NOBEL

Next generation Optical networks for Broadband European Leadership

Publishable Final Activity Report

January 1st 2004 – February 28th 2006

Project no. **FP6-506760**
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Project coordinator organisation name: **TELECOM ITALIA**

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1 Introduction

This document reports on the major activities and results of the IST Integrated Project NOBEL during its whole life: 1st January 2004 – 28th February 2006.

Section 2 presents a quick overview of the major project objectives and figures, the project organization and the Consortium.
Section 3 contains a summary of the activities and technical results achieved by the 8 work packages of the project.

2 General description of IST NOBEL

The main goal of the IST Integrated Project NOBEL "Next generation Optical networks for Broadband European Leadership" is to study and validate innovative network solutions and technologies for core and metro infrastructures enabling a wide penetration of broadband services in Europe.

The major project figures are:

- Start date: 01/01/2004
- End date: 28/02/2006
- Total person-months: 1980
- Total budget: 24.5 M€ (EC Contribution: 13.7 M€)
- Action lines: Broadband for all
- Cluster: Broadband for all

2.1 Project objectives

The main objectives of NOBEL are:

- to define network requirements, architectures and solutions for core and metro transport networks based on an "optimum techno-economic balance" between optical/electrical and circuit/packet routing/switching (e.g. as potentially offered, at different network layers, by ASON/GMPLS);
- to identify the main drivers and the roadmap for the evolution of current core and metro networks towards the project network vision supporting a wider and wider penetration of end-to-end broadband applications;
- to find and study innovative multi-layer traffic engineering and resilience strategies in multi domain networks;
- to assess and describe social and techno-economic aspects regarding the deployment of the Nobel solutions and technologies in the core and metro networks;
- to define and evaluate solutions for providing end-to-end Quality of Service at different network layers;
- to identify network architectures, concepts and solutions for advanced packet/burst switching;
- to propose simplified strategies for the end-to-end management and control of intra/inter-domain connections in multi-layers multi-domains networks;
- to find enhanced solutions and technologies for physical transmission in transparent optical networks;
- to identify the key functional requirements from the architectural, management, control and transmission viewpoints and translate them into specifications, feasibility studies and prototype realizations for multi-service/multi-layer nodes with flexible client and adaptable transport interfaces;
- to assess existing technologies, components and subsystems in terms of efficiency and cost-effectiveness, deriving requirements and specifications for next generation components and subsystems, with respect to the network solutions identified;
- to integrate equipments, prototypes and emulators into already existing test beds for validating advanced ASON/GMPLS functionalities.

The following table provides an overview of the Nobel innovation compared with the state-of-art / open issues for core and metro networks, at the beginning of the project.

Main Areas	*State-of-Art and Open Issues*	*Innovation by NOBEL*
1. Network architecture and solutions for core metro	In the last decade Network Providers largely deployed Sonet/SDH in core and metro transport networks. Further investments have been made in the last few years for introducing WDM point-to-point systems in the core long-haul networks. Nevertheless these network were basically designed for leased lines and voice service. Now all applications are migrating to IP.	The NOBEL vision is based on ASON/GMPLS network solutions maybe integrated in the future with innovative burst/packet switching techniques. The NOBEL solutions will allow a full integration of data, voice and video transport (fixed and mobile) reducing costs, increasing the operational efficiency and improving the quality of end-to-end broadband services.
2a. Multi-layer Network Advanced functionalities: Multi-layer network resilience	A cohesive resilience approach is missing and this is causing in current multi-layer networks contentions among layers and inefficiencies.	NOBEL is proposing multi-layer resilience solutions to optimize the allocation of network spare resources (thus reducing CAPEX), and to avoid contentions among layers.
2b. Multi-layer Network Advanced functionalities: Multi-layer Traffic Engineering	Current networks don't allow an integrated multi-layer resource and QoS optimization, thus resulting in waste of CAPEX and reduced efficiency.	NOBEL is proposing Multi-layer Traffic Engineering concepts to optimize resource and avoid congestions.
3. Network Management and Control	Current networks are managed through long and rather unefficient provisioning procedures, with a negative impact on OPEX and Customers' satisfaction.	The NOBEL control plane solutions will allow automatic provisioning of connections and automatic network discovery (OPEX reduction). Also, the inter-working between control and management Planes will allow a more efficient management of the network.
4. Transmission aspects	Until now, the full exploitation of (true) optical transparency has been prevented by the difficulty of the dynamic esthablishment of optical paths.	The NOBEL control plane will enable the dynamic configuration and esthablishment of transparent, adaptive optical paths through the transport network.
5. Network Services	Bandwidth on demand services are desirable but not easily compatible with existing network technology.	The NOBEL control plane will enable the offering of a new class of services: e.g. Bandwidth on Demand and Dynamic Optical VPN network services, etc

2.2 Project structure

Given the technical and management approach that the Consortium has adopted for NOBEL, the Integrated Project is not partitioned in Sub-Projects but is running as a single integrated and coherent entity. Specifically NOBEL is structured into eight WPs according to the following structure.

- WP1 Architectural aspects for end-to-end services
- WP2 Survivability, traffic engineering, techno- and socio-economic studies and evaluations
- WP3 Advanced Packet/Burst Switching
- WP4 Network Management and Control/Protocols
- WP5 Transmission and physical aspects
- WP6 Multi-service node architectures
- WP7 Enabling Technologies and Components
- WP8 Integrated test bed and related experimental activities

In addition to these technical WPs, WP0 is dedicated to the consortium management and coordination activities.

2.3 Partners and Consortium

The NOBEL Consortium consists of a large number of European global players of the telecom industry, network operators and research institutes. The Partners are:

- Telecom Italia
- Alcatel SEL AG
- Alcatel CIT
- Alcatel Italia
- British Telecom
- Ericsson AB
- Lucent Technologies Network Systems GmbH
- Lucent Technologies Nederland BV
- Ericsson GmbH (formerly Marconi ONDATA GmbH)
- Marconi S.p.A.
- Pirelli Labs
- Siemens AG
- Telefonica I+D
- TeliaSonera
- T-Systems International GmbH
- ACREO
- AGH Akademia Gorniczo - Hutnicza
- CISCO BV
- Telecommunications Technological Center of Catalonia
- France Telecom
- FhG-HHI
- Interuniversity MicroElectronics Center (IMEC/IBBT)
- Institute of Communication and Computer Systems (ICCS)
- AIP - Politecnico of Milano
- Scuola Superiore S.Anna
- Telenor
- University College of London
- Budapest University of Technology and Economics
- University of Stuttgart
- Universitat Politècnica de Catalunya
- Ericsson Magyarorszag KFT
- Italian Institute of Nuclear Physics
- MIP - Politecnico of Milano

3 Workpackage activities and main results

3.1 WP1 Architectural aspects for end-to-end services

3.1.1 Scope and state of the art

Over the next few years we shall attend to a process that has already begun: the exponential growth of the information produced by electronic applications and carried by communication networks.

In particular, multimedia applications, storage services and Grid computing will drive traffic demand in the nearby future. Traffic forecast figures show that the growth of the information produced, and that should be transported on the communication network, is not uniform for every kind of application. There will be a stronger growth for some applications than for others. In fact, consulting groups' researches confirm that the traffic generated by network based storage applications will double in next 3 years (in agreement with major European network operator forecast), while for some multimedia applications (IP-TV or video-conference) it might be not hazardous to foretell a growth of 2000% in the same period.

This data confirms that some network applications (storage in particular) are mature. The growth of traffic is not only the result of new kinds of applications, but it is also simply the result of growth of generated information; on the other hand, multimedia applications are going to conquer "contiguous markets"; video on demand will become a substitute of DVD rental, sophisticated telepresence applications will be a substitute for face-to-face meetings and IP-TV will probably dominate video broadcast in the future.

Different kinds of applications have different traffic profiles; they require different amounts of bandwidth and QoS parameters (set-up/tear-down time, bandwidth and dynamicity, latency, Jitter, BER, availability). As a consequence, they need a diversity of network services to carry their traffic; therefore a plurality of network services will be necessary.

For this reason, instead of thinking about a limited set of existing network services that can meet application requirements, WP1 have investigated through concrete case-studies on what the network services need to be, for carrying the traffic generated by emerging applications, to better meet precise applications requirements.

The researches made in WP1 are not only an investigation on existing network services, but the achieved results - in terms of traffic forecast, architectures of network based applications, identification of precise requirements - clearly feed the research of innovative network services towards the integration of new important functionalities on existing ones. There is value in enhancing (adding functionality to) the network services to meet application requirements and to foster network evolution.

NOBEL WP1 investigated the specific nature of traffic as well as the relation with the architecture for Automatically Switched Networks. A coherent architecture is needed for the existing control and management plane together with the management and control of the emerging network services. Furthermore we investigated four important applications:

- Storage Area Networks
- Video Distribution
- TV Broadcasting
- Grid applications
- Convergence of fixed and mobile applications

3.1.2 Objectives

The overall goals of WP1 were:

- to identify and characterize emerging applications and the related network services for the end-to-end delivery to Customers

- to identify the main drivers for the evolution of core and metro networks supporting end-to-end broadband services
- to define evolutionary network scenarios for a seamless inter-working between core, metro and access network segments
- to identify cost-effective, high-quality architectures and network solutions based on an optimum combination of packets-based (IP, Ethernet,...) and circuits-switching (SDH, OTN, wavelength...) technologies
- to study the functional requirements and the applicability of automated provisioning, routing and resource discovery in multi-layer/domain/service networks (for example using GMPLS)
- to design a functional modelling of transport and service platforms to be exported to Standards

3.1.3 Main activities

The activities of WP1 started from defining the main drivers and requirements for a seamless inter-working between the network segments and within each network segment between domains (partitioning) and layers (layering). Once the functional requirements are defined then the Work-package 1 investigated and simulated cost-effective, high-quality network solutions based on an optimum combination of packets and circuits-based approaches.
In this context the applicability of automatic provisioning, switching, routing and discovery in multi-layer/domain/service networks were evaluated. The activities also covered initial studies on the architectural requirements regarding the extension of optical transparency, for example: path computation and routing of optical circuits accounting for transmission constraints for transparent transmission in optical networks.
WP1 participated actively to the work of the different project-wide Task Forces, which are focused on particular issues. These issues are considered as very important bottlenecks for the definition of network architectures:

- Transparency Task Force that had the task of

  Investigating whether the transparency defines new classes of network services:
    - Definition of drivers and requirements for transparency services
    - Building blocks of transparent networks
    - Node architecture implementation examples

  Creating a broad multi-disciplinary effort in collaboration with other WPs (in particular WP5, WP4, WP6, WP7) about network transparency issues

- VPN Task Force (in collaboration with WP4) that had the task of

  Investigating on some principal concrete scenarios using L1, L2 and L3 VPNs and tailored for certain classes of applications:
    - TV broadcasting
    - Network based storage services
    - Grid applications

The access segment (already covered by the IST IP Muse) will be considered only from the perspective of the aggregated traffic offered to the metro core.
Nevertheless, cooperation with IST IP Muse is already established in order to define an overall architecture for providing end-to-end broadband services.

3.1.4 Major results

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Deliverables

WP1, during the two years of activity, delivered:

- D6 "Preliminary definition of drivers and requirements of core/metro networks for end-to-end broadband services"; D6 reported preliminary results:
  - on the definition and characterization of emerging applications and the related network services for the end-to-end delivery to Customers;
  - on the high-level architectural requirements for the evolution of core and metro networks (preliminary results).
- D11 "Preliminary definition of network scenarios and solutions supporting broadband services for all". D11 reported preliminary results:
  - on the definition of architectures, technologies and solutions for network scenarios (preliminary results).
- D21 "Definition of drivers and requirements of core/metro networks for end-to-end broadband services"; D21 reported on the following results:
  - The definition of drivers from applications to feed the evolution of core and metro networks
  - The definition of emerging network services that benefit of ASON/GMPLS technologies
  - Particular focus on VPNs (in particular O-VPN or Layer 1) and the interaction with G.8080
  - The analysis of particular application specific scenarios including:
    - Storage applications
    - TV broadcasting
    - Video on Demand
- D30 "Definition of network scenarios and solutions supporting broadband services for all". D30 reported results on:
  - The definition of architectures, technologies and solutions for network scenarios
  - The definition of detailed scenarios of future networks (core and metro segments) that are able to carry traffic generated by emerging applications
  - The migration strategies to assure a smooth evolution from the present network architectures a goal progressive network defined in Nobel project
  - The solutions to major bottlenecks in defining network scenarios, such as transparency, resilience, network topologies, etc.

Definition of emerging applications

<u>Drivers</u>

The fundamental driving forces for future communication systems, identified by WP1, can be categorized as follows:

- **Environmental drivers**: reflect changes that have been happening in the telecommunication business environment over the past decade and a half. In this period, the global telecommunications industry as a whole has been gradually moving away from the model of state-owned and/or regulated monopolies to that of a competitive industry operating in an open market
- **Service/market drivers**: reflect the continuously expanding set of capabilities and features customers in various markets demand to satisfy; their constantly evolving set of personal and professional needs, as either end users of services (consumers) or intermediaries (wholesalers).
- **Technology drivers**: Include all the technological enablers a service provider, in partnership with its vendors, can take advantage of in the process of architecting and composing its repertoire of services

These drivers, operating against the backdrop of some trends - including the growing diversity and complexity of new services, the increasing variety and power of end-user devices, and the competitive push to minimize time to market - underline the urgency of fundamental transformation in communication network and service infrastructures.

Application requirements

Let us briefly review the characteristics of the network service according to the applications to be carried out:

Table 1 - Classification of types of applications

QoS \ BW	Low	Medium	High
Real time	Legacy and IP telephony	Gaming	Video conference, Grid computing
Streaming	UMTS	Remote backup, network supervision	TV and Video Broadcast
Transactional	e-buy	Telnet	SAN
Best Effort	e-mail, domotics, VoIP	p2p file exchange, Data acquisition	VoD

Where QoS categories are defined, in turn, as follows:

Table 2 - Definition of QoS parameters

	Blocking probability	Network availability	Set up time	Mean delay	Packet loss rate
Real time	< 0.1%	> 99.99%	< 1 s	*	< 5 E-5
Streaming	< 0.1%	> 99.9%	< 1 s	*	< 1 E-3
Transactional	< 1%	> 99.9%	< 3 s	< 200 ms	< 1 E-2
Best Effort	*	*	*	*	*

The five given variables are obviously related to elasticity, interactivity, availability and symmetry of Table 2

- **Blocking probability**: The ratio between blocking cases (failure of a network to establish a connection on demand from the user, because of alack of resources) and the number of attempts.
- **Network Availability**: The ratio between time when the network is not available and the total time. This parameter describes the requirement for uninterrupted service with acceptable quality. That is, the availability of the network as a whole guaranteeing the exchange of data between A-party and B-party.
- **Set-up time**: Delay between the user application request and the response. For example, in broadcast TV, the required time to change from one channel to another.
- **Delay**: Network delay corresponds to the time it takes for application data units to be carried by the network from the A-party (source) of the session to the B-party (destination). Network delay is caused by the combination of network propagation delay, transmission delay, processing delays and variable queuing delays at the intermediate routers on the path to the destination host.
- **Packet loss rate**: Packet loss is typically the result of congestion in the network. Packet loss rate is defined as the fraction (or percentage) of data packets, out of the total number of transmitted packets that are lost. Packets can be dropped due to congestion, or due to transmission errors... It is usually given as a ratio between the number of lost packets and the number of transmitted packets.

As for the best effort class, for which no value appears in Table 2, telecommunication companies are supposed to specify them as a matter of cost of service versus customers demands and other competitions performances.
In fact, the values above can be adapted by carriers implementing their own solutions to traffic engineering, network design and commercial strategy always taking into account the real evolution framework since departure points are different for different companies. Some standardized values for QoS would help carrier companies to provide their own customers with unified quality levels throughout regions and countries.
Finally a precise characterization of actual and potential users must be carried out to outline the whole network evolution for they are the mighty driver. Related to this, distribution of residential, companies and institutions as well as their wishes like nomadism, word wide business and so on are of paramount importance for carriers' analysis.
Since network services can also be analyzed from the resilience point of view (QoR), the following table must be considered as well:

Table 3 - Definition of QoR classes

Resilience class	Recovery time τ	Bandwidth guarantee
High	τ < 100 ms	Yes
Medium high	100 ms < τ < 1s	Yes
Medium low	100 ms < τ < 1s	No
Low	τ > 1s	No

Identification of network services and network scenarios

Network evolution

Core and metro networks will have to get adapted and improve their performances to cope with the new kind of traffic and its volume increase. In fact, this point of view is the leading consideration of the whole deliverable and will be extended in future ones with more precise

technical and economic considerations. Thus traffic growth forecast and new services requirements are presented but regulatory factors cannot be predicted obviously.
With the dominance of IP data services, carriers must offer competitive networking solutions for the increased IP data traffic in the backbone. IP networks today must be enhanced to provide a mission-critical networking environment. Ultimately, the vision is of IP packets carried directly over an efficient transport technology (Ethernet, SDH, optical core network) to simplify the network layers, consolidate traffic, and reduce cost.
Another aspect of the multi-service IP data transport infrastructure is the unified and automated control and management architecture for both the IP and transport layers. NOBEL WP4 provides the specifications of the appropriate control and management architecture, which is likely to be radically different from what was designed for the single IP layer.
The following key issues must be considered in a carrier's network evolution strategy:

- Investment protection: The migration toward the future transport infrastructure should protect and leverage current multi-service and IP networking investments to offer carriers a competitive advantage.
- IP-centric infrastructure and performance, providing an overall solution that delivers QoS support, traffic engineering capability, and robust control for IP networking is essential for the realization of the envisioned IP-orientation for capacity expansion and cost reduction.
- Efficient transport layers at Layer 2 and layer 1, allowing the necessary transport technology for the IP-centric infrastructure.
- Interworking capabilities: the interworking of multi-service switched networks and IP routed networks, which coexist at both the access and backbone, demands a flexible, robust solution in the evolution phases.

Figure 1 gives a more detailed overview of the key challenges that will be addressed in the short, the medium- and the long term scenarios, that are subdivided into the data-, control- and management plane issues. Control and management plane are further subdivided in layer 1 / 2, layer 3 and an application supportive session view. Note the role of MPLS with certain layer 2 and layer 3 aspects.
The short-term data plane aspects will be focused on the enhancement of the data awareness. Implemented by protocol agnostic adaptation of data oriented protocols on the transport plane, namely via GFP on the SDH layer.
In the medium-term, native Ethernet implementation will play a more important role and will migrate from more locally oriented applications into the whole network. In parallel, the SDH transport and switching layer will be supplemented by OTH technology for handling broadband and coarse granular traffic.
The trend of implementing OTH might be not completed in the medium-term but continue in the long-term timeframe. Furthermore new layer 2 technologies might be introduced in the long-term timeframe and partly complement, partly replace Ethernet as dominating layer 2 technology.
The most severe steps of the evolution will take place on the control plane. In the short-term control plane functionality is implemented based on IP and on MPLS technology only. Interdomain coverage is restricted to IP, even MPLS control planes will be terminated at the border of each domain. First proprietary control plane solutions for layer 1 and layer 2 are also already part of the short-term scenario and especially on layer 1 might be restricted to serve enhanced resilience functions. In the medium-term control plane functions can be assumed on all layers, but these control planes will be separated and act independent from each other. In the long-term scenario the vertical integration of the control plane for all involved layers according to the GMPLS approach, will be assumed.
On the management plane we will still see the already existing separation of management entities on a per layer and per domain basis for a couple of years. This will change in the long-term scenario, where an integration of the control plane across the layers is assumed.

		Short-term 2005-2007	Medium-term 2008-2010	Long-term 2011-2015
Data plane		• Protocol agnostic adaptation • SDH	• Ethernet • Protocol agnostic adaptation • SDH • OTH	• NextGen. Layer L2 • OTH
Control plane	Session	• End to End (SIP etc)	• End to End (SIP etc)	• End to End (SIP etc)
	IP	• Routing (signalling)	• Routing (signalling)	• Integrated Routing & signalling (End to End)
	MPLS	• Signalling per domain	• Signalling End to End	
	L2/L1	• vendor specific signalling for restoration only	• Signalling (routing)	
Mgmt plane	IP/MPLS	• Per Domain Per Layer	• Per Domain Per Layer	• Per Domain Across Layers
	L2/L1	• Per Domain Per Layer	• Per Domain Per Layer	

Figure 1 - Challenges of Nobel

Figure 2 lists some exemplary implementation issues. In a matrix view, the key concepts are grouped together using the data-, control- and management plane as well as the different scenarios. The implementation issues will be discussed in more details in the following chapters.

	Short-term 2005-2007	Medium-term 2008-2010	Long-term 2011-2015
Data plane	• Minimal optical functionality, R-OADM, protection, increase transparency, dispersion tolerance, diversified approaches.	• Standardised, cost-effective 1+ Tb/s systems starts volume deployment.	• How to achieve cost-effective spectral efficiency? • Spectral efficiency of burst-mode systems? • All-optical functionality? • OA technology?
Control plane	• “First” generation • Test & develop • Standardise	• “Must work” generation for ASTN/ASON/GMPLS - first mistakes and incompatibilities ironed out. • First set of functionality	• Can at least two distinct stages in ASTN development be foreseen? • High/full set of functionality
Mgmt plane	• Classic management with “internal” automation and GMPLS functionality	• First large roll-out of “OPEX-minimised systems” generation	• See above.

