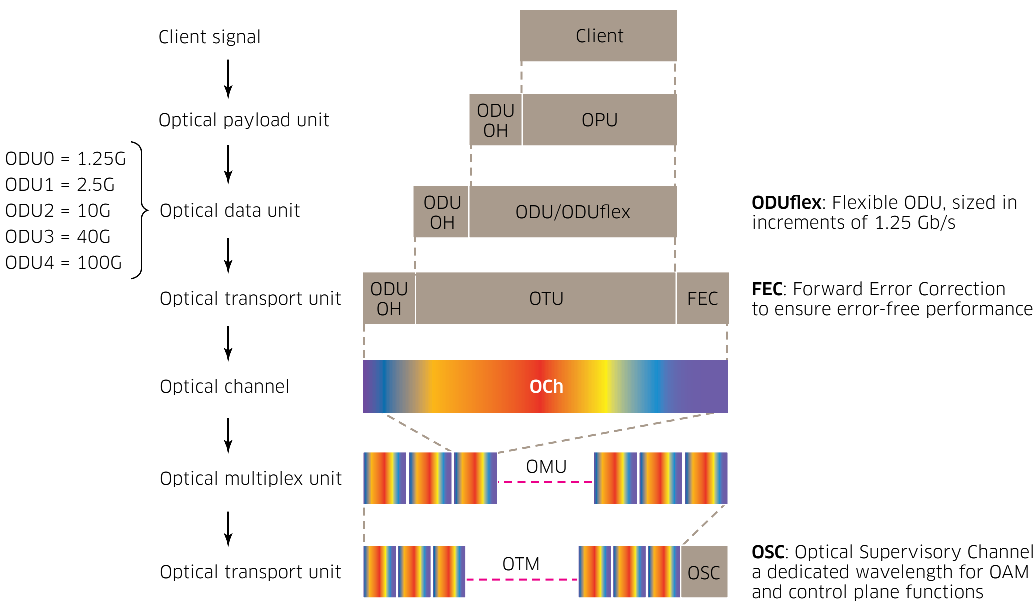
4.4.2 Optical Multiplex Section

The Optical Multiplex Section (OMS) layer is devoted to the management and multiplexing of wavelengths, and therefore to the management of multiplexers/demultiplexers. The OMS represents a managed multi-wavelength signal over multiple optical spans (for example, between DWDM equipment).

4.4.3 Optical Channel

The Optical Channel (OCh) layer is devoted to end-to-end management of wavelengths within the OTN. The OCh represents a single optical channel over multiple optical spans with flexible connectivity.

Figure 3. OTN hierarchy



The OCh signal consists of an Optical Payload Unit (OPU), an Optical Channel Data Unit (ODU) and an Optical Channel Transport Unit (OTU).

The OPU provides the functionality for mapping client signals, such as STM-64/OC-192, 40 Gigabit Ethernet (GE), 100GE or Fibre Channel (FC), into the ODU.

The ODU is a network-wide managed transport entity that functions as the primary bearer for client traffic and can transparently transport a wide range of client signals. In-band ODU operational tools support managed transport services in multi-operator optical networks in a client-independent way that is essential to the operation of these networks. These tools support monitoring functions that enable Service Level Agreement (SLA) assurance for end customers, service providers and network operators. The tools provide for multiple levels of nested and overlapping connection monitoring and reliable performance using sophisticated fault localization capabilities.

Each ODU can carry a single client signal (Lower Order client container, LO ODU) with rates at 1.25 Gb/s, 2.5 Gb/s, 10 Gb/s, 40 Gb/s and 100 Gb/s, or it can carry multiple (multiplexed) client signals (Higher Order server container [HO ODU]) with rates at 2.5 Gb/s, 10 Gb/s, 40 Gb/s and 100 Gb/s.

In addition, a flexible-sized ODU container, the ODUflex, has been standardized as capable of supporting the transport of variable-rate packet streams — for example, Virtual Local Area Networks (VLANs) within a 100GE port — to provide maximized bandwidth utilization and scalable transport of client services at the lowest cost per bit.

The OTU comprises the ODU plus transport overhead (e.g., FEC). The OTU is the fully formatted digital signal that is transmitted over a wavelength that constitutes the OCh. Robust protection schemes with deterministic performance are available in the three hierarchical transport layers to ensure both network and client survivability under 50 ms, along with GMPLS control plane-based restoration that supports flexible options for network resilience against multiple failures.