Figure 2 - Challenges of Nobel – exemplary implementation issues

<u>VPN</u>

Investigation about VPN (Virtual private network) was a core point of WP1 research. As stated in Y1312, “A VPN has the appearance of a network that is dedicated specifically to the users within the subset.” If it looks like a network this implies that the user can choose between what SAPs (Service Access Point) of the VPN it wants to exchange information. This

is the difference between a link and a network, a link provides no flexibility in exchanging information, it can only exchange between the two endpoints of the link. A network however provides flexibility; in general it can transfer information between any pair of endpoints.
It is easy to see that this connectivity flexibility is provided by a VPN for a connectionless technology, e.g., Ethernet or IP. The VPN service interconnects a set of interfaces, and the user sends the IP/Ethernet traffic. Based on the addresses in the datagram's (put in there by the customer) the VPN service can select the destination interface (SAP) and deliver the frame.
For a VPN for a connection oriented technology the flexibility in connectivity is more difficult. Connection oriented technology only allow transfer of information from one SAP to one other (p2p) or to a set of others (p2mp). A VPN cannot consist of one such connection, as it does not provide the flexibility in connectivity as expected from a network.
In order to talk about a VPN for connection oriented technologies the control plane needs to be taken into account, as the flexibility in connection oriented technologies comes from the control plane. In WP1 studies about VPNs, the ASON architecture as defined by the ITU-T in G.8080 was taken into account.
In fact, G.8080 introduces an architecture making a clear distinction between data plane and control plane. Furthermore a distinction between a call and a connection is introduced. The call describes an abstract relationship between users describing the permitted transfer between users. This call is supported by one or more connections providing the resources for the actual transfer. Call control is a signalling association between users and the network to control the setup, release and modifications of a connection. Connection control assigns resources for the connection and creates the connectivity supporting the call.

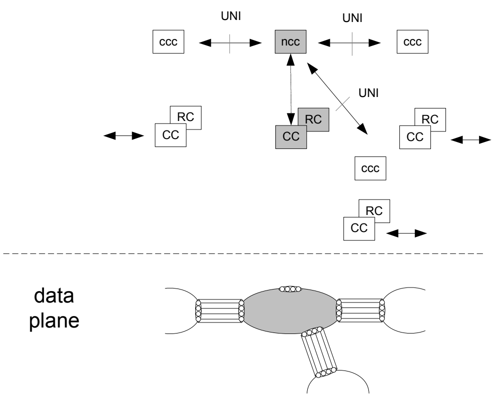


Figure 3 - G.8080 Architectural Model

Figure 3 shows the G.8080 model. At the bottom of the figure the data plane is shown. It consists of three nodes connected to a single node (grey one). Each of the nodes has a connection controller (CC) and Routing Co (RC) associated to it. The RC exchange routing information and the CC's cooperate to create a connection. The links are shown as the set of possible link connections. The link as a whole and its corresponding endpoints (Sub Network Point Pool, SNPP) are used for routing purposes. The routing algorithm advertises available capacity between the SNPPs. The individual link connection and its endpoints (SNP) are used for actual connections that use the link. The link is e.g. a fibre, whereas the link connections identify different SDH timeslots or MPLS labels being used over it. If a connection needs to be created over the link, one of the SNPs is selected, corresponding to the selection of a particular timeslot (SDH) or Label (MPLS).
In the example the grey node belongs to a service provider and the other nodes belong to a customer. The CC's/RC's of the customer do not directly interact with these of the provider. Instead the interaction between the provider and the customer is via the UNI interface between the Call Control components in the user (CCC) and provider network (NCC), this will be illustrated using Figure 4

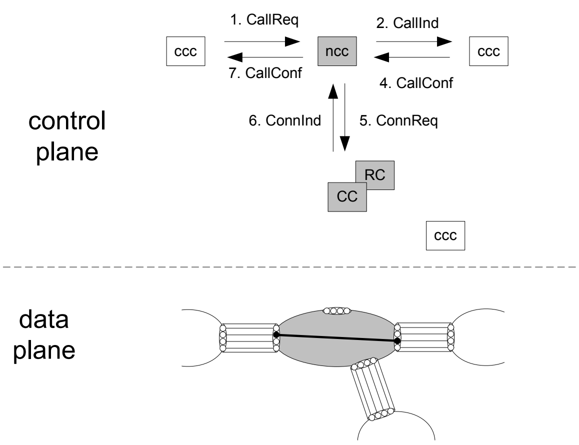


Figure 4 - G.8080 Connection creation

In this figure a connection needs to be created from left to right. The user CCC initiates a Call Request over the UNI (1). The NCC in the provider network validates the call, and informs the called party (2). After receiving the confirmation (3), and if the call is allowed, the NCC requests the CC to create a connection to support the request (5). If this is successful (6) the Calling side is informed (7).

Note that so far we were talking about nodes being interconnected by links. However a node might be in fact a whole network, being controlled by a single set of control components. So instead of node, one might read network, or sub network as well, according to the G.8080 architecture.

Network architectures for metro and core networks

At present, the first step of traffic aggregation is mostly achieved by SDH rings at present with the city shape. This is the metro-access level or first aggregation level but big cities, like Madrid, aggregate traffic again within a second SDH ring in an upper aggregation level: The metro-core level (Figure 5, a). Another current architecture, developed on the basis of Ethernet technology, is presented in Figure 5, b: Clusters of routers (and DSLAMs) linked to GbE switches that, in turn, are part of a mesh.

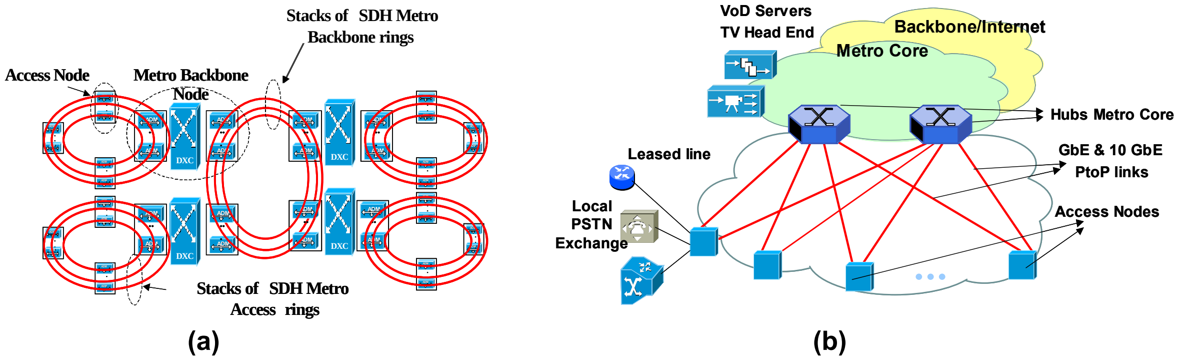


Figure 5 - Present metro network architectures: (a) Two levels SDH rings and (b) Ethernet stars linked through a mesh of GbE switches

The introduction of IP is a paradigm that leads to transform metro network architectures: Migration of almost all services to (packet oriented) IP, and adaptation of the (low cost) Ethernet technology to them. There is a general consensus about the advantages of transforming the upper level of aggregation into a mesh (Figure 6) not only for the possibility of implementing more efficient (cost-effective) resilient mechanisms as IP capacities go to the optical layer but also for the benefits of it under a distributed control plane (upon the basis of GMPLS governed devices): Fast traffic engineering allow carriers to optimise network resources (transferring traffic in/from business areas in the morning to residential areas in the evening, for instance).

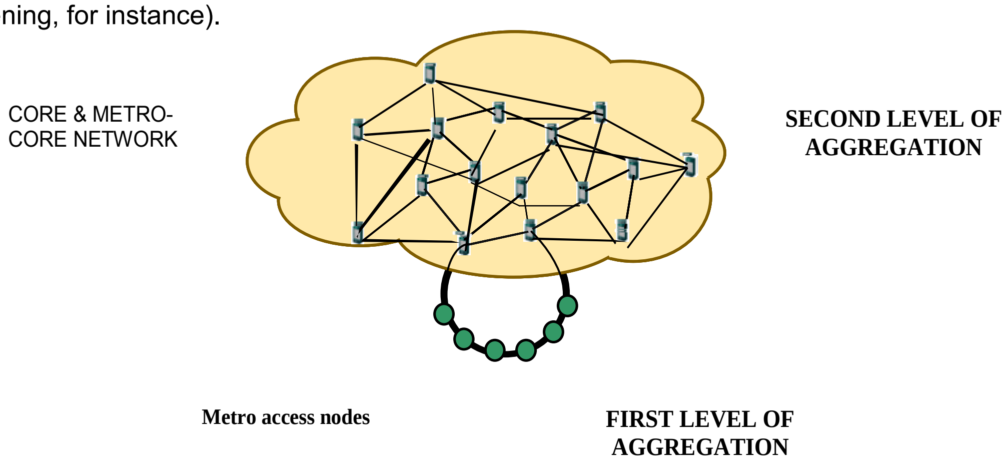


Figure 6 - Metro network with a mesh as second level of aggregation

The architecture of a metro/core network is really different from the metro/regional network design.

Figure 7 depicts a situation where routers are connected among them via physical links. The transmission layer is very easy because it consists of a set of point-to-point connections (e.g. lambdas in WDM systems). Resilience is provided only at IP (or MPLS) level and, to fast the revelation of failures, often expensive PoS (packet over Sonet/SDH) ports are used. The logical topology of the IP network is identical to the physical one, so that no high mesh degree is possible. For this reason, to minimize the number of node pass-through, a hubbed topology is usually adopted. In the hub nodes, a large-size router (e.g. a teraRouter) is often necessary.

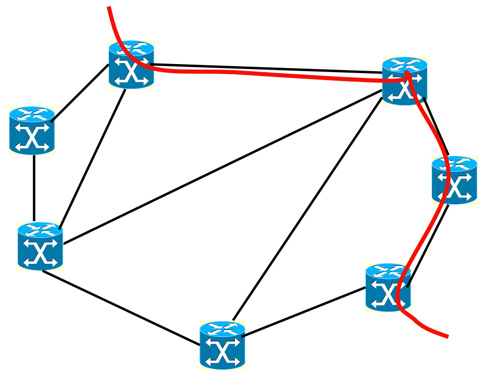


Figure 7 - the routers are connected by point to point physical connections. The switching is provided only at IP layer, no grooming between IP and circuit traffic is possible. The resilience is possible only at IP layer.

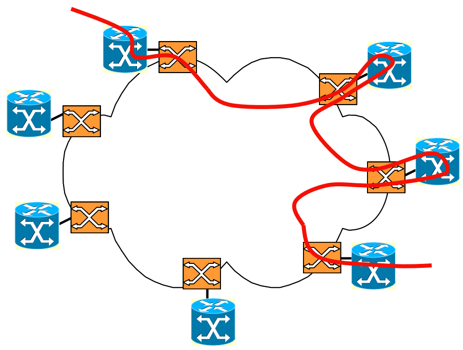


Figure 8 - the OTN receive the traffic from the IP network (i.e. from routers) and their role is only to groom IP traffic with circuit native, but the switching is provided at IP layer. A second role of the OTN is to provide a more cost-effective and fast restoration

Figure 8 depicts an intermediate network design, where a transmission network exists and collects the traffic generated by IP networks coming from routers; the logical topology is identical than in the previous case and, for this reason, the switching of IP traffic is provided by routers. The advantage of this solution is twofold:

- The possibility of groom packet and native circuit traffic, so to save bandwidth
- The possibility to implement resilience at circuit level for failure interesting the physical layer (e.g. fibre cuts) that is faster and more efficient.

The cons might be the cost of this solution. It is necessary to valuate if the bandwidth saving due to grooming between packet and circuit traffic and the possibility to connect routers and O(D)XCs with GbE interfaces, cheaper than PoS adopted in the previous solution can balance the cost of the installation of the transmission devices.

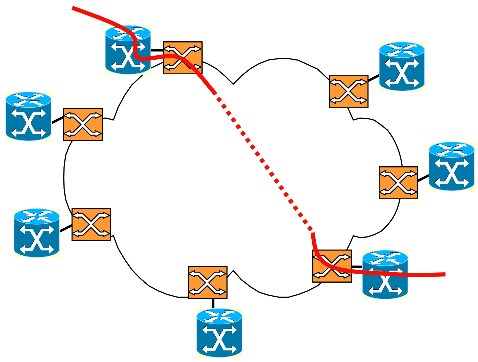


Figure 9 - the switching is provided at transmission layer: the routers are connected by a fully-meshed topology and the switching is provided by the optical network. Grooming between IP and optical-native traffic is of course possible. All the techniques of multilayer resilience are possible.

Figure 9 depicts a solution where the “intelligence” and the switching capabilities are moved toward the transmission level. The logical topology of this solution is usually (quite) full-meshed, such as the routers see the others with a single hop.

The advantages of this techniques is the possibility of groom bandwidth between circuit and packet traffic and this solution allows multilayer resilience techniques with a further bandwidth saving and the possibility to implement classes of resilience.

This solution may be not too expensive, due on the minor cost of L1 internal node transit than L3, but it depends on traffic pattern and on the interface granularity.

Fixed-mobile Convergence (preliminary results)

The convergence of fixed and mobile user services is expected to be one of the issues of major concern for operators in the short and medium term. In this section, we will describe the current situation of the available technologies for Fixed and Mobile Convergence (FMC). Furthermore, we will also include a brief description of some results derived from MUSE project related to potential scalability problems of current standardization approaches.

Fixed and Mobile Convergence covers both infrastructure and services. On the one hand FMC deals with the capability of a unique network to support fixed or mobile applications. On the other hand FMC is also related to those convergent services that can be offered to users (residential or professional subscribers) through a common infrastructure.
In this respect, there exists a widespread agreement about that fixed and mobile services will converge on a common IP infrastructure. However, there exist two divergent viewpoints about how these common IP networks should be built:

Table 4 - Models for FMC networks

PSTN-like	Internet-like
Application-aware	Application-unaware
QoS definitions and guarantees per flow	QoS per aggregated flows

Under an operator point of view there are two main drivers for an evolution towards common IP networks fro fixed and mobile services:

- Cost reductions (OPEX&CAPEX) by implementing common core infrastructure and service platforms for different access networks: Any combination of mobile and fixed voice, video and data services decrease operational costs by using common resources, transport, operation and maintenance, etc
- FMC leads to a new market with unique list of services and high revenue potential. So, revenues may increase due to an easier and quicker provision of new convergent services (e.g Fixed&Mobile VoD).

However, operators are aiming to evolve to this common IP backbone without losing important capabilities (e.g VoIP infrastructure should preserve as many PSTN attributes as possible). So, operators are supporting the "PSTN-like" model where the convergent IP network, which is called Next Generation network (NGN), can provide specific QoS for a particular application, such as VoIP, VoD, videoconference, etc. To facilitate the migration towards this model, many carriers started participating in a major international standards development effort.
The theme of fixed/mobile has been developed also in WP2, taking into account business and regulatory aspects.

3.2 WP2 Survivability, traffic engineering, techno- and socio-economic studies and evaluations

WP2 has been one of the broader and more complex work packages of the Nobel project, mainly devoted to survivability, traffic engineering, techno- and socio-economic studies and evaluations. This wide range of objectives aimed to cover several aspects not yet covered by the remaining WPs, in order to analyse solutions for resilience and traffic engineering for multi-service / multi-layer / multi-domain networks, as well as to assess the techno and socioeconomic viability of new network concepts for end-to-end broadband services for all. These objectives are split into two main areas:

- **Traffic engineering and Resilience strategies for NOBEL solutions.** Comprises activities like research of advanced survivability, new traffic engineering concepts, and finally address the convergence of both TE and survivability. More concretely:
    - **Survivability:** This activity deals with the investigation of efficient resilience strategies inside MMM networks. The objective was to cover both static and dynamic schemas, and to research on new recovery strategies in order to address the multilayer, multidomain, and multiservice problematic.
    - **Traffic engineering:** Study of traffic engineering concepts for e2e broadband services in multilayer/multidomain/multiservice networks. The NOBEL network vision of providing end-to-end QoS in a multi-service, multi-layer and multi-domain network scenario requires advanced Traffic Engineering solutions. Proposal and evaluation of new methods for Route Management, based on inputs from Traffic Characterization and Modelling studies, so that the QoS requirements are taken into account in the design and operation of optical core and metro networks. Different sub-activities may be identified:
        - **Route Management.**
        - **Traffic modelling and Characterization.**
        - **QoS aspects.**

- **Socio and techno-economic analysis and business models.** These activities cover the assessment of new social and economic opportunities, techno-economic analysis of network solutions and evaluation of their economic viability and definition and assessment of business models for the solutions proposed by NOBEL. These activities may be classified as follows:
    - **Techno-economic analysis** of network solutions and evaluation of their economic viability. The main goal in this activity is to identify efficient network solutions and evaluate their economic viability considering both CAPEX and OPEX costs.
    - **Socio-economic feasibility studies** for investigating and assessing new social and economic opportunities. It is important to innovate by identifying: new business opportunities, new business roles and processes, new value chain and its potential impact on the society.
    - **Business models**. Definition and assessment of different business models for the solutions proposed by NOBEL

3.2.1 TE & Resilience

This section reports on the results for advanced traffic engineering and resilience strategies obtained during the first phase of the project. Multiple case studies on different aspects of multilayer, multiservice and multidomain resilience and traffic engineering mechanisms have been carried out along the project, highlighting the complexity of traffic engineering and resilience in the case of network convergence. This section is structured as follows: Firstly, solutions are described which mainly address traffic engineering or resilience issues, and secondly both aspects are jointly investigated. The major conclusions of these case studies can be summarized in the following strategies for traffic engineering and resilience in metro and core transport networks.

3.2.2 Traffic Engineering guidelines

Current transport network architectures are static by nature, typically use a single service class for all data to be transported (e.g. SONET/SDH), use over-provisioning to meet the service requirements of higher layers (e.g. IP), and have difficulties in adapting capacity on a short-term basis to changing needs (manual control plane). In future networks, however, multiple services will be converged onto the same platform (most likely IP-based), and then be transported through the backbone network using the most efficient combination of L1, L2, and L3 technologies.

However, this strategy will not hold in the future, where much more delay sensitive real-time services are required to transmit the data of the highly diverse multimedia applications with the necessary Quality of Service (QoS). Guarantees on network resources, availability, and reliability will be required, that cannot be satisfied and provided by simple over-provisioning.

QoS

QoS differentiation is a very important issue with respect to the applications. The first step in the network level QoS work was to study the required QoS requirements and the economic framework for QoS differentiation (acceptable costs to users for different QoS levels). Applications requirements were deeply explained in D17 and D27. The following four QoS classes are proposed as one of the possible ways to implement QoS classes in optical networks:

Table 5 - Classification of types of applications

BW / QoS	Low	Medium	High
Real time	Legacy and IP telephony	Gaming	Video conference, Grid computing, Tele-Medicine
Streaming	UMTS	Remote backup, network supervision	TV and Video Broadcast
Transactional	e-buy	Telnet	SAN, Trading/Financial
Best Effort	e-mail, domotics, VoIP	p2p file exchange, Data acquisition	VoD, IPTV

Parameters values and ranges for the proposed QoS classes were defined to enable a comprehensive Service Level Specification (SLS). To characterize these parameters, a measurement platform for IP traffic with wide range of analyzed parameters has been implemented.

Table 6 - Definition of QoS parameters

	Blocking probability	Network availability	Set up time	Mean delay	Packet loss rate
Real time	< 0.1%	> 99.99%	< 1 s	*	< 5 E-5
Streaming	< 0.1%	> 99.9%	< 1 s	*	< 1 E-3
Transactional	< 1%	> 99.9%	< 3 s	< 200 ms	< 1 E-2
Best Effort	*	*	*	*	*

Traffic characterization

Traffic measurement and characterisation at packet and flow level has been carried out in several different network contexts. The aim of the study was to understand the impact of emerging broadband services and traffic statistics on the metro and core networks and provide models for performance evaluation and network planning.

Promising traffic models for aggregated traffic on different levels (packet, flow) were studied in details, as well as, new models for transport services (e.g. multi-point connection demands) were developed.

Traffic models, especially suitable for aggregated traffic in the metro and core context, are applied, ranging from packet level models, flow/burst level models and connection level models to demand models.

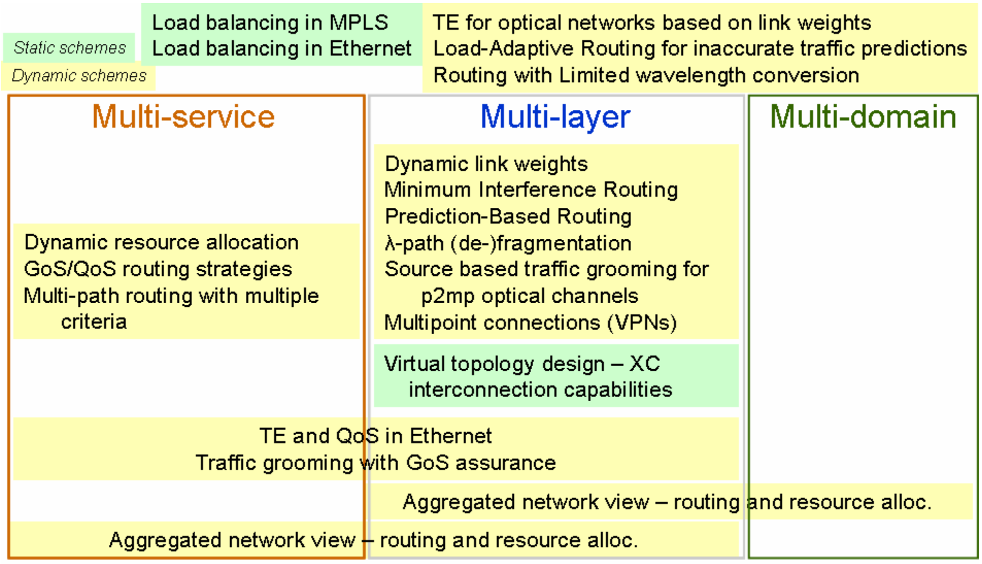
Requirements and options for a traffic demand model for forecasting pan-European traffic have been elaborated. Based on that, a pan-European traffic forecast model has been developed for the period 2003 – 2010, taking into account the NOBEL classification of traffic and updated data sets. This model will be used in case studies and evaluations.

TE mechanisms analysis

Optimizing traffic flows across several layers, for different service classes with distinct service class attributes was in the focus of the studies done in WP2 and summarized in D27. Indeed it was the first time this wide topic (Multi-layer/ Multi-domain/ Multi-service) was covered by such large consortium, so the studies done in NOBEL I WP2 is an ongoing work to evaluate and compare the different advanced TE and resilience mechanisms in order to give recommendations when each mechanism is advantageous compared to the others. So within WP2 several MTE mechanisms have been analysed.

In any case, it was acknowledged that **multi-domain issues are of key importance for providing seamless end-to-end service guarantees**, *although those studies are difficult due to the wide range of possible options available to carriers and service providers, ranging from mere signalling at the boundary to full peer control*. Prior to solving the multi-domain issues, however, it is relevant to develop an appropriate understanding of the combined multi-layer and multi-service problem. A number of novel solutions and strategies (see a summary in Table 7 - Disciplines and activities on Traffic Engineering in NOBEL) were developed by the partners, which are classified according to single-/multi-layer, single-/multi-service, single-/multi-domain problems.

Table 7 - Disciplines and activities on Traffic Engineering in NOBEL



The proposed techniques provide solutions that optimise network dimensioning and allow for faster adaptation to changing conditions absorbing link congestions.

In D27 Part A and B are described in detail all the TE case studies and its major conclusions. Below is a brief summary of the work done within the activity:

Single layer, single-service, single-domain:

- *Load balancing Ethernet over MPLS networks (Pseudo-Wires) and Ethernet networks*. It is shown that the resource requirements for Ethernet Load Balancing (ELB) outperforms because number of physical links traversed by a packet flow with ELB is always equal or smaller than that with Pseudo-Wires (MLB).
- *TE for optical networks based on link weights*. It is a flexible path selection scheme for optical networks which promotes the allocation of light-paths in an optical network without presuming any knowledge of future requests
- *Load-Adaptive Routing*. Load-adaptive routing has proven to be more robust than other schemes if information from planning, e.g. the details of criteria used for shortest path calculation, is not available during operation under dynamic traffic.

Single layer, multi-service, single-domain:

- *Dynamic resource allocation in multi-service IP network*. This solution uses traffic measurements in predicting future resources' need
- *Multi-Qos/GoS routing strategies*. GoS routing in optical networks is focused on providing controlled blocking probability for connection requests that belong to different traffic classes. It could be used to guarantee proper treatment for different traffic classes for a broad range of network conditions
- *Multi-path routing with multiple criteria for dynamic TE*. The criteria include: hop count, transit delay, administrative cost and available bandwidth. It shows a good performance for traffic balancing across IP core network.
- *Effective bandwidth methods can adapt the channel bandwidth* to a much wider range of traffic statistics than conventional Poisson traffic models.

Single layer, Multi-service, multi-domain:

- *Multidomain routing.* Routing and resource allocation with topology aggregation based on routing information.

Multilayer, Single-service, single-domain:

- *Dynamic setting of link weights* method investigate the operation of shortest path first routing with various settings of the link weights in a two layer network architecture: packet network (IP) over a circuit network (lightpath) and provide the impacts of control at the optical transport layer on the light-path characteristics such as length, loops. The min-phys-hop algorithm provides the best results for light-path routing and data traffic bandwidth requirements.
- *Minimum Interference Routing (MIR):* in a multi-layer peer architecture, the improvements of MIR based algorithm were provided with two versions of the class-based MIR algorithm (MIRO). A comparison of MIRO algorithms performance with MIR and Least Criticality Path First (LCPF) with proportional cost assignment strategy was reported showing that it is an effective light-path allocation solution.
- *Prediction-Based Routing in Multi-layer TE*. An existing MTE strategy was extended to cope with large demands requiring the setup of multiple parallel optical connections between IP routers and in addition, the Prediction-based Routing (PBR) was applied as a Routing and Wavelength Assignment (RWA) mechanism in the optical layer. PBR performs RWA optical based on minimal information exchange, instead 'learning' the network and predicting suitable paths. Optical connection request pattern (e.g. from a traffic engineering process in a client layer) has an influence on blocking rate performance of PBR. The PBR can handle their RWA without a spike in information flooding, so it is very suited for supporting MTE.
- *λ-path (de-)fragmentation:* by allowing both the data and the optical transport networks to be dynamic with end-to-end signaling often leads to long light-paths that can increase the total network load with a lot of spare resources (low global resource usage). In case of low data traffic bandwidth requests longer lightpaths with little grooming are preferable configuration, while for high network load (i.e. high rate of data traffic bandwidth requests) short lightpaths with plenty of grooming interface capabilities are preferred.
- *Virtual topology design – XC interconnection capabilities*: reports the impacts of the node interface costs in function of the configuration of cross-connect forwarding adjacencies i.e. Virtual Topology design. It is shown that aggregation and multi-hopping in a greater number of upper layer network elements has a serious impact on the interconnection interface resource needs. The 10GEth transmission capabilities between the data and transport layers can be shared between traffic coming from source nodes or going to different destinations. It enables to use efficiently transport resources leading to a great reduction of transmission interfaces need, around 35%.
- Source based traffic grooming for p2mp optical channels to overcome the mismatching between optical and client granularities. Particular p2mp simulations of traffic grooming have also shown interesting result for MLTE approaching
- Multipoint connections (VPNs). Likewise a TE study for L1 VPN has been accomplished.

Multilayer, Multi-service, single-domain:

- *TE and QoS in Ethernet*: in metro networks; Diffserv-like model insufficient to achieve desired QoS service levels.
- Ability to implement traffic grooming with GoS assurance.

Multilayer, Single-service, multi-domain:

- Multidomain routing based on topology aggregation.

3.2.3 Resilience guidelines

One of the most critical requirements of core and metro transport networks for operators is network resilience, i.e. the ability to protect client traffic against failures of links and nodes. Many different protection and restoration schemes exist in order to provide resiliency in case of failure on the primary/working path. In fact, as transport networks become more intelligent and flexible, new resilience mechanisms are available for switching technologies already well established (like SDH/SONET).

Multi-layer and multi-domain resilience

In addition to the generic QoR issues, several multi-layer and multi-domain resilience approaches were analysed in D17 and D27:

- **Multi-layer resilience**: Several multi-layer recovery methods have been compared: single-layer recovery in multi-layer networks, static multi-layer recovery approaches and dynamic multi-layer recovery using the ASON characteristics. These analyses comprise all aspects and methods for protection and restoration combining, harmonizing and coordinating resilience mechanisms at different layers, and including novel resilience methods and algorithms for two-level dynamic routing with optimal grooming. The key aspect of multi-layer investigations is the interworking and coordination of the independently developed methods at the different layers within the network.
- **Multi-domain Resilience**: Study and development of recovery techniques in multi-domain networks and their impact on the network cost and availability. Important topics for multi-domain resilience are the aggregation of network information, the routing information calculation, hierarchical and flat structures of network domains and providers, and multilayer resilience in a multidomain network.

These resilience mechanisms have been assessed according to their CAPEX requirements and the connection service availability in function of the user application needs. The main results are highlighted in the following:

- **Restoration and shared protection require lower resources than dedicated protection**. Dedicated protection needs more than 100% backup resources. However, shared protection can reduce this amount of backup capacity by about 30%. In case of path restoration a pool of spare resources has to be provided, which can be slightly different than for shared protection.
- **Restoration at level 1 is more CAPEX efficient than at level 3.** Restoration mechanisms based on end-to-end TDM connection (e.g. SDH, SONET, G.709) recovery are more efficient in terms of interface utilization than end-to-end Packet connection (e.g. IP, ATM, FR) recovery schemes. According to some techno-economic studies carried out in WP2 these savings can go up to 40%.
- **Multilayer scheme in IP over optical network costs approximately as single layer scheme** from the point of view of allocated channels on the optical layer. Extra cost dues to the use of a sophisticated optical network are compensated by flexibility allowed by these functionalities. Dynamicity in establishing back-up capacity through UNI, seems the key factor to achieve savings in resources and then in cost.
- **Introducing common pool together with dynamics** in establishment of transport connections in an IP over OTN network **reduces the CAPEX** and introduce many advantages. Common pool implies a significant saving in network resources dedicated to the restoration while dynamics a beneficial effect both on resilience (reduce the number of node interfaces and the number of lines) and on other aspects like the opportunity to introduce BoD services as commercial offer and reduce the times and cost of circuit provisioning too.

The main results regarding recovery schemas analysis are the following:

- **Layer 3 vs. Layer 1 restoration**. Applying distributed restoration mechanisms at each network layer in order to protect Packet Label Switched Paths and virtually concatenated SDH network connections might be of interest if the proper layer to perform the restoration mechanism is selected. Recovery coordination has to be set between the SDH/GMPLS transport network and the IP/MPLS network in order to trigger GMPLS restoration first and MPLS only when needed:
  - MPLS-TE LSP for which reserved bandwidth is higher than the basic SDH bandwidth (i.e. 155 Mbps) should be restored by the MPLS layer.
  - Soft-provisioning SDH/GMPLS recovery is slower than IP/MPLS because of the additional ½ RTT required for resource activation.
  - For SDH/GMPLS, MPLS-based recovery is used as fallback mechanism in case of GMPLS recovery failure. To coordinate the two recovery mechanisms an MPLS hold-off time of about 100 ms can be configured before which the IP/MPLS layer should not initiate any recovery attempt.
- **Protection vs. restoration**. Protection mechanisms present higher availability than dynamic restoration in single failure situations. So, for network with enough spare resources serving delay-sensitive user traffic dedicated protection should be configured.

  On the other hand, dedicated protection mechanisms to prevent multiple failure situations are very CAPEX expensive. For example, the costs of 1+1+1 mechanisms are about twice the cost of those based on restoration after a first failure. Total availability figures for networks dominated by link failures are better when restoration schemes are applied. An optimal solution is the combination of the two recovery schemes:

  1. Dedicated protection is used for single failures in the high QoS class user data traffic demands (e.g real time and streaming flows) and
  2. Restoration is triggered for multiple (two or more cases) failures and for the lower QoS class user traffic demands (e.g best effort).

  Finally, the level of availability strongly depends on the network wide distribution of the backup resources A certain level of network over-dimensioning can guarantee an appropriate network availability.

QoR concept and service differentiation
Within NOBEL, the novel resilience-oriented **QoR (Quality of Resilience)** parameter has been defined in addition to the existing Quality of Service (QoS) classes included in Service Level Agreements (SLAs). QoR concept has been introduced, as a single combined measure for the assessment of quality of recovery. Basic components of the QoR are parameters such as the availability of connection, quality of the backup path, recovery time, cost of the recovery or affected traffic.
In addition, different **QoR classes** have been proposed based on the different service requirements as explained in the Table below:

Table 8 - Definition of QoR classes

Resilience class	Recovery time τ	Bandwidth guarantee
High	τ < 100 ms	Yes
Medium high	100 ms < τ < 1s	Yes
Medium low	100 ms < τ < 1s	No
Low	τ > 1s	No

The basic idea behind a differentiated resilience approach is that not all traffic requires full recovery guarantees in cases of failure and the requirements for recovery response times will also differ. From this fact, different resilience classes can be defined based on the specific requirements of services and user groups. This has also obvious implications for dimensioning, since we do not need to dimension capacity for full recovery of all traffic in case of failure. It also has implications for TE, and may increase network complexity.

These classes definition aims to support **service level differentiation** while reducing Capex (and possibly Opex) according to the level of QoR provided by the network. A strategy has been defined after analyzing QoR requirements and comparing different resilience strategies. For these studies, an Availability Model and a Recovery Time model have been defined.
The results are showed in Figure 10:

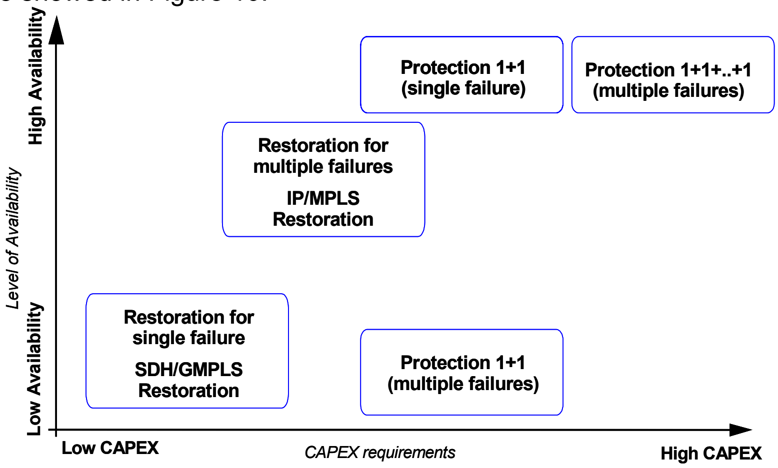


Figure 10 - Resilience guidelines

3.2.3.1 Relationship between Traffic Engineering and Resilience

The higher dynamic and agile characteristics of future networks and network architectures, together with the growing automation of control and management functionality pushed by the upcoming introduction of ASON and GMPLS, will result in breaking up the boundaries of today's separation of TE and resilience concepts and in converging of the two areas.
TE and Resilience have many commonalities concerning the methods with which traffic is directed / redirected through the network and how the resources are allocated to transport the traffic. Therefore, many network operators consider Resilience to be a critical sub-set of TE, since both mechanisms are required to provide an overall acceptable service level to the customer. In addition, performance monitoring is an integral part of both TE and Resilience.

The results of Nobel show that the two basic measurement parameters of TE and Resilience, QoS and QoR, may be correlated, especially in dynamic network operations. If QoS classes for different kinds of user traffic are used in a transport network, different types of protection and restoration mechanisms can be defined for each of these classes. For instance, in the case of failure not all services have to be resumed instantaneously (e.g. best-effort type).This raises a direct relationship on the required QoR properties of the traffic per QoS class.

Considering the multi-service aspect, differentiated resilience was matched to QoS classes used for traffic engineering, combining QoS and QoR concepts and establishing a way to the convergence of TE and resilience.

Obviously, there is a straightforward correspondence between Table 2Table 6 and Table 8 as represented by Figure 11 that also maps applications requirements.

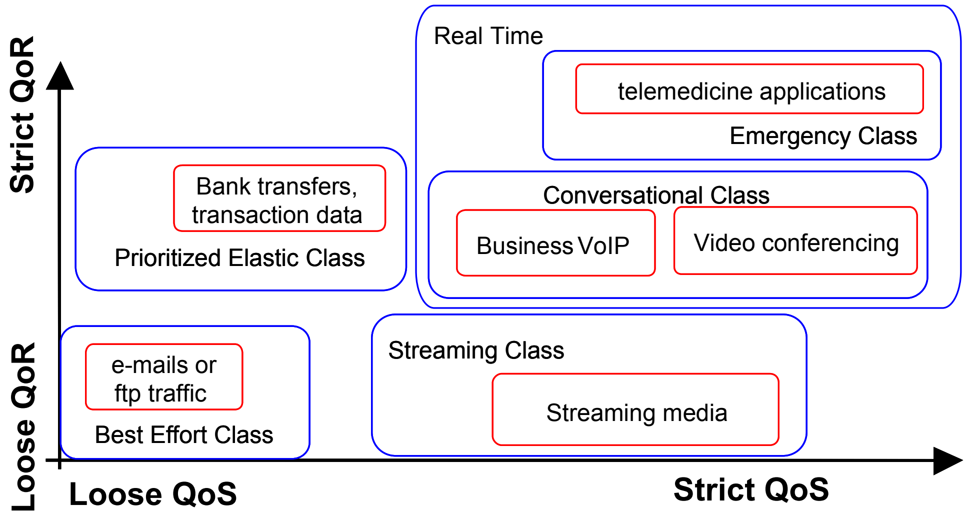


Figure 11 - The QoS and QoR requirements of various applications

So, there exists a defined relationship between resilience and traffic engineering functions. For example, in case of restoring a path dynamically due to a failure in the network where no 1:1 protection is used, or for pro-active redirection of traffic in case of upcoming overload conditions, TE mechanisms are required for rerouting the traffic, e.g. load balancing, QoS routing, multi-criteria routing etc.
A possible standardization of QoR could be obtained as shown in Table 9:

Table 9 - Relationship between QoS and QoR classes

	Real Time		Streaming	Interactive data	Best Effort
QoS class *Resilience class*	Emergency	Conversational			
High	x	x			
Medium high		x	x		
Medium low			x	x	
Low				x	x

In conclusion, we can state that due to the upcoming dynamic distributed network control plane and management plane, and due to the future migration to multi-layer, multi-service and multi-domain TE and resilience strategies, the mechanisms for TE and resilience will merge in future broadband networks. The combination of both concepts lead to high performing, reliable and always available network.

3.2.4 Techno-socioeconomic analyses and potential opportunities for new business models

Socio & Techno-economic analyses

One main goal of WP2 has been identification of new social and economic opportunities generated by the breakthrough of NOBEL concepts as well as relevant aspects related to the evolution of the Information Society in Europe which can impact on the implementation of the NOBEL networks and services vision.

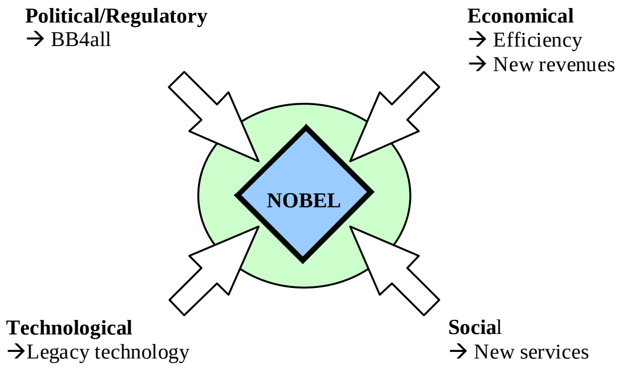


Figure 12 - Information Society impact on NOBEL vision

Core and metro networks and services evolution will be influenced by several social, technical and economic conditions:

- **Economic conditions**. NOBEL concepts deployment could be hasten by the rise of ICT market. Furthermore, there are expectations of increasing and generating new revenues for ICTs companies, mostly due to new services. These revenues and the need of reducing OPEX may favor the deployment of advanced and efficient metro and core networks.
- **Technical conditions**. The increase in broadband access penetration in the residential segment and SMEs, will impact directly on NOBEL deployment. Despite the fact that NOBEL concept of "direct customers" are large enterprises and operators, a great penetration in residential and SME segment will favor the increase of unpredictable traffic in core and metro networks as well as the appearance of emerging companies offering more services and applications to these customers. To provide these new services, companies will need advanced core and metro networks that will assure them QoS requirements. In addition, the expected increase of mobile access penetration (3G, Wi-Fi, etc) and the widespread coverage of broadband access networks will also favor the increase of users mobility as well as the introduction of network services in any environment. Therefore, flexible core and metro networks, which can manage high amounts of unpredictable traffic and provide QoS anytime anywhere will be needed.
- **Social conditions**. Residential segment can influence greatly in the core network. For instance, P2P (mainly in households) is changing the asymmetry of data flow in the core network. Enterprises will be direct customers for NOBEL services, requiring fast provisioning of flexible services and applications such as VPNs with bandwidth on demand that current backbone networks cannot cover. Even though grid applications are not expected to have a direct impact in core networks, they are expected to be used not only for increasing computing capacity but also for distributed data storage.
- **Political conditions**. New public initiatives promoting the usage of telecommunications networks and services as well as a stable regulation of the telecommunications market will favor new investments by network operators and the deployment of NOBEL concepts.