5. OTN BENEFITS

The multiservice-capable core infrastructure of the OTN is based on lessons learned from SDH/SONET, incorporating additional high-bandwidth optical technology to meet the challenges of evolving toward full IP. OTN provides the gigabit-level bandwidth granularity required to scale and manage multi-terabit networks and offers service providers the tools to simplify operations and improve network efficiency. Some of the main benefits of OTN are:

- It provides a standards-based common framework across optical wavelength transport that also includes TDM switching and aggregation.
- It provides data and timing transparency for packet, TDM and wavelength services, making it ideal to transport any type of client signals, particularly IP, Ethernet and other packet types.
- Switching at the electronic (ODUk) layer improves wavelength utilization, so fewer wavelengths are needed to transport a given amount of traffic.
- OTN maximizes nodal switching capacity to the multi-terabit level, the gating factor for reconfigurable network capacity.
- It minimizes the need for large numbers of fine-granularity pipes that complicate network planning, administration, survivability, management systems and control protocols.
- OTN management tools are complete and fit well within existing carrier networks, enabling end-to-end quality assurance of client services while decoupling transport granularity from DWDM line capacity.
- OTN enhances SLA verification capabilities in support of multicarrier, multiservice environments.
- By enabling transport at the lowest technology layers, OTN minimizes transport cost and power consumption.
- It gives service providers confidence as transmission speeds continue to increase that OTN provides a clear evolution path.
- It is well-suited to automation through the GMPLS control plane, enabling a wide range of resiliency techniques.

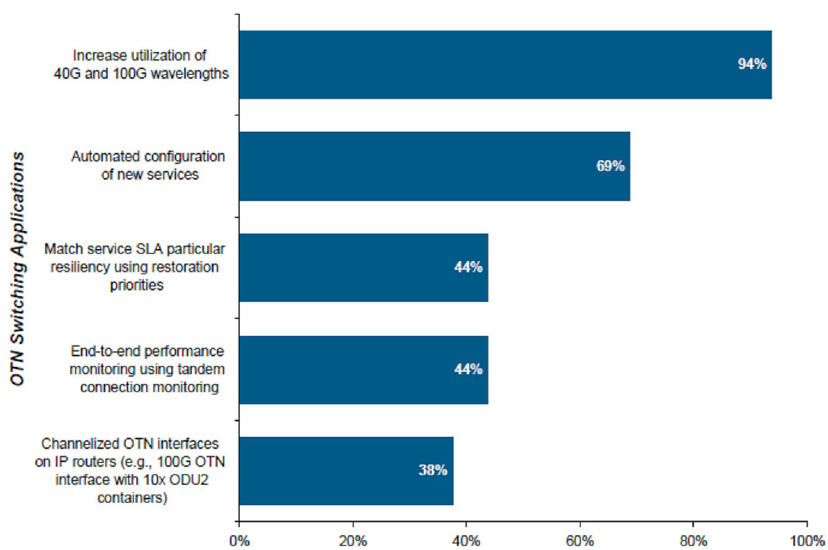
OTN is also a catalyst that helps realize the full potential of two other key optical technologies: high-speed coherent transport and the GMPLS control plane. The electronic switching layers of OTN ensure that high-speed coherent wavelengths are well utilized, helping to contain CAPEX. The OTN structure also provides the basis for seamless evolution to higher line rates. Finally, OTN works hand-in-hand with a GMPLS control plane to implement rapid service provisioning as well as mesh restoration.

6. OTN APPLICATION AND DEPLOYMENT STRATEGIES

OTN is being applied to a number of transport networks, including both Greenfield and legacy applications, across both metro and core areas. One measure of OTN strategy is a survey of network operators by Infonetics Research.

Figure 4 shows responses to the question, “How do you plan to apply OTN switching?” Not surprisingly, the need for increased utilization of 40/100G wavelengths is rated highly by almost all operators. The deployment of these wavelengths is enabled by the deployment of OTN switching as customers look to efficiently fill the 40/100G wavelengths by packing in 10G client traffic. Another finding is that 69% of operators view the move to OTN switching as an important tool for automated configuration of new services.

Figure 4 . OTN switching applications



Source: Infonetics Research Operators Survey, April 2012

7. OTN ON THE ALCATEL-LUCENT 1830 PSS PORTFOLIO

The Alcatel-Lucent 1830 PSS portfolio (see Figure 5) combines multi-terabit electronic ODU switching functionality with DWDM networking capabilities, including 100G coherent, Tunable ROADM [T/ROADM], long optical reach, photonic OAM, design tools and more.

Figure 5. Alcatel-Lucent 1830 PSS Portfolio

- Scalable product size variants from access (1830 PSS-1) to core (1830 PSS-64)
- T/ROADM configurations and WDM mesh
- OTN switching at Terabit capacity
- Single carrier 40G/100G coherent optics
- High performance restoration with GMPLS
- Common network management
- Common cards across the product portfolio

The 1830 PSS portfolio fits a wide range of applications from access with the PSS-1 and -4, all the way to backbone capacity with the PSS-32, -36 and -64. The PSS-36 and -64 provide ODU-level electrical switching in addition to photonic wavelength transport. OTN is the ideal technology to unify key network features, and the 1830 PSS family is the ideal platform for these features. The OTN and the 1830 PSS portfolio work together to provide numerous capabilities, including:

- Terabit switching
- 100G+ wavelength transport
- Tunable Zero Touch Photonics
- DWDM convergence
- GMPLS intelligence and efficiency

The 1830 PSS supports ODU-level switching through a non-blocking, protocol-agnostic fabric, for aggregation of any type of client signal to maximize fill rate of the transport wavelengths. This means fewer wavelengths will be needed, relieving fiber exhaust issues. The colorless, directionless features of the 1830 PSS provide the flexibility to manage these wavelengths. Transporting traffic at the lowest technology layer also conserves power. Finally, the supervision functions of the OTN overhead allow transparent services to be carried between vendor domains and even across carrier network boundaries.

Alcatel-Lucent is the leader in 100G technology and was the first vendor to offer coherent 100G on a single wavelength carrier. This allows us to offer industry-leading 100G performance in terms of optical reach and tolerance to physical impairments, which are extremely challenging at 100G. Coherent technology also allows our 100G to coexist with adjacent wavelengths carrying 10G or 40G signals, something most of our competitors cannot do.

The Digital Signal Processors (DSPs) that power our innovative coherent processing also provide fast reconfigurations for high availability. Various interface types are supported, including 10x10G muxponders and direct 100GbE client. And the 1830 PSS architecture provides future-readiness to grow beyond 100G when the time comes.

Highlights of the Alcatel-Lucent 1830 PSS portfolio include:

- Single products integrating WDM and OTN switching modules
- Scalable product size variants from access (1830 PSS-1) to core (1830 PSS-64)
- End-to-end networking at the WDM and OTN layers across product variants, allowing for sub-wavelength ODU switching and any-client/any-line assignment to maximize the wavelength filling factor and add flexible bandwidth management
- New Alcatel-Lucent 1830 PSS-36 and 1830 PSS-64 shelves for scalable multi-terabit OTN switching options at multi-terabit capacity, with support for any mix of client traffic
- T/ROADM configurations
- Next-generation 40G/100G and now 400G coherent optics with the 400G Photonic Service Engine (PSE)
- GMPLS control plane intelligence for cross-layer automation, highly resilient transport and dynamic bandwidth provisioning, ensuring the greatest possible network efficiency
- Common network management
- Common cards across the product portfolio

The 1830 PSS-36 and 1830 PSS-64 offer integrated terabit OTN and DWDM capabilities for the next-generation intelligent optical core and manage traffic at the most economical layer. Extensive automation and GMPLS control plane intelligence minimize the need to reserve network capacity for resiliency. Instead, providers can operationalize more of their available bandwidth, generating additional revenue and maximizing profits.

The Alcatel-Lucent 1830 PSS-36 and PSS-64 feature a unique set of capabilities:

- Industry-first switching architecture
  - State-of-the-art 2 Tb/s capacity
  - 120 Gb/s per slot backplane with built-in readiness to scale up to multi-terabit
- Universal switch unit that can support any traffic mix, from 100 percent TDM to 100 percent packet
- Single, compact, highest-density chassis
  - Lowest power per transported bit
  - Very low power consumption

- Support of OTN with multiple transport networking options, including OTH, Carrier Ethernet, SDH and SONET
  - ¬ Most efficient bandwidth management of low-rate signals (GE, STM-1/OC-3)
  - ¬ Up to 40 Gb/s or 100 Gb/s
- Flexible IP traffic grooming options at the OTN layer, including port-level and subport-level grooming
- GMPLS control plane, enabling fast restoration and protection schemes at ODU-layer service granularity and ensuring superior SLAs

DWDM networks originated as a way to transport high capacity on point-to-point links. With the introduction of wavelength selective switches, T/ROADMs have emerged, providing directionless and colorless options that give service providers great flexibility and a path to efficient photonic mesh networking.