NOBEL solutions will impact on important social and economic aspects:

- **Price of network services**. Multivendor and multiservice solutions, as proposed in NOBEL, will increase networks efficiency and scalability allowing operators to reduce the costs of providing new services and updating their networks. Consequently, this cost reduction will also impact on the price of network services and favor their use by an increasing number of customers.
- **Employment**. A widespread use of NOBEL services and applications may facilitate the creation of new jobs with more specific competences. On the other hand, jobs related to the operation, maintenance and management of network operators will change their functions due to the introduction of optical networks with a distributed control plane.
- **Labour tendencies**. NOBEL services and applications such as dynamic VPNs from everywhere and teleworking will improve the working flexibility. A widespread use of VoIP and Videoconference applications may also change labor relations, thus improving the work efficiency because will reduce expenses on offices or trips.
- **Commercial relationships**. NOBEL solutions may also change the commercial relationships because if customers are connected to the network, companies will be able to use new ways to contact with them (e-Commerce, mailing lists, etc.).
- **Geographical inequalities**. Providing cheaper telecommunication connectivity can reduce geographical inequalities. For example, a company could open a center in a small town and give a VPN connection reducing costs of an office in a large city. On the other hand, teleworking may also favor the development of rural areas.
- **Public services**. NOBEL will provide an infrastructure that could be used by Public Administration not only to connect their buildings but also to offer efficiently their services (like e-Government, e-Health, etc.).
- **Broadband development**. The main factor, which influence residential users attitude to pay for broadband, is connection speed and persistence, a well as the price and quality of contents. NOBEL solutions allow for a cheaper network management, which will influence in contents prices, and network flexibility, which will provide enough resources for quality in contents products.

Case studies

According to the results of the case studies, the proper selection and design of switching and resilience schemes may strongly impact on the CAPEX and OPEX requirements of metro and core transport networks. Cost aspects will play a dominant role to balance both the additional costs through static over-provisioning of resources and the additional costs through the complexity of dynamic, flexible, and adaptive TE and resilience mechanisms. Therefore, the concept of over-provisioning requires a detailed analysis to justify its benefit specially in a multi-service, multi-layer, multi-domain network environment envisaged in NOBEL.

A number of technical case studies has been developed (focusing on CAPEX and OPEX analyses) to define what impacts will have each case study on the BMs. These BMs have been defined through a survey to the principal realities of the Italian marketplace and a questionnaire to Nobel partners.

In order to support the case studies, a NOBEL network cost model has been defined:

- A proposal for CAPEX model has been described with partitioning of big equipment categories and cost weights, considering equipment on SDH/SONET, OCh and OMS/OTS layers. Relative cost numbers were defined for different pieces of equipment depending on their characteristic parameters.
- OPEX was also classified in several subparts. A questionnaire was set up to validate the suggested classification and estimate the importance of the identified OPEX subparts to model generic business processes for operating a transport network. Further steps included the indication of the cost driving parameters, description of the operational processes, and definition of the needed methodologies to derive OPEX formulae (and thus estimate actual OPEX costs) from those processes.

The following list summarizes the different case studies considered:

- **Feasibility of Automatically Switched Transport Network.** The use of ASON/ASTN technologies impacts both network operations and services that can be provided. ASON/ASTN technologies promise automated network operations, which are expected to significantly reduce operational expenditures.

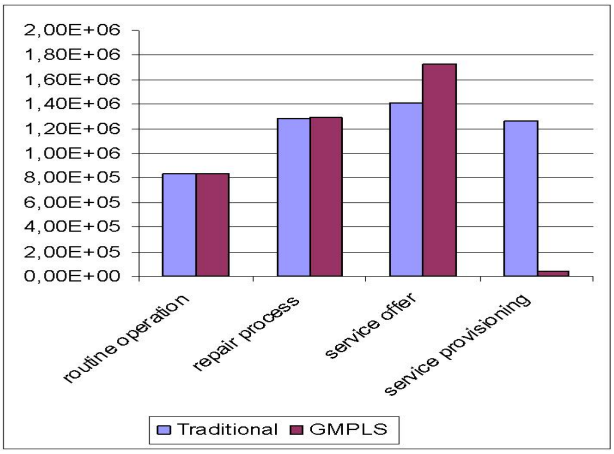


Figure 13 - Yearly OPEX (€) for all processes

When network configuration is performed in an automated, the cost for service provisioning goes down. In addition, the probability of a misconfiguration reduces, so that the amount of failures decreases leading to a lower reparation cost. Finally, introduction of automatically switched network will also influence the service that can be offered, e.g. bandwidth on demand.

Other conclusions are the following:

- The impact of ASTN functionality strongly depends on the size of the applied network scenario, as smaller the network lower the benefits of ASTN.
- Scheduling of connection requests increases the network performance especially in small introduction scenarios.
- Restriction of network reconfiguration to discrete times can help to reduce network operation complexity compared to permanent network reconfigurations.

- ***IP/WDM multilayer interaction in core networks.*** WP2 carried out a techno-economical evaluation of the traditional link-by-link traffic grooming approach versus the end-to-end grooming solution where OXCs are present in all network nodes. In addition, it has been developed a method that determines where to place the grooming nodes and how many of them. The goal is to minimise the costs, while keeping blocking at a moderate rate in a single-domain two-layer (e.g., IP/MPLS over WDM) network. The main guidelines are:
  - As traffic grows, there comes a point where the savings in IP layer expenses realised by end-to-end grooming compensate the extra expenses of introducing the needed optical cross connects.
  - This point is very sensitive to changes in the SDH line card cost. It is important to estimate network equipment costs as accurate as possible, and It is very recommendable to try to find the cheapest vendor.
  - For lower granularities, the cost advantage of the optical pass-through solution increases in terms of interfaces. Conversely, the coarser the granularity the cheaper the IP transit.

- **Optical layer pass-through in core networks.** Current optical networks are mainly opaque and rely on ODXC which perform OEO at each node port. Transponders (i. e.

OEO conversions), which have a significant impact on the whole cost of the network due to their current prices, are massively employed. For this reason **transparent or semi-transparent solutions**, which can reduce considerably the number of transponders compared to current opaque networks, seem promising for achieving significant reductions in network cost. Anyway, transparency implies additional costs in control plane and monitoring system and, on the other side, vendors claim for transponder prices cut-down in near future making the opaque solutions more competitive.

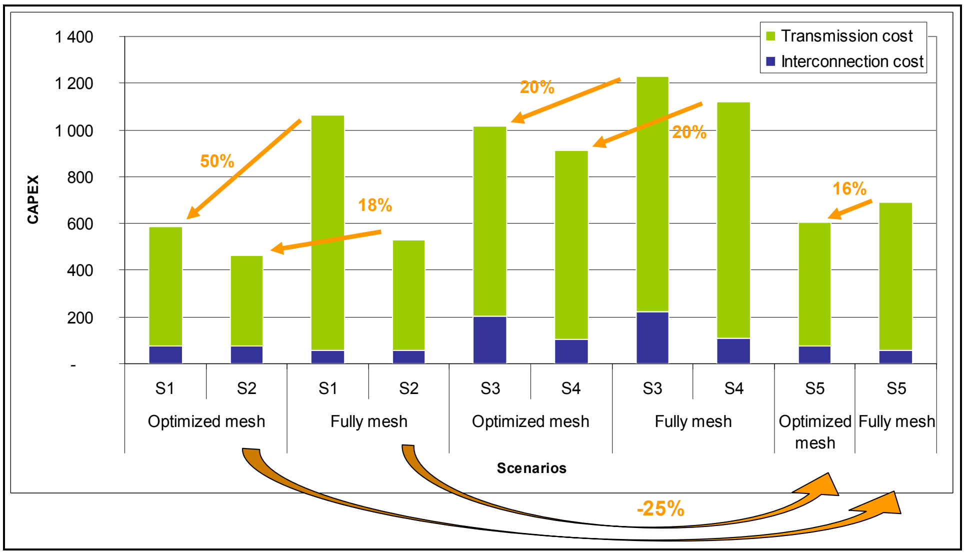


Figure 14 - CAPEX results of the defined scenarios

- **Techno-economic comparison in the feeder/metro** network segment between different network alternatives (SONET/SDH rings, Metro Ethernet rings or trees, Resilient Packet Rings, Optical Ethernet). In the short term, it is found that SDH rings upgrading is not cost-effective. However, in the medium-term, when Gb/s granularity becomes cost-effective, RPR, DBORN solutions will be competitive with the star Ethernet.
- **Wavelength conversion.** The introduction of the wavelength conversion significantly improves the network performance and results in lower network capacity requirements. The results of analysis show that the blocking probability decreases with the increase of the conversion distance. Link utilisation values grow with the increase of the conversion distance (with certain threshold).
- **Dynamic bandwidth allocation strategy.** Dynamic allocation enhances network exploitation, and could achieve the future increase of “on demand” traffic in a better way than today’s static strategy. To deploy it, it will be necessary to implement time dependent traffic matrix to better look like real traffic needs.
- **LEX CO reuse by upgrading to NGN architecture.** An upgrade of network equipment to an IP/OTN network architecture can result in significant savings in terms of space, energy, cabling systems, switching and transmission equipment.
- **Multi-layer resilience in an IP over Optical network.** Restoration at level 1 is more CAPEX efficient than at level 3 in terms of interface utilization. Multilayer scheme in IP over optical network costs approximately as single layer scheme, from the point of view of allocated channels on the optical layer. Cost dues to the use of a dynamic optical network are compensated by the gained flexibility. Introducing common pool together with dynamics in establishment of transport connections in an IP over OTN network reduces the CAPEX. **Layer 1 recovery** might be usually preferred in multilayer networks, and trigger MPLS only when needed.
- **Impact on network cost and service offering of introduction of new classes of resilience.** Dedicated protection should be used for single failures in the high QoS class

user data traffic demands (e.g real time and streaming flows) and restoration should be triggered for multiple (two or more cases) failures and for the lower QoS class user traffic demands (e.g best effort).

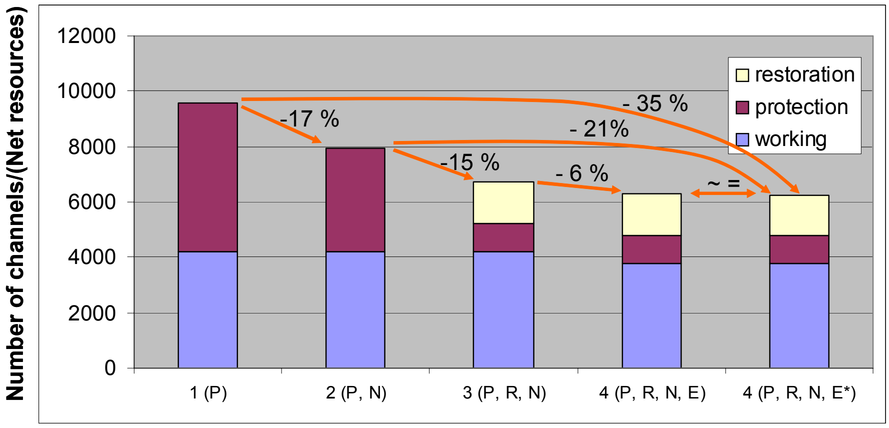


Figure 15 - Results of network dimensioning for the different CoR scenarios

New market roles due to Nobel solution

From the results on the socio-economic analysis, another main goal of WP is the description of a new vision for innovative business models and charging models for broadband network services. This general vision is based on a new reference model and the evolution to an unbundled value chain in telecommunication services. The business model of two kinds of operators was analyzed: the established incumbent network operators and the emerging virtual operators. The intention was to highlight how Nobel technologies will impact and change such BMs and which new business opportunities could arise. In order to better illustrate the position in the value chain, a common scheme has been developed, grouping together all the principal activities which characterize the provisioning of broadband services.

The main results achieved show the opportunity for the emergence of new roles such as the **Transport Network Virtual Operators (TNVOs)**, feasible thanks to the enhanced control plane technologies and the standardised interfaces. Such new technologies enable virtual operators, that do not own a network infrastructure, to indirectly control the network of the Incumbent Operators through the standard interfaces, just operating the signalling. As a consequence, other operators like big Vendors or big Media Companies could be interested in controlling the network for the provisioning of their services to customers, “climbing” the value chain. In this context, a multi-operator solution creates an open market in which operators will be interconnected. Leasing network infrastructures is the complementary business for traditional carriers.

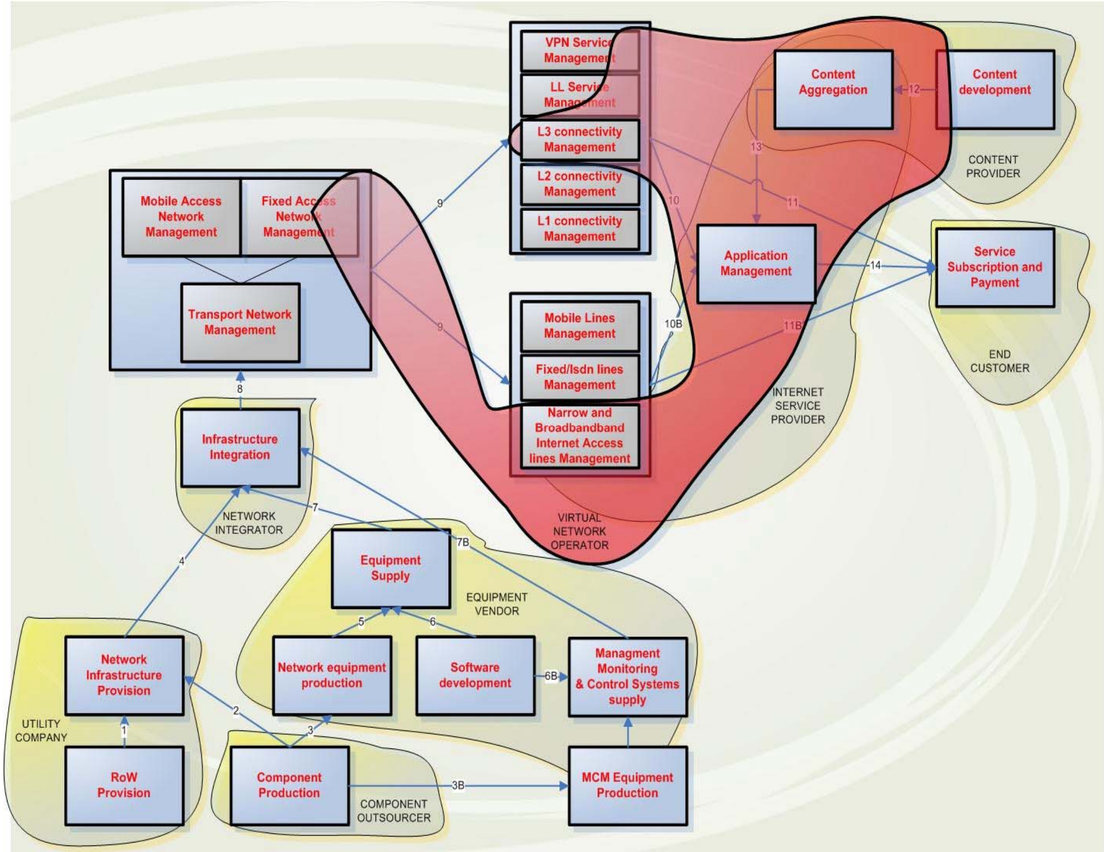


Figure 16 - The value chain scheme

Another important result is represented by the new services on demand enabled by Nobel technologies, such as BoD, L1 VPNs, Ethernet dynamic link provision and L2 VPN for Mobile Communication Companies, SAN, GRID, etc. These services will give a competitive advantage to the first adopters in the market and cannibalise the market share and, consequently, the revenues generated from old static services.

New opportunities also arise regarding improvements in network exploitation, comprising more revenues for dynamic connectivity provision, adapted SLA for different QoS, more efficient resilience or technologies convergence.

Finally, WP2 has studied the impacts from a regulatory and business perspective the Fixed-Mobile Convergence. Nowadays, pure mobile operators tend to motivate the process of substitution of fixed traffic to mobile traffic, while pure fixed operators try to “recapture” voice traffic. However, integrated operators are better positioned to take advantage in this scenario by means of a complete communication services offer, allowing them to use the most efficient technology for each case in a transparent way to the user. There are a lot of signs that show the fixed-mobile convergence scenario as the ideal one for an integrated operator to increase revenue and reduce costs.

3.3 WP3 Advanced Packet/Burst Switching

The overall goals of WP3 were:

- To define requirements and scenarios of future transport networks carrying mainly burst/packet type traffic leading to hybrid network and node structures supporting both circuit and burst/packet signals.
- To define network and node architectures and develop optical burst/packet switching techniques for high throughput core networks and flexible, effective metro networks adopting data centric protocols
- To sketch evolutionary paths from wavelength switched to burst/packet switched optical networks
- To exploit transparent optical wavelength/burst/packet switching to reduce O/E/O conversions and other electronic hardware for reduced overall cost and find an optimal balance between optical and electronic technologies in terms of performance and cost
- To define requirements and specifications for control plane extensions specific to burst/packet techniques to support QoS in the optical burst/packet layer (emphasis on reservation, allocation, signalling, signal regeneration etc.) and study novel network management functions adapted for optical burst/packet networks to provide configuration and fault management functions (in particular performance monitoring, protection and restoration).
- Elaborate possible extensions and/or evolution of standards

WP3 delivered:

- D4 "Requirements for burst/packet networks in core and metro supporting high quality broadband services over IP "; D4 reported preliminary results:
    - on the motivation for the introduction of burst/packet techniques in transport networks,
    - on the requirements for future “IP aware” optical transport networks and the related traffic profile evolution,
    - on the evolution towards burst and packet based networks with possible optical and opto-electronic solutions,
    - on control and management of burst/packet networks (preliminary results).
- D16 "Preliminary definition of burst/packet network and node architeectures and solutions"; D16 reported preliminary results:
    - on general requirements and characteristics for burst/packet switching networks and nodes,
    - on evolution scenarios,
    - on general architectures and solutions of hybrid circuit/burst/packet networks and nodes,
    - on general architectures and solutions of burst networks and nodes,
    - on general architectures and solutions of packet networks and nodes
- D23 “Definition of hybrid opto-electronic burst/packet switching node structures and related management functions”; D23 reported results:
    - on structures for hybrid opto-electronic burst/packet switching networks and nodes
    - on migration scenarios from IP networks towards OBS/OPS
    - on data plane aspects of OBS/OPS networks and nodes – dimensioning and performance, including specific aspects of TCP-over-OBS transport
    - on control and management aspects of OBS/OPS networks – adapting GMPLS to OBS networks and routing issues in OBS and OPS networks
- D32 “Preliminary report on feasibility studies on opto-electronic burst/packet switching nodes”; D32 reported preliminary results:
    - on classifications and definitions of hybrid optical network architectures

- o on requirements and feasibility of opto-electronic burst/packet switching nodes
- o on feasibility analysis of electronic burst/packet switching networks
- o on performance analysis for TCP-over-OBS transport
- o on techno-economic feasibility

In the following, we will give a summary of results on various architecture, performance, control and feasibility aspects of burst/packet networks.

3.3.1 Motivation for burst and packet switching in transport networks

Transport network evolution is and will be driven by the continuously increasing traffic demand due to the introduction of broadband Internet access and new end-user and business applications as well as the continuing paradigm shift from voice to data services. Also, operators target improved cost efficiency in the face of declining market prices and technological enablers to create new market opportunities by means of differentiation against competitors. Scalability, flexibility in service provisioning, the capability to effectively transport highly dynamic traffic, support for end-to-end quality of service and quality of protection in a multi-service context can be derived as key requirements respectively.

For voice-centric networks, the connection-oriented circuit-switching technique is a very powerful and efficient technology as the traffic characteristics of a superposition of several different CBR connections. In the 'packet' world, the traffic is typically characterized as being very bursty and packets are often variable in length. Additionally, while a typical voice call is quite predictable in duration, durations of data transmission sessions in the Internet can vary by orders of magnitude and often have to be characterized by heavy-tailed distributions. A 'packet' world example is today's global Internet.

The main driver to adopt data-centric transport network technologies is the fact that the Internet is based on this packet-based connectionless technology, namely IP. Secondly, 80% of IP generated traffic is sourced from Ethernet attached networks (LANs). Additionally, carriers have shown a significant interest in adapting the cheap enterprise Ethernet technology to integrate it into their transport infrastructure. To accelerate the integration of data in the transport network and data as transport technology, standards bodies have been created to promote this effort. It should be noted that the current proliferation of data as transport technology still lacks some important features before it can fully qualify as a carrier-class technology.

Next generation networks are envisioned to have an intelligent control plane suitable and capable of controlling the network with minimal human interaction offering automatic service provisioning, performance management, fault detection, and security. While circuit switched communication yields a defined QoS, packet switching has no inherent concept of QoS. But also in the packet-world scenario, it is clear that certain user applications or users have more importance and/or higher urgency than others, leading to the introduction of different QoS schemes.

New burst and packet switching approaches and new layer 2 protocols can become a cost efficient complement to circuit switched transport solutions and Tbps IP core routers. Especially as flexibility is no longer only needed in access and metro networks which are close to the users and are controlled by their behavior and dynamics but also in core networks. Due to the effects of broadband access and the current convergence of bit rates in metro and backbone networks (both Ethernet and SDH transport interfaces are applied for 10 Gbit/s) high burstiness can reach the core and has to be carried with higher utilization and less operational effort and costs compared to pure WDM or WDM multilayer architectures.

In this context, optical technologies can obtain an essential role in creating advantageous solutions.

3.3.1.1 Terminology of burst and packet switching

During the past years, definition of burst and packet switching networks in the optical domain and especially their difference has become less clear due to the large number of new proposals claiming either name.
Burst and packet switching (BS and PS) architectures as investigated in NOBEL's WP3 both provide sub-wavelength granularity by employing asynchronous time division multiplexing. In case switching is performed all-optically and data stays in the optical domain until the destination edge node the concepts are referred to as *optical* burst switching (OBS) and *optical* packet switching (OPS).
Following characteristics either individually or in combination can be regarded defining for burst switching in contrast to packet switching:

(i) Client layer data is aggregated and assembled into larger variable length optical bursts in edge nodes.

(ii) Control information is signaled out-of-band, processed electronically in all core nodes and used to set up the switch matrix before the data bursts arrive.

3.3.1.2 General requirements and characteristics for burst/packet switching networks and nodes

The rapid evolution of the user bandwidth observed (1 Gbit/s offered now in Japan) and the source of revenues being in the access part (FTTH, and new xPON technologies are some examples) will rapidly create a need for new technologies in the metro and in the backbone area.
An intense debate has been ongoing about which is the optical network model to adopt, aiming at identifying the degree of the optical transparency to be achieved, and the proper flexibility of the optical interconnections. In perspective of network optimization, the first expected step is the implementation of Wavelength Switching (WS) networks where some resource flexibility is achieved through the dynamic establishment of circuits. Nonetheless, to achieve full network utilization, the implementation of packet switching techniques directly in the transport network will bring more statistical sharing of the physical resources to reduce the connection costs and cope with the gap between transmission speed and switching capacity. In this direction, two different approaches are being deeply studied by the research community, namely Optical Burst Switching (OBS) and Optical Packet Switching (OPS).
WS presents a clear advantage from the implementation point of view since the majority of the necessary components and subsystems are commercially available. In contrast, they are only partially available for OBS and there is a clear need of a technological breakthrough to implement OPS. The advantage of having better granularity in OBS and OPS is counterbalanced by the high blocking probability (in OBS) and packet losses (in OPS). Therefore, there is a strong requirement for contention resolution mechanisms and solutions (wavelength conversion, FDL buffers, and deflection routing, opto-electronic solutions) that can be applied in hardware or as an accurately operating control algorithm. Moreover, routing algorithms should be enhanced to incorporate Traffic Engineering (TE) functions to alleviate the contention resolution issue by appropriate traffic load distribution over the network.
The next future is for WS networks, but there is a big investigation effort for development of both OBS and OPS networks, which seem to be further successors in the optical networks world. We introduce a brief distinction between considered switching paradigms to deal with the specific characteristics in selected domains such as physical aspects, control plane and route management.
Wavelength Switching in optical networks is typically defined for circuit-switched connection model, where at intermediate nodes the data is transmitted between network end-points on pre-established paths or circuits. In the case of optical circuit switching networks technology, the switching nodes are referred to as Optical Cross-Connects (OXCs) and are responsible for all-optical switching of data carried on a specific wavelength λ from input port to a specific λ on destination output port. The duration of a connection can last from several minutes to several hours, as the connection set-up and deletion can take up to several milliseconds.

On the other hand, Optical Packet Switching and Optical Burst Switching are both based on statistical multiplexing of optical packets in intermediate nodes with a full link-resources sharing capability between different connections. OPS nodes switch optical packets according to the information carried in their headers, which are O/E converted while the payload part is switched and buffered in all-optical way.

In the OBS networks, in contrast to OPS, the client layer data packets are aggregated and assembled at the edge nodes of the network into larger variable length data units, called bursts. Moreover, the control channel is signalled out-of-band in such a way that the control information is transmitted prior to the data burst is transmitted to allow the intermediate nodes sufficient time to reconfigure the switching matrix. Statistical multiplexing at the optical bursts level introduces OPS-like flexibility. Additionally, OBS provides capability to setup aside some wavelengths to be used as in WS scenario (by two-way resources reservation scheme). Hence, the same optical infrastructure can simultaneously support static (by wavelength switching) as well as dynamic (by burst switching) traffic. In order to make a distinction further discussion concerning the OBS model assumes the one-way reservation scheme since WS model reflects well the OBS network working with the two-way reservation scenario.

Advantages and drawbacks of WS, OBS and OPS are summarised in Table 10.

Table 10 - Advantages, drawbacks and foreseen for future implementations

	WS	OBS	OPS
Advantages	Natural QoS; reliability Components & subsystems commercially available	High flexibility (traffic dynamics) Efficient network utilization Possible using of lower speed switching elements	Very high flexibility (traffic dynamics) Very efficient network utilization Reduced node size
Drawbacks	Low flexibility and network utilization Very high wavelength consumption, large node sizes	Components & subsystems partly available Control complexity (QoS, routing etc.) Effort for traffic aggregation Resilience more complex	Only preliminary components & subsystems available High control complexity (processing effort. QoS, routing etc.) Resilience more complex Requires more effort for packet reordering
Foreseen for the future	A short term deployment	OBS is an interesting solution for efficient optical network A mid term deployment	Waiting for technological breakthrough, especially for compact, low-cost optical components A longer term deployment

3.3.1.3 Network evolution scenarios

The ASON/GMPLS network is the currently proposed solution to integrate the TDM based optical layer transport protocols and the dominating packet based data traffic. Its switching capabilities comprise optical fibres, wavelength bundles, wavelengths and TDM containers which are usually circuit switched in a quasi-static configuration. On the other hand, there are Ethernet frames and IP packets switching capabilities which are usually handled in a very flexible, connection-less manner.

There are a number of factors in this long term scenario which need to be further studied and improved when considering future networks with dramatically increased traffic and end-to-end QoS demands to be offered on such integrated networks, in particular for packet based network services:

- The circuit switched optical layer is well scalable for high bandwidth demands, is very reliable and offers superior QoS by providing end-to-end paths. However, there will be bottlenecks with respect to the adaptation to dynamically varying traffic demands and thus potential sub-optimal usage of network resources.
- Networks exploiting mainly big IP routers and very limited switching capabilities in the lower layers (just point-to-point WDM links) have some problems because the IP routing protocols are quite complex, may suffer from faults, and offer only low reliability (best effort transport!) and QoS level differentiation. In addition, due to the high processing effort (per frame or packet), the port costs of IP routers are quite high and technology constraints are limiting the scalability for high bandwidth.
- The granularity gap between the bandwidth available per wavelength and the IP packet data rate per circuit is still very high and will hamper the network optimization.

These main factors and a number of supporting arguments lead to the conclusion that a new layer 2 network technology based on burst/packet switching is desirable. This new layer 2 will offer the following functionalities:

- The proper size of bursts will close the granularity gap by offering much finer granularity than wavelength channels or TDM connections but much less processing effort than with short IP or Ethernet packets.
- Burst/packet switching will offer the required dynamic behaviour and flexibility already in layer 2 at much less processing effort and costs and thus can also provide the scalability to higher throughput per node.
- Reliability, monitoring and QoS functionalities will be provided in layer 2 thus offering a solid carrier class network service supporting higher layer network services at low cost.
- Hybrid circuit and burst/packet switching capabilities will be provided at layer 2 and can be used on demand for network optimization. Thus, inexpensive circuit switched pipes can be used for fixed high traffic demands between dedicated points in the network while flexible burst/packet communications can be provided for other parts of the network with less traffic or high dynamics.
- The new L2 network technology with its hybrid circuit/burst/packet switching capabilities will be fully integrated into the GMPLS control plane philosophy (full vertical integration).

The burst/packet switching capabilities of the new layer 2 network technology could be introduced in several ways resulting in different reference network configurations. Some potential technologies for the introduction of this new layer 2 concepts referring to the solutions studied in NOBEL are shown in Figure 17.

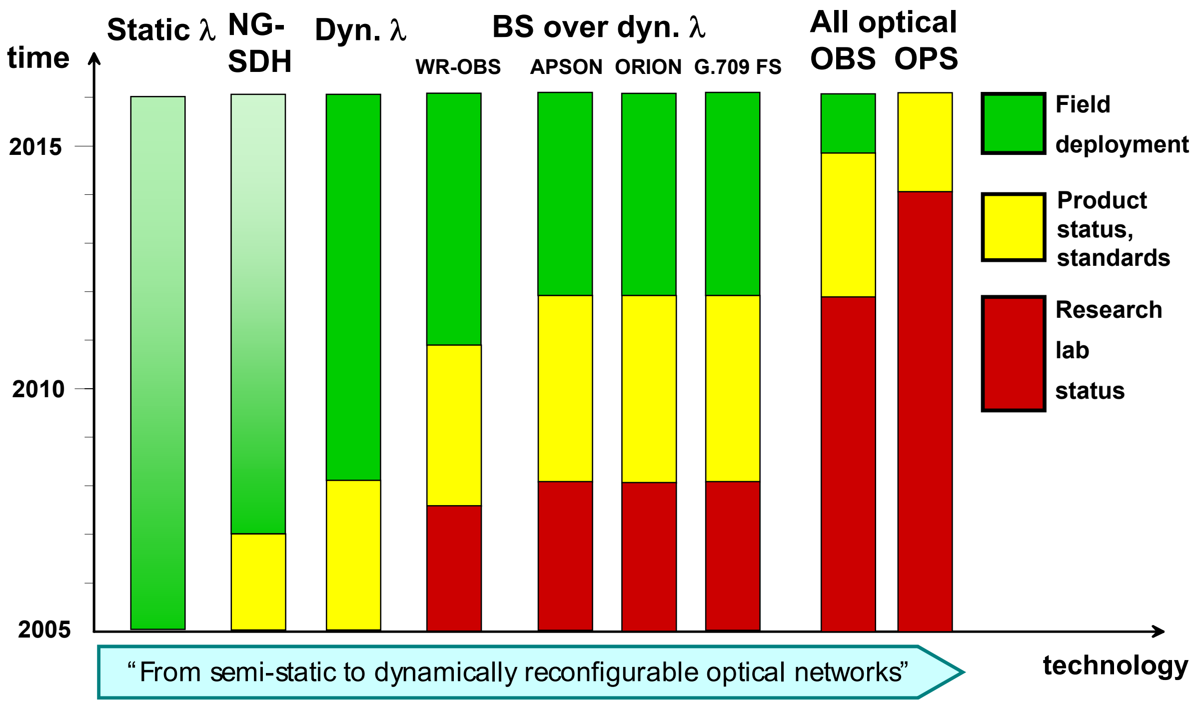


Figure 17 - Evolution steps in optical networks

3.3.1.4 General architectures and solutions – Hybrid circuit/burst/packet networks and nodes

Overspill Routing in Optical Networks (ORION)

The ORION concept aims at having as much as possible traffic being wavelength (i.e. circuit) switched for scalability reasons, while a minority is sent hop-by-hop as packet traffic to improve the capacity efficiency. When an end-to-end circuit is fully used, packets that would have been dropped are marked with an overspill-marker and sent to the next hop. Depending on the technology used for this overspill-marker, one may consider transmitting these overspill packets on wavelength channels belonging to other end-to-end connections: the next node detecting this overspill-marker is then able to remove overspill-packets from the wavelength channel and handed over to the (electronic) packet switch. One possibility is to implement the overspill-marker as an FSK-signal.

The simulation work was validated with help of an emulator platform, which is fully compatible with GMPLS. This electronic router platform mimics the behaviour of an optical ORION node on an electronic PC in every functional aspect to allow for more accurate results and validation of earlier work, as well as quality measurements of live (multimedia) traffic and proof of compatibility with GMPLS and RSVP-TE.

The G.709 Frame Switching concept

The concept of G.709 frame switching is a hybrid solution designed to combine circuit and burst switching capabilities in a novel Layer 2 transport. G.709 is an emerging standard for optical transport networks and like SDH, it is a synchronous, circuit switched approach. With the new concept of frame switching, the frames of the transport data stream (e.g. the Optical Data Units ODU) are provided with an additional functionality, i.e. the possibility to switch them as separate entities. The handling of the long (16320 bytes), fixed sized frames is significantly easier than the routing of – for example – the short and variable sized packets of the internet protocol or individual Ethernet frames. Figure 18 explains the principle.

The fixed sized frames are generated by a frame aggregation unit, which aggregates the user traffic and transforms the data signals at the client interfaces of any arbitrary format into the adapted G.709 frame format.

The frames can either be switched in a connectionless or connection oriented mode and thus an easy adaptation to traffic and quality requirements is possible. The transmission links between the frame switching nodes carry continuous G.709 OTUx connections, thus being compliant with the existing G.709 standard in the best possible way and avoiding any physical layer complications caused by burst mode transmission. (Please note that a certain evolution of the G.709 standard will be required to enable a full burst mode operation based on individual frames).

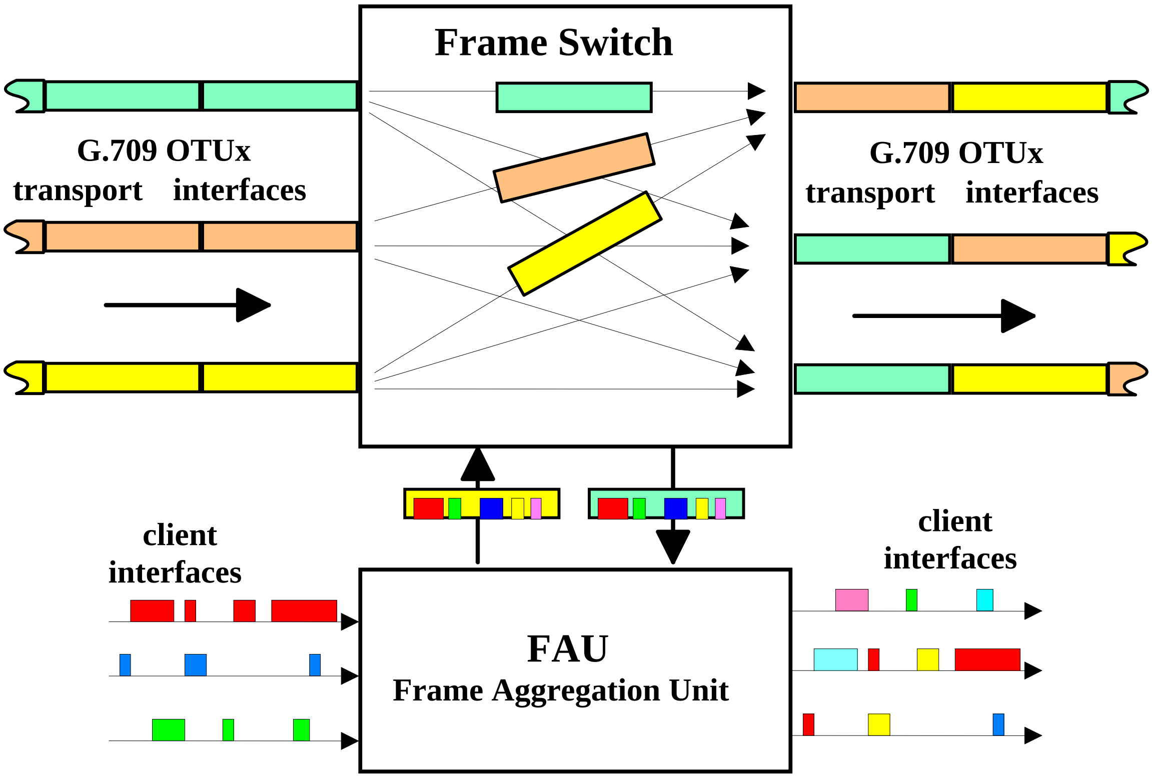


Figure 18 - Concept of G.709 frame aggregation and switching

The APSON concept

A new hybrid burst/circuit concept "Adaptive Path Switching Optical Network" (APSON) offers a compendium of the main advantages of OBS networks and Automatically Switched Optical Networks (ASON). In particular, APSON results in a low blocking probability and delay, as well as a very efficient use of bandwidth resources. Furthermore APSON networks are backward compatible with ASON and with static Optical Networks. These and other advantages make APSON a very appealing candidate to be placed close to ASON on a migration strategy towards the next generation of optical networks.
The main difference between APSON and pure OBS networks is that after having sent a burst the end-to-end path remains open letting the source edge node send more (IP) packets "on-the-fly" without additional signalling (see Figure 19). This mode of operation persists until another edge node wishes to send a new burst (e.g. burst 2 in the figure).

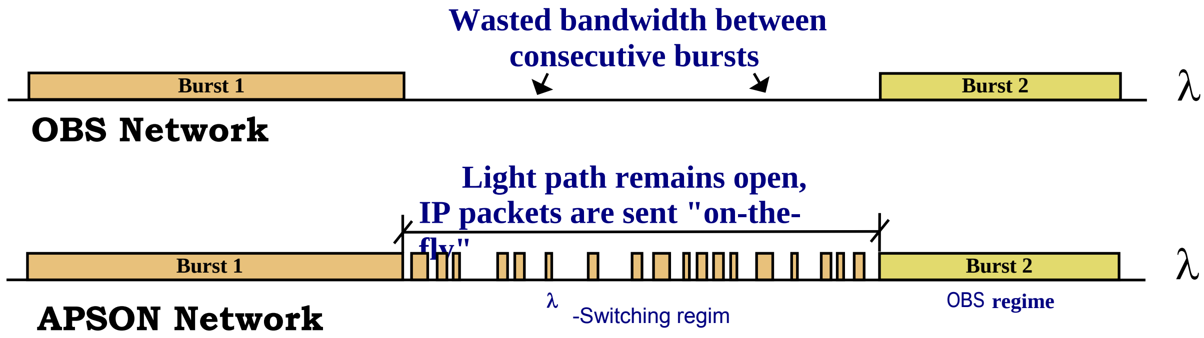


Figure 19 - Basic data plane of APSON

Some IP packets are sent in normal optical bursts, while other IP packets are sent "on-the-fly" (zero delay and delay jitter) between consecutive bursts through the already established optical path.

For low loads an APSON network behaves **like a λ-switching network** which is precisely the situation where λ-switching networks perform best providing low delay, low delay jitter and low signalling overhead. The reason is because for low loads most of the IP packets will be transferred in the λ-switching regime, and very few of them in bursts.
For high loads, APSON behaves **like an OBS network** which is precisely the area where OBS networks perform best providing high multiplexing gain, high flexibility, and a low blocking probability. The reason is because for high loads most of the IP packets will be transferred in bursts, since the λ-switching regime between bursts will last less time.
The APSON concept is versatile and can be implemented in a wide range of possible network scenarios like centralized/distributed, One-way/two-way-reservation, Uni- vs. bidirectional edge-to-edge path, No use of λ–conversion (cost savings, early deployment). The resulting blocking probability must be studied.
APSON should define generic signaling messages that can be represented as GMPLS messages to be compliant with GMPLS standards.

- QoS in APSON

The basic idea uses two new parameters, the *reservation time* and the *burst transmission time*. Both can be easily set in software at the edge nodes.

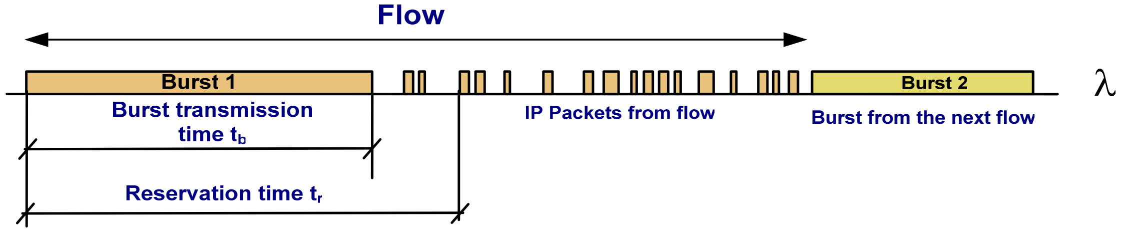


Figure 20 - Some definitions in APSON

During the reservation time, blocking-free guarantees are provided. This parameter has therefore a high impact on the price that the customer pays for a given service level agreement. For the IP packets of the flow outside the reservation time (see Figure 20) contention might take place. The burst transmission time (or the burst size) has a high impact on the delay, the delay jitter and the multiplexing gain. If the burst size equals the size of an IP packet, we achieve a minimum delay and delay jitter, but the amount of bandwidth that the customer has to reserve might be quite high. If the customer wishes to save some money at the cost of increasing the delay and delay jitter, the burst size can be increased.
By manipulating these two parameters we can adapt the network to the needs of each individual customer, finding a perfect-fit solution in each situation. In fact, the discrete concept of "service class" itself disappears.