The Wavelength Tracker is a unique feature in the Alcatel-Lucent DWDM portfolio that automates the commissioning, turn-up and supervision of wavelengths. It works by modulating a management signal onto the wavelengths so that each wavelength can be identified and monitored all along the path without being terminated and regenerated. This provides operators with an integrated view of all wavelengths at different points across the network, allowing them to trace the behavior of the wavelength, isolate faults, monitor performance and correlate alarms. When coupled with the overhead provided in the G.709 wrapper, the Wavelength Tracker provides complete end-to-end management for the OTN.

8. ALCATEL-LUCENT/NORDUnet OTN SOLUTION TESTING AND DEPLOYMENT

8.1 Introduction

From the beginning of the trial, a central objective was to investigate the possibilities of integrating the 1830 PSS OTN/WDM platform with existing legacy networks. Therefore, the equipment was integrated into NORDUnet's live production network, with Alcatel-Lucent 1830 PSS's installed at the Copenhagen and Hamburg sites.

Utilizing NORDUnet's diverse fiber routes to Germany (one passing Fyen and one passing Sealand), two 1830 PSS nodes were linked to the separate fiber routes through the DWDM layer and joined again in Hamburg on third 1830 PSS node, to form an OTN triangle (see Figure 6).

After the installation phase, testing was performed alongside existing NORDUnet services. The focus was on testing:

- Integration and adoption of the OTN layer on the legacy network
- OTN service trials: service creation, service options and resilience testing
- OTN technology benefits in multi-domain scenarios and advances in OAM capabilities
- GMPLS add-on operational value and possibilities (for example, restoration testing)
- OTN delay measurement in collaboration with the Danish Technological Institute (DTI)

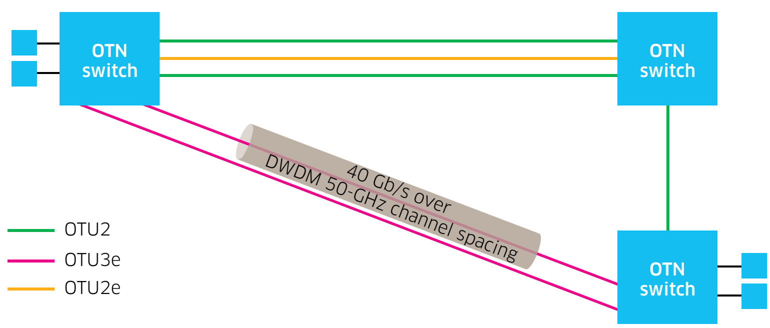
8.2 Bench topology

To have good restoration options and to exploit the multistage mapping, multiplexing and switching possibilities, the aim was to have at least ODU3 capacity and a ring structure topology. Furthermore, the nodes were set up with several optical interfaces to have as many options as possible for the services.

Three 1830 PSS-36 nodes were installed, two in Copenhagen, Denmark (collocated) and one in Hamburg, Germany.

The link between the three nodes used a DWDM 50-GHz channel spacing link based on the Alcatel-Lucent 1626 LM. However, in principle any optical platform would work. The testing performed is listed in the following sections.

Figure 6. The test network



8.3 OTN layer tests

The following OTN layer tests were performed:

- Service provisioning: 1OG ETH/STM-64/1-GBit/s/STM-16
- Add a new lambda at the photonic layer: DWDM 50-GHz channel spacing link based on the 1626 LM
- Mix of different LO-ODU1s and LO-ODU0s over the same HO-ODU2
- Mix of different lower bit rates (STM-16/1G-Bit/s) over the same ODU1 container
- Supervision: in-band communication using GCC0 at OTU3E and OTU2 level
- ODU2 protection: switching based on loss of signal (LOS)and signal degraded (SD)
- Alarm and OAM and performance monitoring
- Equipment redundancy/controller redundancy
- Overhead transparency

8.4 Restoration tests: restoration GMPLS-based

- Path life cycle: unprotected
- Path life cycle : source-based restoration (SBR)
- Path life cycle: guaranteed (GR)
- Path life cycle: protection restoration combined (PRC)

8.5 Equipment redundancy tests

Tests were performed on controller and matrix redundancy.

8.6 Tandem connection monitoring

The following tandem connection monitoring tests were performed:

- Simulation and testing of multi-domain environment
- Test of alarm scenarios in cascaded Tandem Connection Monitoring (TCM) sections
- Test of domain-specific protection scenarios such as signal fail and signal degrade

8.7 Delay measurement tests

Tests were performed by the Danish Technical University on delay measurement in different loop configurations.