Taskforce: TCP over Optical Burst Switching Networks
Introduction
Some OBS features have an impact on the TCP (Transmission Control Protocol) performance, mainly the **burst assembly process** in the ingress router and the **contention** that occurs in the intermediate nodes when several bursts are competing for the same output port, which usually leads to a **loss of a burst** due to the lack of practical optical buffers.
TCP is the dominating transport protocol in the internet today. More than 90 % of the IP traffic today uses TCP on the transport layer. TCP is typically used by applications that require guaranteed delivery. TCP establishes a full duplex virtual connection between two endpoints. It was introduced in the eighties of the last century. Since then a lot of different TCP versions were developed. Beside the delivery guarantee it implements flow control and congestion avoidance mechanisms introducing a complexity which impacts the network performance. The interactions between TCP and OBS are shown in Figure 21.
Because of the relevance of TCP, a Taskforce was established in WP3 to study the behaviour of TCP in OBS networks, to harmonize the simulation environments of the different partners and to find commonly agreed parameter sets for the simulations. This effort made the different approaches and results of the partners comparable and avoided duplication of work.

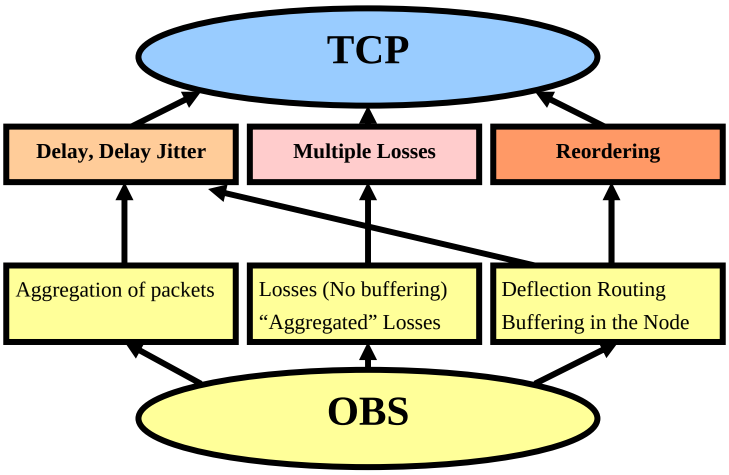


Figure 21 - Interaction between TCP and OBS

Simulation Scenarios
Current work in the literature is based on a model with a single client and server. NOBEL has performed the study using more realistic scenarios, considering multiple flows. One of them considers up to 900 TCP clients and another one models a novel scenario, which consists of a single TCP client and server and a fractal traffic generator which simulates traffic from a LAN (Figure 22).

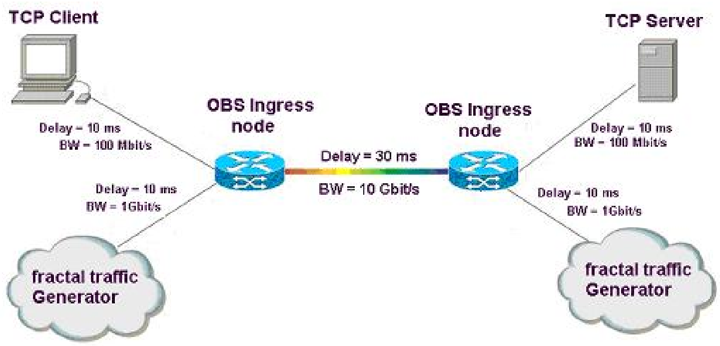


Figure 22 - New NOBEL scenario with multiple data flows

The used client-server models were slightly different amongst the task force partners. The following topologies are possible:

- 1:1 (Each client has an individual server as counterpart for connections.)
- N:1 (Many clients are connecting to one server.)
- N:M (Many clients are connecting to many servers.)

File-transfers and web browsing have been used as applications for the simulations. For the FTP application, the download response time and the TCP goodput were the key parameter to be measured; the web browsing application studied the TCP throughput. We compared results of lossless transmission in OBS networks with the results of transmissions with a pre-defined burst loss probability (1% up to 5%).

As a main result, we can confirm that OBS is a valid technology to transmit TCP traffic. However, it is important to adapt the TCP parameters in an optimal way, and/or to adjust the OBS transmission procedure slightly to optimize the transmission of TCP flows.

Conclusions

When we study TCP considering multiple traffic sources in a OBS network, we can see that **a burst loss is not always as adverse as** it was thought in previous studies, because most of bursts have only a few segments. **The classical model used in the literature overestimates the number of TCP segments of a single TCP flow**. This fact explains the difference between NOBEL simulations and the general opinion in the literature.

In spite of published results, it was found that realistic TCP controlled traffic is much more robust against aggregated losses than expected when running on top of an OBS network. In particular, with burst loss probabilities as high as 1% (which are actually unacceptable for optical networks) only delay increments below 20% on average were registered. The size of the downloaded files influence the delay variance (higher variance for smaller files).

Very short round trip times (RTT < 50 ms) in combination with default TCP timer values and 1% loss can increase the additional delay and reduce the goodput by more than 50% but never to the published values of goodput much smaller than 10%.

Probably the claimed extreme sensitivity of throughput (i.e. TCP goodput) to burst losses depends on old (simulated) TCP versions (no fast retransmit and recovery like in real TCP Reno) or on too few traffic sources.

3.3.1.5 Control Plane aspects

Adapting GMPLS to Optical Packet/Burst switching networks

Different attempts have been made to implement a control plane for OBS networks, trying to achieve an efficient use of the bandwidth, low latency and a high degree of transparency. All proposed strategies have a common point: routing and signaling are independent, which implies that burst routing, scheduling and protection are then really complex functions. An integrated approach based on time-space labels can be the right solution in order to match the GMPLS protocols with OBS. It takes into account not only the resources (space) but also their occupation (time) so a complex routing algorithm allows optimizing the network performance. The combination of time-space is actually intrinsic to the OBS paradigm. The main advantage of such a scenario is the possibility to time multiplexing on the optical channels, so time-space based approaches are right.

The GMPLS-UNI

The User-to-Network Interface (UNI) is defined to convey user requests for network services between client nodes and edge nodes of a corresponding server transport network. Upon such requests connections are set-up, maintained and torn down across the transport network using internal control plane (CP) communication. The UNI is designed for connection oriented packet switching (CO-PS) and therefore perfectly usable when IP/MPLS clients want to send packets over an optical server transport network (e.g. GMPLS OTN), for instance.

An enhanced UNI was developed that extends existing UNI specifications (e.g. UNI1.0 of OIF) aiming at multi-layer interoperability and scalability. A certain focus is on traffic engineered (TE) connection and service provisioning but, particularly, cross-layer resilience co-ordination and efficiency aspects were considered and implemented. Depending on these specific demands, recommendations for the respective use of an overlay, or augmented, or peer domain/region integration model for the control plane inter-working were given. A general finding was, that an enhanced overlay model with only limited, additional and controlled information exchange is completely satisfactory for clearly improved inter-layer recovery co-ordination, thus keeping administrative separation between client and server in terms of routing and other sensitive information, what often is strictly required by network operators. For inter-networking, flexibility and scalability reasons a GMPLS based control plane was used for the UNI.

Detailed GMPLS RSVP-TE compliant signalling extensions for UNI are described which mark an evolutionary step towards augmented and peer CP interaction models and serve for intelligent and optimised inter-working between the layers of an IP/MPLS-over-SONET/SDH/GMPLS network. On the other hand the overlay model basically is kept, i.e. the UNI improvements still respect (routing) domain separation of both layers. Moreover, it is designed such that the server network has full control over the additional signalling information which may be exchanged for the widened UNI functionality. Also, such an overlay based model can be most easily implemented by carriers with an installed base of legacy equipment when they need to adapt networks to the significant growth in IP traffic and related services. So, smooth migration from existing networks is guaranteed. Major UNI enhancements are:

- **Single end-to-end signalling session** (client-OTN-client).
- **GMPLS compliance** (e.g. for enhanced QoS capabilities which guarantee efficient transport of different classes of service over a single network).
- **Fast notification** process of transport network failures to the client (cross-layer notification). Failure information for many affected sessions can be aggregated in a single notification for **scalability and efficiency** reasons.
- Client driven explicit routing in order to allow for **path diversity**. Use of ERO, RRO and XRO to achieve e.g. diversity of protected and protecting path.
- **Failure recovery co-ordination** between client and server layer. More efficient multi-layer recovery mechanisms that optimise the sharing of recovery resources will reduce **CAPEX** considerably. In addition, automated recovery (avoiding expensive and error prone manual intervention) further shrinks **OPEX**.
- **Scalability** is guaranteed by means of sophisticated CP features, which limit the amount of CP traffic even for very large networks with multiple protocol/technology layers and many network elements. This comprises additional **cross-layer information** exchange and/or **information aggregation** methods.

3.3.1.6 Optical solutions

AWG-based OBS node architectures

Non blocking structures with a single AWG require a very large AWG, a huge number of internal wavelengths (N*M) and wavelength converters at the input and output ports of the AWG.

To reduce the required large number of internal wavelengths, enhance scalability, and at the same time maintain non-blocking, more sophisticated architectures are proposed. These architectures benefit from the cyclic properties of AWGs. One of the resulting architectures is a highly scalable, strictly non-blocking concept as presented in Figure 23. When rearrangeable non-blocking would be sufficient, the required hardware resources could be halved.

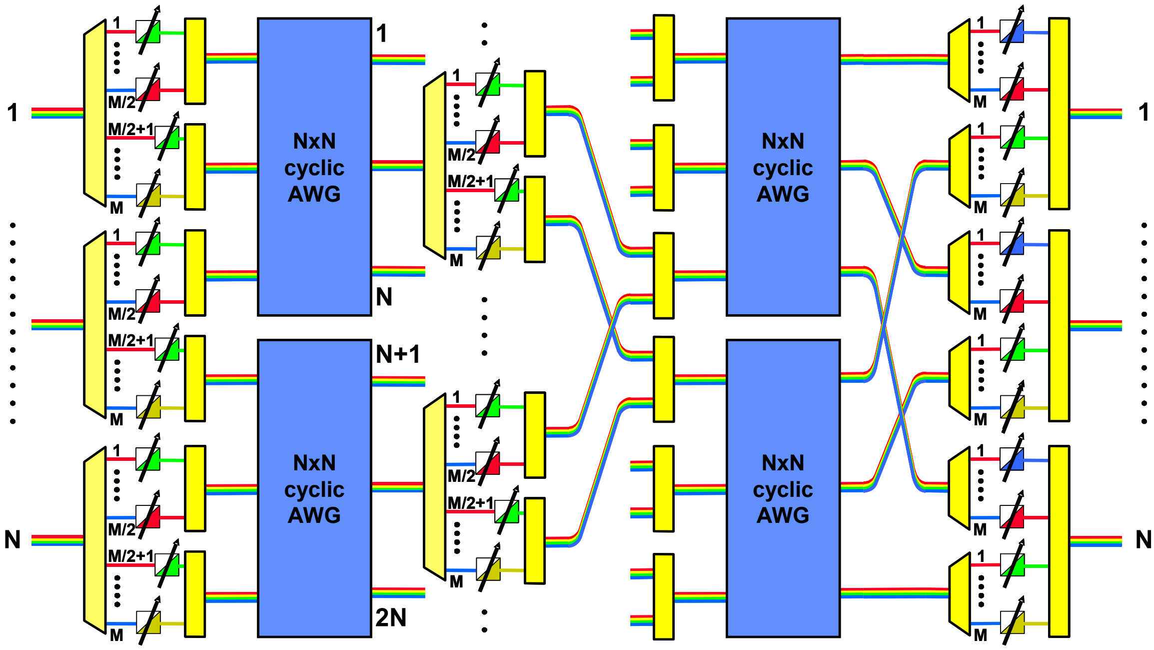


Figure 23 - Strictly non-blocking cyclic AWG-based OBS node architecture; central wavelength converter section not displayed in full for reasons of clarity

Further studies on cyclic AWG-based OBS node architectures have been performed regarding scalability, upgradeability and cascadeability. A comparison on these aspects with respect to Broadcast and Select architectures has also been made.

Scalability

The overall scalability of cyclic AWG-based OBS architectures is the easiest observed for M being an integer multiple of N. All components scale linearly in M and N. Three scaling factors are observed:

1. Fixed size, quantity scales by N·M ⇒ tuneable wavelength converter
2. Size scales by N, fixed quantity ⇒ AWG
3. Size scales by M, quantity scales by N ⇒ demuxes, combiners

Upgradeability

Two upgrade scenarios are discussed, first, how to upgrade in number of fibres with M wavelengths each is explained, second, upgrade in number of wavelengths per fibre. Simultaneous increment of both number of fibres and number of wavelengths can then be tackled using a scenario that is a combination of the two separate scenarios.

Cascadeability
Compared to an architecture based on an N·M x N·M AWG, we gained considerably on scalability. However, due to the observed architectural differences we may expect an impact on the cascadeability, the main factors being internal node losses, crosstalk and noise.
Comparison with Broadcast and Select architectures
We have performed a high-level comparison with four classes of Broadcast and Select (BAS) architectures as described in "Optical Networks Magazine, Vol. 4 (3), pp. 92-107, 2003". We limit ourselves to a comparison between Figure 23 and these four BAS classes on number of components, internal node losses, and first-order estimates of in-band noise accumulation. For the sake of convenience, we also assume M to be an integer multiple of 2N. The results are summarised in Table 11.
No clear winner emerges, but three candidates that justify further investigation can be distinguished: fully AWG-based, BAS Class III with active switches, and BAS Class IV with active switches.

Table 11 - Qualitative comparison between the cyclic AWG-based strictly non-blocking architecture of Figure 23 and a number of Broadcast and Select architectures from "Optical Networks Magazine, Vol. 4 (3), pp. 92-107, 2003" (+, O, — have only relative meaning within the same category)

Configuration	Number of Wavelength Converters	Number of Switches	Number of AWGs	Number of (De)muxes	Number of Splitters/ Combiners	Link Budget Reduction	OSNR
Figure 23	O	++	O	+	O	O	+
Class I	–	++	––	––	+	O	++
Class II (i.e. class III in NOBEL D24)	–	++	++	––	–	––	O
Class III passive switches	++	–	++	++	–	––	––
Class III active switches	++	–	++	++	–	O	++
Class IV (i.e. class I in NOBEL D24) passive switches	++	–	–	––	+	––	–
Class IV active switches	++	–	–	––	+	O	++

3.3.1.7 Feasibility aspects of burst/packet switching network and nodes

Nodes for Optical Burst switching

Studies on the feasibility of different optical burst switching nodes have been carried out. One option to realize OBS nodes is based on SOAs as ON/OFF switches. We studied a further OBS node option which is based on AWGs in combination with wavelength converters. The physical size limitations of these nodes were studied and described.

3R-regenerating wavelength converters are assumed to be used in the SOA based “Tune and select” (TAS) nodes. If all-optical wavelength converters are used instead, the 3R regeneration is not implemented and the cascadability of the TAS nodes is limited. Therefore, the maximum size of the TAS nodes depends on the number of passed nodes. This effect was quantitatively analysed, it results in further severe size or cascadability limitations.

Three different models for the SOA have been used in the studies: The reference SOA is only described by a static gain and a noise figure, the conventional SOA includes chirp and dynamics, and the gain clamped SOA model includes additional gain clamping by laser action. The analysis of TAS nodes was extended wrt. the impact of SOA chirp on the dispersion compensation characteristic of the fibre link. It was shown that there is no essential degradation due to SOA chirp.

The characteristics of the signal passing the OBS core nodes will strongly depend on the modulation format, if SOAs are used as switching gates. The use of conventional SOAs without gain clamping results in severe signal degradation due to dynamic gain saturation and inter-symbol interference both for NRZ and RZ modulation. So by using conventional SOAs only small TAS nodes can be achieved for NRZ modulation, GC-SOA and reference SOA lead to similar results (128 wavelengths, 5.12 Tbit/s maximum throughput for both). The node size achievable using GC-SOAs and RZ-modulation is smaller than that for NRZ modulation, due to the dynamic characteristics of the SOAs.

Regarding the design of the OBS core nodes based on SOAs, the following general design guidelines can be derived:

- Gain-clamped SOAs have to be used.
- The maximum size of the nodes is mainly determined by amplifier noise and crosstalk between the WDM channels. While the crosstalk limitation only plays a role for a very large number of wavelengths per fibre, the noise dominates in all cases. Therefore, the amplifiers used in the nodes must have low noise figure.
- For such noise-limited nodes, the achievable maximum number of wavelengths per fibre is proportional to the optical signal-to-noise ratio (OSNR) of the node.

A similar analysis of physical size limitations was performed for two AWG based node architectures. The physical limitations of the node size are caused by:

- **Crosstalk:** Crosstalk in AWGs appears because a small part of the input signal is not fed to the correct output port corresponding to its wavelength, but is distributed to the other output ports, where it interferes with the other signals. The degradation by crosstalk is especially strong, when inferring signals are delayed versions from the same source, or come from different sources but have the same nominal frequency (coherent crosstalk).
- **Loss:** The mean loss of AWGs that can be achieved with current technology is approximately 5 dB. The loss may be wavelength dependent with more loss at edges of the free spectral range. This effect is especially a problem for implementing cyclic AWGs, when the total free spectral range has to be used.
- **Non ideal filter response:** Special flat top designs have been developed. Without such design the filter response is parabolic in the center, and cascading such filters leads to filter narrowing. Non-ideal filtering causes pulse distortions.
- **Non-perfect wavelength/frequency grid:** It is not possible to design an N×N AWG with an evenly spaced frequency grid for all combinations input and output ports

without deviations. This is necessary for a N×N AWG used in an OBS switch, because the signals in WDM systems have be compliant with the ITU frequency grid.

An AWG with NM×NM ports is necessary to build a single stage, blocking free AWG based node. Additionally such a node needs wavelength converters at the input and ouput ports and needs NM internal wavelengths for non-blocking switching behaviour. If a certain amount of blocking is accepted, the wavelength converter at the AWG's output ports can be omitted, and only M wavelengths are used for switching.

A scalability enhanced version of this node has been suggested which needs only N*N cyclic AWGs. The major result is the maximum allowed crosstalk level for the AWGs. State of the art crosstalk levels are close to -35 dB.

The maximum allowed crosstalk level is shown in Figure 24 versus the dependence of the number of wavelengths for the conventional and the scalability enhanced node architecture for N=4. The calculations have been done for 2.5 Gbit/s, 10 Gbit/s, and 40 Gbit/s. A bit error rate of 10^{-22} is chosen as a limit. Based on the system design, there is a rather low noise level so that the BER starts to increase only when the signal eye begins to close considerably. This can be seen from the rather marginal differences between the results for the different bit rates.

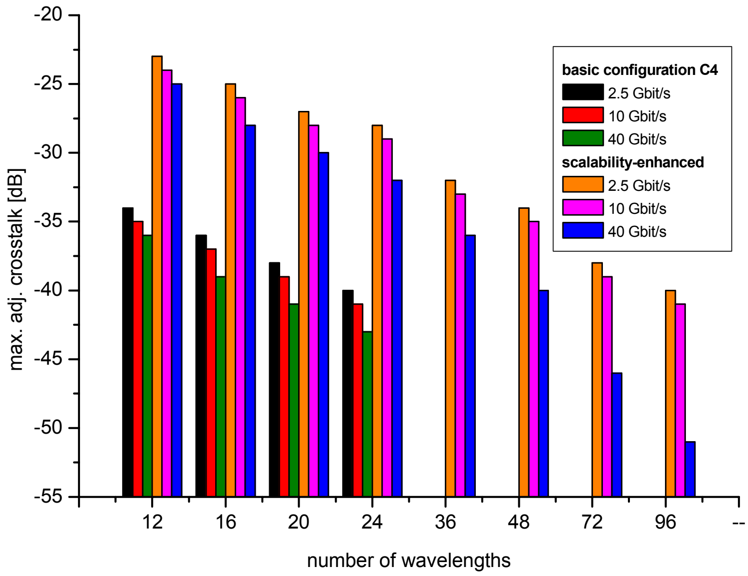


Figure 24 - Maximum allowed adjacent crosstalk (BER< 10^{-22}) for N=4 versus number of wavelength in the conventional and the scalability enhanced AWG-based OBS node configuration

For the conventional solution already at wavelengths counts of 12, the limit of today's technology is reached. For the scalability enhanced node, 72 wavelengths per fibre seem to be possible.

3.4 WP4 Network Management and Control/Protocols

3.4.1 Overall WP4 Goals and Focus

WP4 has been targeted at network management and control issues of metro and core network scenarios. The overall goal of the network management and control activities in NOBEL, performed in WP4 were to study, evaluate, propose, and validate emerging network management and control solutions for end-to-end networking in a multi-service, multi-layer, multi-domain network supporting innovative services and mostly bursty data applications.
For this purpose, it is important to understand specific application requirements and properties of relevant services and service models. WP1 specified and derived requirements for innovative services, defined network architectures, evolutionary guidelines and a roadmap for intelligent core and metro optical transport networks.
Hence, WP1 defined the basic NOBEL network scenarios and solutions for core and metro networks in the short term, medium term, and long term time frame. On the other hand, WP4 concentrated on the Network Management and Control/ Protocols aspects of future core and metro network concepts in the NOBEL network scenarios. Also, WP4 contributed to the NOBEL testbed with NM&C prototype implementations and tests of selected MP and CP functions.

Methodology applied in WP4

The methodology adopted in WP4 for capturing optical network control and management requirements, as depicted in Figure 25, started with the identification of future proof applications and innovative services. Based on them, the high level functional specifications of network management and control solutions for future transport networks were derived, from the application and service point of view.

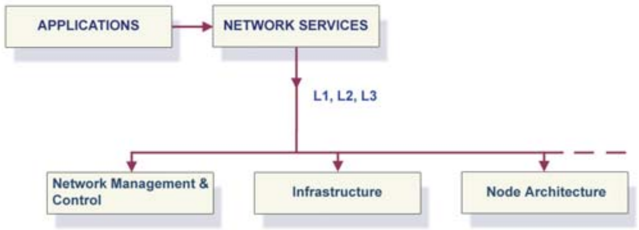


Figure 25 - Deriving network control and management requirements in NOBEL

In detail, the main objectives of WP4 were:

- To analyze and propose simplified strategies and interworking of Network Management and Control of core and metro networks.
- In collaboration with work packages, to investigate MP and CP aspects, and to develop strategies/functions for evolutionary NOBEL network architectures and scenarios.
- To identify future application and network services on layer 1/2/3, derive their functional requirements, and propose architectural solutions
- To investigate a comprehensive set of aspects and functions in detail, leading to simplified solutions which will be communicated towards standardization.
- Accompanying the conceptual studies, to perform management and control prototype implementations and experimental evaluations, in collaboration with WP8.
- To investigate in detail specific CP requirements and solutions in multi-service/layer/domain optical networks.

WP4 Deliverables

- D2 "Definition of Network Management and Control requirements of network scenarios and solutions supporting Broadband Services for All".

  - Identification and discussion of the high-level management and control requirements of the NOBEL network, for the provision of network services to user-applications triggered from client networks.
  - High level network service requirements, with focus on Layer 1, Layer 2 and Layer 3 VPNs.
  - Description of reference points and domains in the NOBEL network.
  - Overview of network and service operations that provide a high-level description of relevant functionality, and provided requirements for the CP and MP, as well as for MP-CP interaction.
  - High-level description of service delivery capabilities of the optical network infrastructure, i.e. elaboration on functional requirements of the planes involved in optical networking, managing and controlling the transport plane (TP): a) control plane (CP); b) management plane (MP); c) CP-MP interaction.
- D18 "Conclusions on NM and CP functional scope and standardization approaches; NM and ASON prototype functional scope"; D18 reported preliminary results:
  - Main functional architectures, generic modelling concepts and key features of ASON/GMPLS
  - Network scenarios that standardization bodies are marginally studying (e.g., Policy Management and Charging Information Management functionality)
  - Short comparison between centrally implemented databases and full-distributed databases for the control plane
  - General problem statement and high-level requirements that are common for the control, operation and management of Layer 1, Layer 2, and Layer 3 Virtual Private Networks (VPN).
  - Issues, alternatives and preferred directions and structures for a NOBEL information model (IM) for the NMS-EMS/SubNMS interface.
  - Overview about the NM and ASON prototype functional scope and the implementation plans of the partners involved in the implementation activities in WP4
- D25 “Solutions for inter-domain and multi-layer NM & CP and Service Management concepts; NM and ASON prototype functional and design specification and test plan”
  - Analysis of network scenarios that standardization bodies are marginally studying
  - In-depth survey about control plane issues, taking special attention to multi-domain and multi-layer aspects as well as solution for all-optical Metropolitan Area Networks.
  - Detailed analysis about signalling traffic from which can be derived criteria for the dimensioning of the control plane network
  - Control and Management scenarios related to two groups of applications that are going to be the most attractive for the provisioning of VPNs
  - Current UNI/UPI abilities are critically reviewed in order to highlight the limitations with regard to the scenario in which a transport network is able to provide services that go beyond the pure network services
  - Overview of the NM and ASON prototype functional scope and the implementation already outlined in [D18]

- D33 "Conclusions on Network Management and Control solutions supporting broadband services for all"
    - VPN solutions, i.e. CP and MP in support of GRID applications; CP and MP architecture for VPN services
    - Control Plane Issues, i.e. cooperation between MPLS-GMPLS; convergence between ASON and GMPLS concepts and paradigms; multi-layer networks and common control plane, including TE and unified Traffic Engineering in GMPLS networks; restoration in multilayer optical ring networks
    - Information Modelling requirements and scope
    - Service supportive GMPLS networks requirements and general concepts
    - Implementation activity report and test results

The scope of WP4 is divided into 5 activity areas. In short, the goals of WP4 in Year 2 (2005) were the following:

<u>A4.1 - Network Management (NM) and Control/Protocol (CP) requirements and functional scope</u>

This activity started with the identification of Network Management and Control/Protocol requirements from the point of view of European providers. The results of the analysis are described in deliverable D2. This activity continued with detailing the Network Management and Control/Protocol requirements from the point of view of European providers, based on the results of deliverable D2. This activity concentrated especially on deriving the network management and control requirements of network services on layer 1, 2 and 3. The functional scope and solutions of Network Management and Control/Protocol which meet the derived requirements were proposed.

<u>A4.2 - Performance, fault management, fault localization and QoS monitoring requirements and solutions</u>

This activity performed an analysis of requirements and a definition of solutions for monitoring functions in the Control Plane and in Network Management, esp. at the E-NNI. It takes specifically into account aspects of multi-layer and all-optical network scenarios (as defined in WP1 and WP5), as well as specific aspects of end-to-end QoS monitoring for Layer 1, Layer 2 and Layer 3 services. A Task Force had been setup which specifically elaborated on the mentioned issues. This activity continued with an analysis of requirements and a definition of solutions for monitoring functions in the Control Plane and in Network Management. Detailed aspects of signalling and routing functions in all-optical networks were investigated.

<u>A4.3 - Inter-domain, multi-layer NM and CP and Service Management aspects</u>

This activity analysed in detail requirements of simplified solutions, and proposed concepts for NM and CP with respect to inter-domain aspects of MP and CP approaches; end-to-end aspects for configuration and fault management for the NOBEL network scenarios. Multi-layer MP and CP approaches have been investigated; end-to-end configuration and fault management MP and CP aspects, as well as resilience and TE MP and CP aspects were analyzed, for overlay and integrated layer models. A Task Force on UNI issues has elaborated specific CP aspects on the UNI reference point, and has proposed a GMPLS compliant UNI supporting end-to-end signaling. The further work in this activity was performed in the NNI Task Force, and the VPN Task Force. Furthermore, the Information Modeling Task Force has identified IM related open issues of MP and CP interworking. Specific functions at the reference points were analysed in detail regarding their requirements, their scope and their implementation at UNI, at the E-NNI, the NMI-A, and the UPI interface. Service implementation solutions for network management and control were discussed according to concrete application case studies. Challenges of multi-layer Traffic Engineering in GMPLS enabled networks were discussed. Furthermore, the Information Modeling Task Force has identified the scope and the requirements of an IM for MP-CP interworking at the NMI-A.

<u>A4.4 - Standardization approaches, especially centralized vs. distributed implementation of NM and CP functions</u>

The activity started with a definition of the working methodology, which is described in D2. Following, an assessment of existing standardization approaches was performed, as presented in D2. One major aspect of future simplified MP and CP solutions is the centralized or distributed implementation of specific MP and CP functions. This aspect had been investigated in detail. Suitable distribution approaches of networking functions over the MP and CP functions were discussed. An assessment of existing standardization approaches was performed and open issues were identified. Results of the Information Modeling work were communicated to standardization.

A4.5 - NM and CP prototype function and design specification, implementation and test

First, selections of the features which are suitable to be implemented into prototypes have been chosen. Next, the activity performed a number of prototype implementations of UNI and NNI CP and MP functions that were integrated into the testbeds, in collaboration with WP8. The feasibility of the implemented functions has been analysed and demonstrated in a number of tests. The prototype implementations were integrated into the testbeds. Testplans had been defined and tests had been performed, which demonstrate the feasibility of the proposed MP and CP solution, including interaction between Management Plane and Control Plane.

3.4.2 Results of WP4

WP4 introduced a technology independent, high-level view of the overall network infrastructure reference points applicable to service delivery and network management. The reference points address the CP, MP, their relationship to each other, and their relationship to the TP.

The main goal of WP4 during the start of the project were the identification and definition of requirements applicable to the CP and MP, given different cases and capabilities of the network. The reference points in different network segment cases, which are applicable to WP4 are shown in Figure 26. A Reference Point represents a collection of interaction services, (to be) provided via (specific) interfaces related to one or more pairs of interoperating components.

A bi-directional control interface called UNI generally exists between a carrier optical network and its customers. User-Provider interactions related to service request and management are associated with one or both of the UPI (User-Provider Interface) and the UNI (User Network Interface) reference points. The UPI is currently not specified, but the functions required at the UPI had been discussed. The intra-carrier (intra-provider) E-NNI is a CP reference point between different domains within the network provider. I-NNI, which is a CP reference point internal to a domain, is not shown.

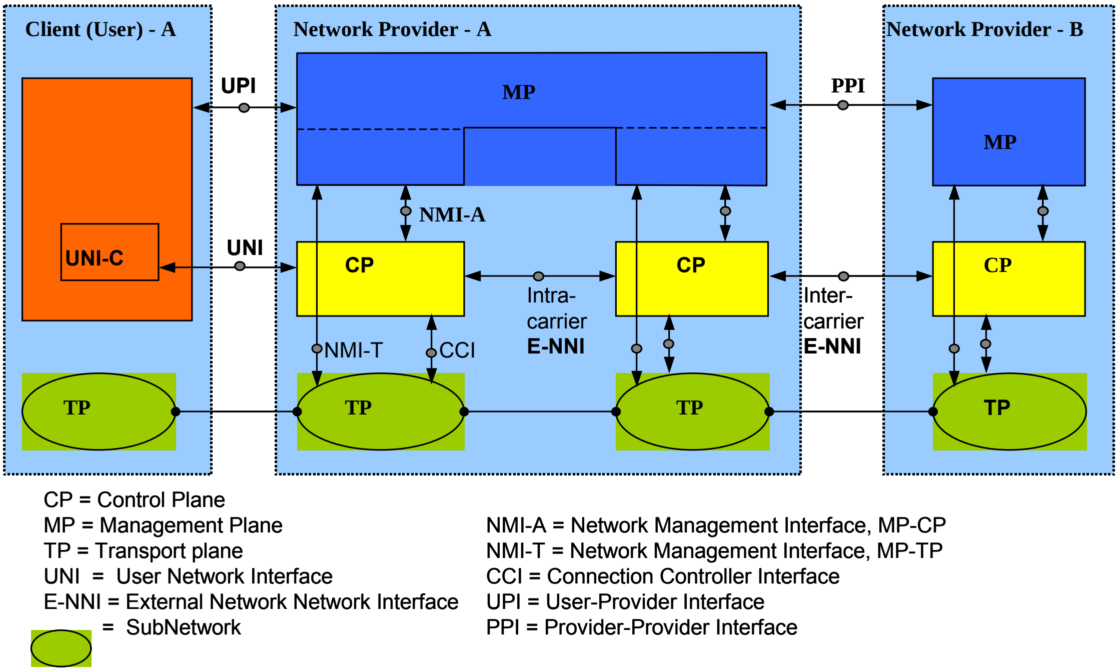


Figure 26 - Reference Points

In order to let the CP deliver services and operate according to the business and service goals of the network provider there is a need for management of the CP and thus, MP-CP interworking. The NMI-A is the reference point assigned for this kind of interworking. Furthermore, the reference point figure also identifies the NMI-T reference point for interworking between the MP and the TP and the CCI reference point for CP-TP interworking.

The issues in WP4 were related to activities with selected topics, as described above, and related to different reference points, as shown in Figure 26. The work was performed in organized Task Forces. The Task Forces were led by different WP4 partners, and were partly interacting with other WPs. The results of the Task Forces are presented in the following:

a) ASON/GMPLS Use Cases

NOBEL WP4 had to focus on a few but highly relevant aspects of ASON/ GMPLS functionality, for which major changes are expected in the way how the network will be operated if the ASON/ GMPLS paradigm will be introduced. These aspects were seen in the following areas:

- Visibility of connections (in the case of switched connections),
- Maintenance philosophy in ASON/ GMPLS networks,
- Provisioning of end-to-end connections over several operator or vendor domains (E-NNI),
- Neighbour and Service Discovery.

Due to the modular nature of the ASON/GMPLS architecture, a smooth migration of existing networks to ASON/GMPLS is feasible and individual pieces of ASON/GMPLS functionality can be introduced in the network independently. As this has quite some impact on the details of the use cases, the use case descriptions is made for different steps of migration (called "scenarios" in NOBEL. The Scenarios and Use Cases served as general framework for WP4.

b) Centralized versus Distributed Implementation of CP Functions

A research track was initiated in which the advantages and drawbacks of centralized versus distributed implementations of Control Plane components were analyzed. The study results are consolidated in a task force working document. Some conclusions can be drawn:

- The topology and resource database, may be implemented either centralized or distributed, and in both cases all the functions are feasible. However, the centralized implementation is more deterministic while the distributed implementation provides more flexibility.
- The path selection functionality, when implemented in a centralized fashion, allows for an accurate deterministic path selection. The pre-planned restoration can be easily be implemented, and crankback is not a necessity for the control plane functionality. When memory and process power are a constraint, then it is advised to implement path selection in a distributed fashion. In a fully distributed implementation, the knowledge base of a particular network element is restricted to the provisioned resources for requested demands. Other state resource information is flooded throughout the network, introducing potentially significant delays, which could result in higher call blocking probabilities, and thus the necessity for the control plane to have crankback functionality.

On-the-fly restoration typically shows an improved performance when put into practice in a distributed implementation, due to inherent executional benefits, such as, localization and parallelism. While pre-planned restoration is still possible, it requires, however, more complex implementation due to limited information availability, in particular; the network element supporting a path must maintain the routing and state of both the working and the restoration paths; and the decision time whether or not common resources along a path is deferred at signalling time and may induce crankback.

A traditionally operated network operation, i.e. based solely on Management Plane; assumes that qualified and authorized personnel strictly control the network. While, with the advent and introduction of the new Control Plane into the operator’s networks, more automatism is introduced in such a network. This will lead to a potentially significant reduction in capital and operational expenditure and will enable the network to operate in more complex scenarios and allow for seamless integration of new services. The possibility of specific Control Plane functions to be implemented in a centralized manner allows a generation of the CP network operation that is more similar to the old MP operation and therefore less revolutionary.

c) UNI Task Force

Typically, a UNI is a reference point over which pre-defined, i.e. standardized messages are exchanged with the objective to request services from a network. The reference point is an academic abstract point and is typically associated with a physical point on the physical link between the user and the network.

The UNI TF was conducted with the objective to analyze the different available UNI versions that have been standardized by different standards bodies and elaborate on their inherent differences. The standard bodies that have been considered are the ATM Forum, the ITU-T, MPLS and Frame Relay Forum, Metro Ethernet Forum, and the IETF. Essentially, a UNI separates transport network and its clients, allowing controlled interoperability between data and transport network. In this Task Force, the UNI is seen as a client-server relationship between the user and the service provider.

All of the above listed existing UNI recommendations have been thoroughly analyzed and compared, regarding their definition functional scope, the reference point and interface architecture, and their functionality and message types. The IETF defines two different service models: the unified service model and the domain service model. The latter represents a client-server relationship at the UNI between the client and the network. Usually, no routing information exchange is allowed at this UNI. However, the IETF vision regarding interworking between the IP and optical network, the exchange of routing information at private UNIs is allowed. The unified service model treats the optical network and the IP network as a single consolidated network in the sense that from a control plane point of view it is logically represented as a single integrated network.

All existing definitions have been compared regarding their functional capabilities. The result of this comparison is documented and tabulated. After a detailed analysis, the study concludes that the most applicable UNI definition considered for GMPLS/ ASON networks are the UNI being standardized by the IETF, OIF and the ITU-T. Although, initially these standard bodies started developing from an identical protocol set that evolved into very similar, though different protocol sets, as they added their own protocol extensions, which created standardised UNI versions. Due to this diverged evolution, the different standardised UNIs are not incompatible with each other. The UNI TF has therefore analysed the differences of the IT-T, OIF and IETF UNI definitions and functions in great detail.

A GMPLS-compliant user-to-network signalling interface (UNI) has been proposed within the UNI TF, called GMPLS-UNI. The main objective of this GMPLS-UNI can be summarised as an enrichment to allow end-to-end signalling exchange between different inter-carrier and intra-carrier networks, without the exchange of routing information.

d) GFP LCAS VCAT support for GMPLS/ ASON

Recently, new features are being added to conventional SDH transport networks addressing the problem of efficient transport of data traffic over that kind of networks, mainly designed for leased line services and multiplexed voice traffic. GFP is a standard way of mapping data packets into SDH payload; VCAT allows grouping multiple Virtual Containers to overcome the coarse granularity of SDH technology; at last, LCAS allows hitlessly changing the capacity for virtually concatenated synchronous payload envelopes. These new SDH technologies are key enablers for Bandwidth on Demand services while allowing network operators making efficient use of legacy networks, limiting the amount of new investments. In fact only edge nodes need to be upgraded in order to support GFP/VCAT/LCAS, while core nodes may be left unchanged. Presently they are mainly driven by the network manager: integrating them within the ASON/GMPLS framework it would be possible for networks operators to offer high quality Bandwidth on Demand services where client devices, with cheap Ethernet interfaces, may request dynamic bandwidth allocation to an SDH transport network using an appropriate signalling interface.

The purpose of this Task Force was to investigate the current state-of-the-art of the integration between SDH technologies for transport of Ethernet signals and ASON/GMPLS features, both from control plane and management plane perspective; to analyze use cases and to identify open issues.

e) Information Modeling Task Force

The goal of this TF was to analyse information model (IM) requirements and solutions, addressing MP-CP interworking. The TF focused on the IM issues for the NMI-A interface (see Figure 26). All CP specific results and insight of WP4 found their way into the IM activities.

Only limited work in this area is available. The IM Task Force started by identifying and reviewing relevant sources.:

- ITU-T e.g. G.805, G7718,
- TMF e.g. TMF-MTNM, the interface between NMS and EMS.
- IST LION Project: ASTN Network Element Level (NEL) Information Model, covering also UNI and NNI issues
- IST WINMAN Project: More generic Network Level (NL) Information Model
- IETF GMPLS MIBs
- Note: NEL and NL data structuring for SNMP
- MTNM and LION address specific management and information modelling issues of ASTN
- Review of relevant IETF MIB specifications (e.g. LMP, OSPF, BGP, RSVP MIBs)

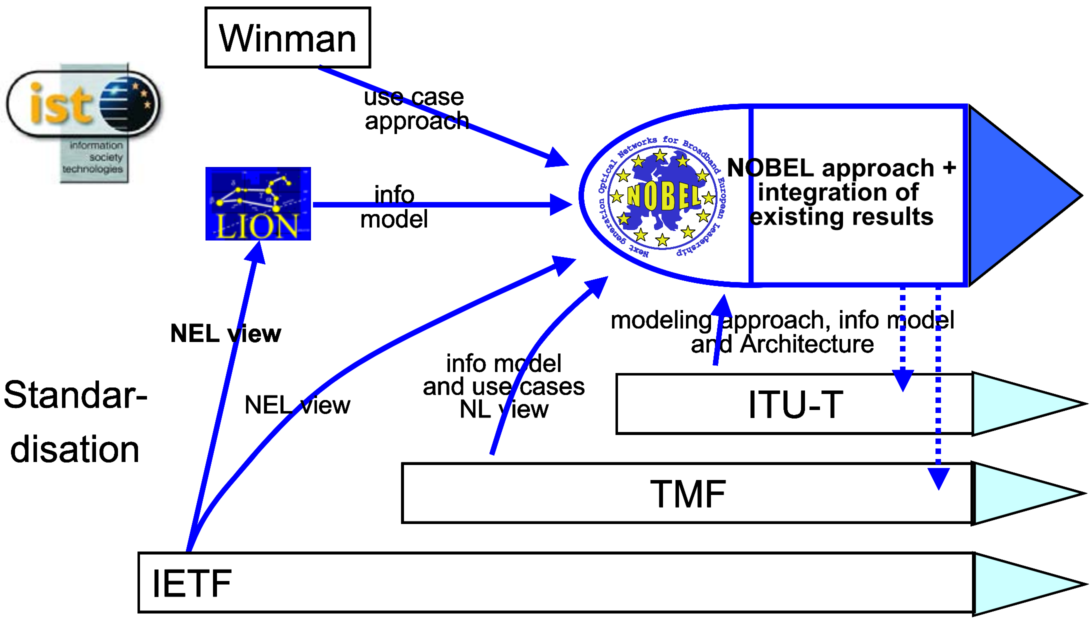


Figure 27 - existing results and ongoing activities on information modelling

The other sources have indirect relevance, and especially GMPLS features are still not included in the information modelling effort. The relevant sources are depicted in Figure 27.