8.8 Results and lessons learned

8.8.1 OTN integration

By using offline planning tools and colored interfaces, a control plane-enabled OTN switching layer was successfully integrated into NORDUnet's production network, thereby demonstrating an example of low-impact, cost-effective network adaptation.

The DCN design needed to be revised because integration with the existing DCN design led to some misunderstandings, which resulted in small delays to the trial.

8.8.2 GMPLS control plane trial

GMPLS control plane configuration needs evaluation before deployment, but when enabled and functional, the GMPLS control plane worked very well and substantially improved service restoration efforts. For example, configuring restorable 10GE service was "a few minutes operation task".

8.8.3 OTN services

The effect of adding the OTN switching layer was that services could be offered immediately on reconfigurable optical interfaces in almost all flavors, both packet- and TDM-based. Furthermore, clients can also be directly adopted on an E-NNI OTN interface capable of handing over the complete overhead for further end-to-end monitoring in, for example, multi-domain environments that are typical in research networks.

8.8.4 Delay measurements

One of the tests was to provide an OTN service for a research project at the Danish Technical University (DTU). The idea was to perform delay measurement testing by connecting a GE circuit from the university local campus. Connect it to an OTU0 interface at the Copenhagen site and loop it several times in the OTN triangle (using the higher-order ODU backbone), thereby performing delay measurements on a real physical network.

The experiments performed helped in collecting data for the research work.

8.8.5 End-to-end monitoring and OAM

When testing the tandem connection monitoring (TCM) functionality of OTN, it was seen that the task is also filled with careful planning and design considerations. Especially for the TCM configurations, it became clear that end-to-end monitoring in a multi-domain environment implies clear collaborated agreements upon implementation. OAM capabilities are clearly improved (compared to legacy networks) and terms such as "delay measurement" Fault Type and Fault Location (FTFL) and performance monitoring (PM) aid the operator in delivering professional services.

Benefits included:

- Improved performance
- Easier operations
- Application-specific benefits for particular research disciplines, such as medicine, astronomy, high-energy physics and environmental studies

9. CONCLUSION

The trial was a clear demonstration of how new technology can be easily integrated and adopted into legacy networks. With open photonic platforms, utilizing colored interfaces and having solid management integration, OTN technology was adopted as an overlay network. OTN provided cost-effective benefits to the existing DWDM layer for little effort.

The GMPLS control plane addition in the OTN layer has clear operational advantages in ease of provisioning and the added restoration capabilities.

Service management efforts can be considerably decreased and can help the operator with routine operations such as traffic rerouting and service re-establishment.

Furthermore, advances in optics such as coherent detection, new modulation schemes and forward error correction advancements, contribute to line capacity increase and therefore provide an argument for employing a switching layer on which to add agnostic services.

During the trial, it was demonstrated that OTN can provide these services, especially for research networks where applications such as medicine, astronomy and high-energy, physics-related services should be provided in an agile and adoptive manner. Additionally, the OTN technology is well suited for multi-domain environments because OAM functionalities such as tandem connection monitoring improve end-to-end monitoring of any type of service.

10. ACRONYMS

CAPEX	Capital Expenditures
DCN	Data Communication Network
DSP	Digital Signal Processor
DWDM	Dense Wavelength Division Multiplexing
FTFL	Fault Type and Fault Location
GE	Gigabit Ethernet
GMPLS	Generalized Multi-Protocol Label Switching
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
MPLS	Multi-Protocol Label Switching
NREN	National Research and Education Network
OAM	Operations, Administration and Maintenance
OCh	Optical Channel
ODU	Optical Channel Data Unit
OMS	Optical Multiplex Section
OPU	Optical Payload Unit

OTH	Optical Transport Hierarchy
OTN	Optical Transport Network
OTS	Optical Transport Section
OTU	Optical Channel Transport Unit
P-OT	Packet-Optical Transport
QoS	Quality of Service
ROADM	Reconfigurable Optical Add-Drop Multiplexer
SDH-SONET	Synchronous Digital Hierarchy/Synchronous Optical Networking
SLA	Service Level Agreement
TCM	Tandem Connection Monitoring
TDM	Time Division Multiplexing
T/ROADM	Tunable Reconfigurable Optical Add-Drop Multiplexer
VLAN	Virtual Local Area Network
WDM	Wavelength Division Multiplexing

Alcatel·Lucent