The IM TF performed the following tasks:

- Collecting and reviewing requirements (e.g. from D2) and use cases (e.g. from D18 and D25) relevant for our information modelling work
- Service provisioning support such as VPN support
- A first version information model focusing on the CP-C part. (Modelling of managed entities representing the management view of the CP itself, its components and capabilities, how CP components are interconnected and how they interwork.).
- Maintaining an UML version of the information model
- Exploration of policy-based management for GMPLS CP solutions and related (multi-layer) TE.
    - Pointing out PBM objectives and key concepts and features and exploring the context
    - Pointing out and exploring policy information modelling issues including the relationship to management information modelling
    - Providing policy examples and exploration in the area of admission control, TE including path computation and routing control
- Identifying issues and options in the area of multi-layer transport plane entities such as multilayer link and subnetwork
- Experimental activities
    - Simulation test-bed
    - Initial implementation of CP_T as well as CP_C entities

The analysis of the NMI-A and information modelling problem space, the conceptual splitting of information models and first solution approaches are reported in the NOC2004 reference of the publication list below.

f) Integrating Physical Constraints into the Overall Control and Management Plane

Task Force

This Task Force investigated ASON/GMPLS control plane aspects when considering network environments consisting of hybrid/transparent switching data layers. In a hybrid/transparent network – defined by the removal of OEO regeneration stages at each node for express traffic, optical signals are potentially transmitted non-regenerated over significantly longer distances than in opaque networks as they travel from source to destination node. Moreover, since express traffic crossed the nodes non-regenerated, no performance measurement is made available for the bypassing optical signals.

The objective of the OPM Task Force, that was carried out in collaboration with WP5, was to identify the key optical performance parameters, which could be used for assessment of the optical signal quality. From management and control plane perspective, it was important to determine how to evaluate the optical signal quality and how to use it with respect to light path provisioning, optical path computation and fault management.

The results from OPM task force are summarized as follow:

- The optical parameters monitoring were identified which are relevant to the control and the management plane. These parameters include channel power, total power, Optical Signal Noise Ratio (OSNR), channel wavelength and Q-factor. Further the assessment of the technical complexity and the cost for is derived parameters was investigated.
- High-level requirements were derived, regarding the integration of the optical performance monitoring in the control and the management plane for functionality related to light path provisioning, optical path computation and fault management. A number of considerations were taken into account by deriving high-level requirements such as the control plane performance, flexibility and scalability of the management plane.
- The fault management including fault detection, fault localization and fault correlation for transparent network based on the optical performance parameters was analyzed.

It was concluded that the traditional fault mechanisms could not be directly applied in a transparent network due to the lack of electrical information. Further, we identified the probable causes that might be emitted by the optical layers in case of performance degradation or network element failure.

- An optical SLA application was implemented to evaluate the applicability of the optical performance monitoring parameters for performance degradation. It was concluded that the monitors must be placed carefully inn the network to obtain all necessary data, and efficient synchronization is needed between spectral- and time-domain measurements.
- Redaction of the paper “Experimental implementation of dynamic in-service performance monitoring for lambda services” submitted, accepted and presented at ECOC 2005 based on advanced optical performance monitoring

g) VPN Task Force

The joint WP1-WP4 VPN task force dealt with L1/ L2/ L3 VPNs based on advanced control plane functions and accompanying management support architecture. Stated objectives of the work were:

- To capture control and management requirements for VPN services
- To identify Types of L1 VPNs and related UNI/ NNI functionalities
- To describe the network and service delivery architecture in selected VPN scenarios
- To get an in-depth understanding of the transport, control and management plane issues associated to VPNs set up in support of broadcasting, storage and GRID applications.
- To propose a coherent and unified VPN provisioning framework that encompasses all the studied use cases

Virtual Private Networks (VPN) are commonly referred to as the networks which offer secure connectivity over the shared public network infrastructure such as the Internet. “Virtual” in VPN means that there is a logical, not physical connection between the two end points communicating to each other. “Private” means that the traffic through this connection is separated from other traffic passing over the same, shared infrastructure. It is important to distinguish different technologies, which are used as the building blocks of VPN as traffic separation. Virtual connections could be established using various protocols and on the different layers of OSI model.

D18 provided the general problem statement and high-level requirements that are common for the control, operation and management of Layer 1, Layer 2, and Layer 3 Virtual Private Networks (VPN). It produced a coherent description of the significant technical issues that need to be addressed in the design of VPNs and their management solutions for the different network scenarios in NOBEL. Moreover, an initial exploration of alternative approaches to solving the problem was given as a first step towards defining a robust and complete VPN control and management framework.

Once the state of the art was reviewed, a clear view was produced on the problems being faced, VPN Task Force activities moved towards providing detailed descriptions of a number of selected VPN scenarios. These VPN scenarios targeted by NOBEL focus on the control and management implications of the considered VPN service, and propose how the TP, CP and MP components should be organised and interact with each other to provide a better service.

Figure 28 illustrates the VPN CP architecture (note that the boxes in the figure with a darker background indicate an optional CP component).

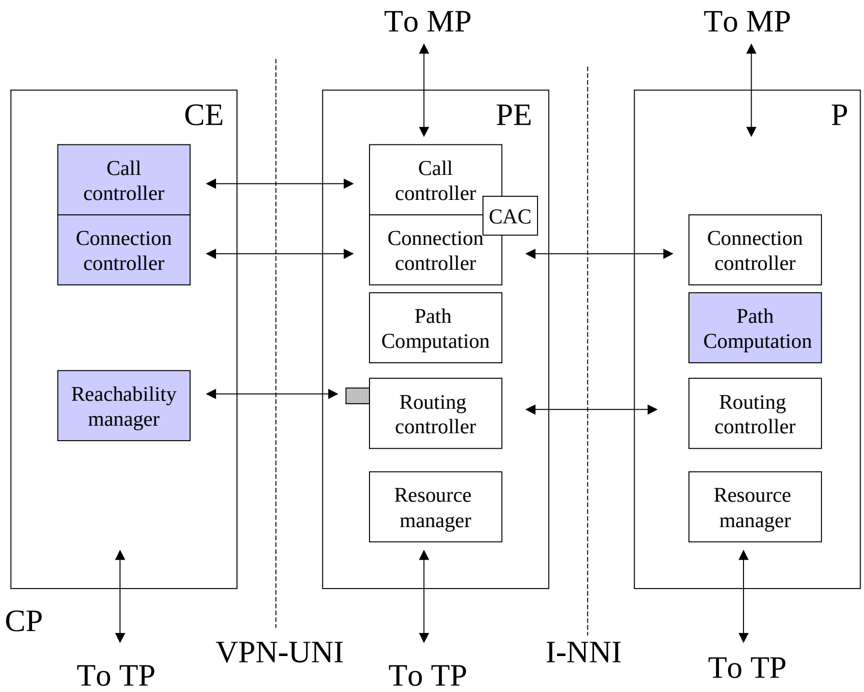


Figure 28 - VPN CP architecture

Figure 29 shows the VPN MP architecture.

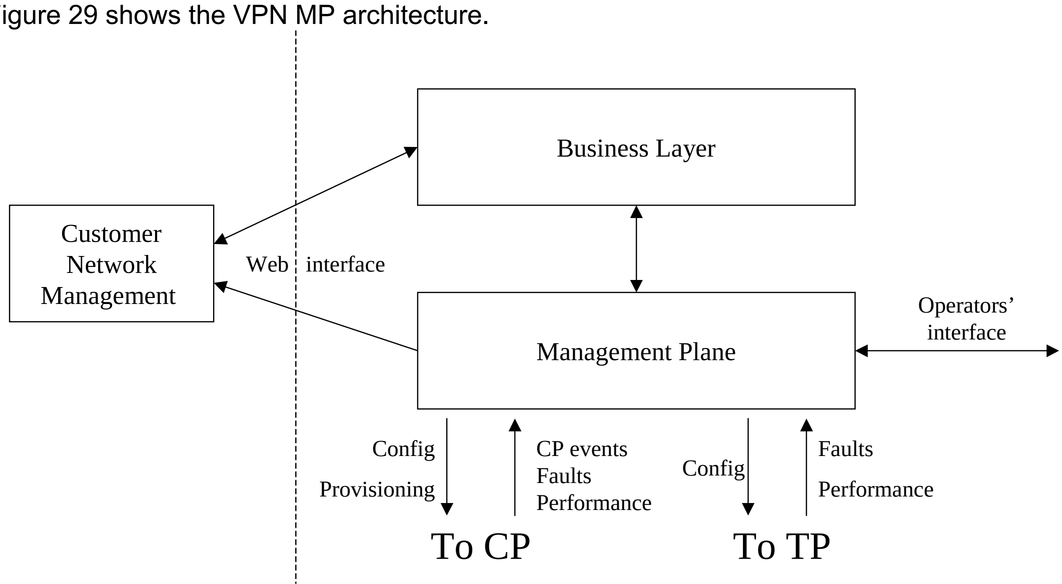


Figure 29 - VPN MP architecture

D25 contains the results of the scenario analysis for two applications:

Video/TV distribution and broadcasting, which gives a definition about realistic network scenarios utilizing VPN functionalities for national TV broadcaster applications. The focus of these scenarios is on the network infrastructure and network services provided to produce TV content by the broadcasters companies and not so much on the distribution of TV signals towards the end-user

WAN based storage, the aim of which was to define some important consideration about the use of VPN for the most important and bandwidth consuming network-based storage applications. In particular, three services are discussed: remote back-up, synchronous mirroring and storage on demand.

The final description of the VPNs for GRID applications scenario can be found in D33, together with a proposal for a unified VPN control and management framework for the simultaneous and efficient support of all three application cases.

h) Control Plane Task Force

The unified control management concept in the NOBEL network leads to both the vertical and horizontal integration of control plane instances. Vertical integration refers to the definition of collaborative mechanisms within a single control plane instance driving multiple (at least two) data planes (also referred to as switching layers). Horizontal integration is defined when each entity constituting the network environment includes at least one common (data plane) switching capability and the control plane topology extends over several partitions, being areas. In the latter case, the integration is thus defined between nodes hosting the same switching capability. For instance, the control plane interconnection between lambda switching capable areas defines a horizontal integration.

The main objectives of the Task Force were:

- To resolve general interoperability issues raised by NOBEL scenarios provided in WP1
- To fine tune protocols as well enable converge toward real exploitation perspectives

The Control Plane Task Force actively monitored intensively the work of international standardization bodies (especially IETF). The Control Plane Task Force performed various activities and produced achievements in both the horizontal and vertical integration in network control. These achievements include the problem positioning, functional specification, detailed specification, and concept validation in the following topics:

- Performance and scalability of protocols: RSVP-TE and OSPF-TE

A case study was performed which evaluation qualitatively and quantitatively the performance and scalability of control plane protocols.

- Horizontal integration: Inter-domain collaborative mechanisms
    - Cooperation between MPLS-GMPLS

Different MPLS-GMPLS scenarios were identified and evaluated regarding functionality and scalability. A specific focus were migration models and strategies, where a network is gradually being upgraded from MPLS to GMPLS. Figure **30** shows an example of a migration scenario. MPLS nodes are upgraded to support GMPLS-based advanced features or to allow interworking with non-PSC (Packet Switched Capable) GMPLS networks. The end-to-end LSPs begin and end on MPLS nodes and are tunneled across the GMPLS island. The MPLS nodes must not be aware of non-PSC technologies. No data plane conversion is needed.

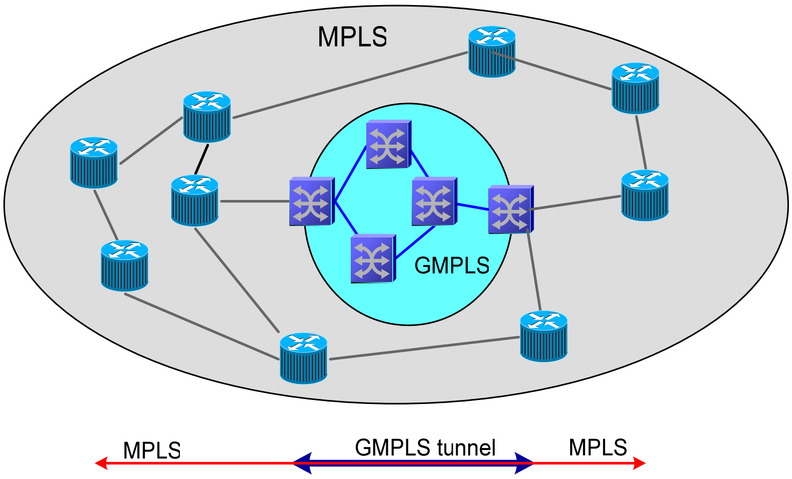


Figure 30 - MPLS-GMPLS-MPLS island model

- Convergence between ASON and GMPLS concepts and paradigms
- Propose enhancements to an IP-based signaling protocol for the end-to-end service and the vertically integrated control plane vision of NOBEL

- Vertical integration: Intra-domain cooperation between different data planes

Networks are often partitioned into different domains, e.g., an AS. In a multilayer environment such a network partition will have equipment with switching capabilities on multiple layers. Label Switching Routers (LSRs) in multilayer networks may have different sets of Interface Switching Capabilities (ISC). For example, a two layer network, with switching capabilities on the layers called Layer-(n) and Layer-(n+1) Figure 31. An LSR could be: Layer-(n) switch capable; Layer-(n+1) switch capable; Both Layer-(n) and Layer-(n+1) switch capable

In general, there is a mixture of the three cases.

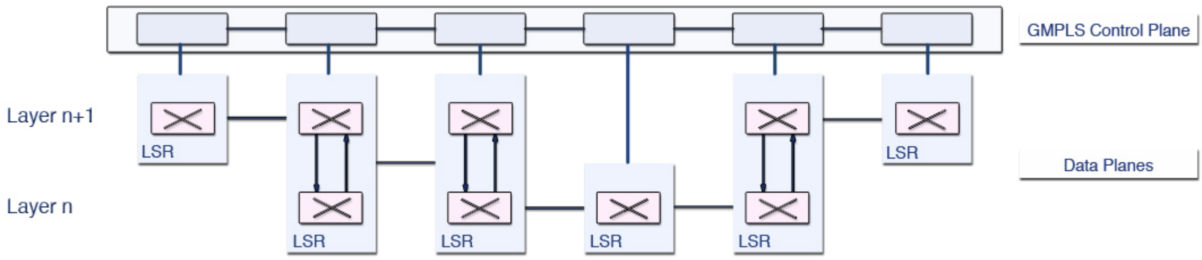


Figure 31 - Multilayer network architecture driven by a common control plane instance

GMPLS control planes in multilayer networks controlled by a common GMPLS control plane are "unified" if the LSRs are either Layer-(n) or Layer-(n+1) switch capable and "integrated" if all LSRs are both Layer-(n) and Layer-(n+1) switch capable. Various topics were studied related to vertical integration of network management and control:

- Multilayer networks and common control plane, including TE
- Unified Traffic Engineering in GMPLS networks
- Multi-domain routing aspects: E-NNI, PCE
- Layer 2 LSP and GMPLS

- Operational aspects for GMPLS

General aspects and limitations of GMPLS Signalling (RSVP-TE) and Routing (OSPF-TE) protocols in transparent (all-optical) multi-domain networks with wavelength-continuity constraint were studied and lead to the following results:

- GMPLS-Based Bidirectional Lightpath Provisioning in future all-optical multi-domain Metropolitan Area Networks (D25):
- Proposal of enhancements to the GMPLS RSVP-TE signalling protocol for provisioning of bidirectional optical connections over DPRings named SRP and WRP.
- GMPLS-based wavelength protection scheme for Och-DPRings based on SRP and WRP.
- Proposal of extensions to GMPLS OSPF-TE routing protocol and RWA algorithm for computing bidirectional lightpath routes under the wavelength-continuity constraint.
- Proposal of a standardization under the NOBEL scope of a GMPLS-compliant model.
- GMPLS-Based Bidirectional Lightpath Protection in Future all-optical multi-domain Metropolitan Area Networks (D33):

e) Service Task Force
This Task Force lead by WP4 was searching the discussion with WP1 on general network architecture and service issues. The following steps were carried out and results achieved:

- Motivation for improved service support in GMPLS networks (D18 and D25). In particular
  - shortcomings of current UNI implementations have been highlighted with respect to service support, e.g. the impossibility of current GMPLS networks of triggering VPNs set-up, status enquiry.
  - A distinction between network services and application services is made and the mapping problem is stated from the implementation point of view.
- Preliminary general architectures for a service supportive GMPLS network (D25 and D33). The following technical results have been achieved:
  - The UPI (user to provider Interface) is discussed as a short-medium term solution for service request support by a client network
  - For the long-term solution, a distributed service functionality “add-on” is introduced in the transport network to support service functions not supported by the CP and not available through the UNI
  - The USI (User to Service Interface), whose requirements are to be defined, is introduced as a new interface between client and transport network. This interface will be harmonized with existing technical approaches coming from the fixed-mobile integration efforts.

d) Implementation & Tests Task Force
An important objective of WP4 was the implementation of novel network and control plane concepts and functions in prototypes and emulators. The goal was to enable the experimental verification and testing of achievements from the other WP4 task forces as well as to provide equipment for the field trials of WP8. Therefore, the TF worked in close cooperation with WP8. Most selected features and functions have been implemented in prototypes based on optical network elements and emulators or simulators with innovative functionalities. Some of the prototypes were already available from previous IST or internal projects, and have been extended with new features and functions specifically developed in WP4. Some test networks have been extended with emulated nodes to enable experiments in larger networks as well as the experimental implementation of features which are not possible to implement on existing network elements. The implementation activities are documented in D18, D25 and D33. D18 gives an overview about the prototype functional scope and the implementation plans. D25 specifies more detailed the function and design specifications, the test plans and first results of lab experiments. D33 describes the experiments, results and overall conclusions.

Publications

H. Lønsethagen, B. Berde: “Achieving information models for management and control of next-generation transport networks”, NOC 2004, June 29 – July 1, Eindhoven, The Netherlands.

B. Berde, M. Canali, P. Castoldi, A. Iselt, M. Jäger, L. Levrau, H. Lønsethagen, A. Mazzini, M. Nathansen, J. González Ordás: “Network Management and Control for Intelligent and Agile Optical Networks”, ONDM2005, February 7-9, 2005, Milan, Italy.

Guillaume Juillot, Martin Nathansen, Cyril Margaria, and Andreas Iselt; "Emulation in GMPLS-controlled Optical Transport Networks"; ONDM2005, Milano, Italy, February 2005.

G. Juillot, C. Margaria, M. Nathansen, A. Iselt; "Emulation of GMPLS controlled Networks"; NOC2005, London, England, July 2005.

M. Vigoureux, B. Berde, L. Andersson, T. Cinkler, L. Levrau, M. Ondata, D. Colle, J. Fernandez-Palacios, M. Jäger; “Multilayer traffic engineering for GMPLS-enabled networks”; IEEE Communications Magazine, ISSN 0163-6804/05, Vol. 43, Nr. 7, July 2005, pp. 44-50.

B. Berde, M. Canali, P. Castoldi, M. Jäger, L. Levrau, H. Lønsethagen, A. M. Mazzini, M. Nathansen, J. Gonzales Ordàs; "Network Management and Control for Intelligent and Agile Optical Networks"; ONDM2005, Milano, Italy, February 2005.

C. Pinart, A. Amrani, G. Junyent; “Design and experimental implementation of a hybrid optical performance monitoring system for in-service SLA guarantee”; 9th IFIP/IEEE International Symposium on Integrated Network Management (IM 2005), Nice, France, May 16-19 2005.

C. Pinart, R. Martínez, G. Junyent; “Experimental implementation of dynamic in-service performance monitoring for lambda services”; 31st European Conference on Optical Communications (ECOC 2005), Glasgow, UK, September 25-29 2005.

L. Valcarenghi, L. Foschini, F. Paolucci, F. Cugini, P. Castoldi; "Topology Discovery Services for Monitoring the Global Grid"; IEEE Communication magazine special issue on "Optical Control Plane for Grid Networks: Opportunities, Challenges and the Vision", to appear, March 2006.

3.5 WP5 Transmission and physical aspects

3.5.1 Scope and state of the art

Today's optical transport networks, both metro and core, mainly consist of static point-to-point links based on SONET/SDH standards, with node functions (switching, add/drop, etc.) realized in the electrical domain. Extension towards higher capacity via WDM technology is currently based on proprietary equipment, but there is already the ITU standard framework for Optical Transport Networks (OTN).

There is ongoing debate, if this technology is suitable for future flexible network architectures (e.g. support of ASON/GMPLS), enhanced network functionality (e.g. layer 1/2/3 VPNs) and the required network management and control functions (e.g., to enable "on-demand" services).
On the other hand the gain in flexibility may demand adapted requirements for the network components (building blocks) or might even require enhanced functionality for certain building blocks.

Increasing the level of transparency in the optical domain is assumed to be a possible way forward. A transparent network is independent of the parameters of the transmitted signal (wavelength, bit rate, modulation format, …) and thus much more flexible regarding the services. Furthermore, reducing the O-E-O conversion inside the network can reduce investments (CAPEX) and operational costs (OPEX).

Until recently the design of optical transport networks follows a point-to-point design approach for the high capacity links. Today Wavelength Division Multiplexing (WDM) networks have begun to migrate from point-to-point links to intelligent, multi-hop transparent optical networks, in order to fully exploit the advantages offered by a wavelength-routed network (Figure 32).

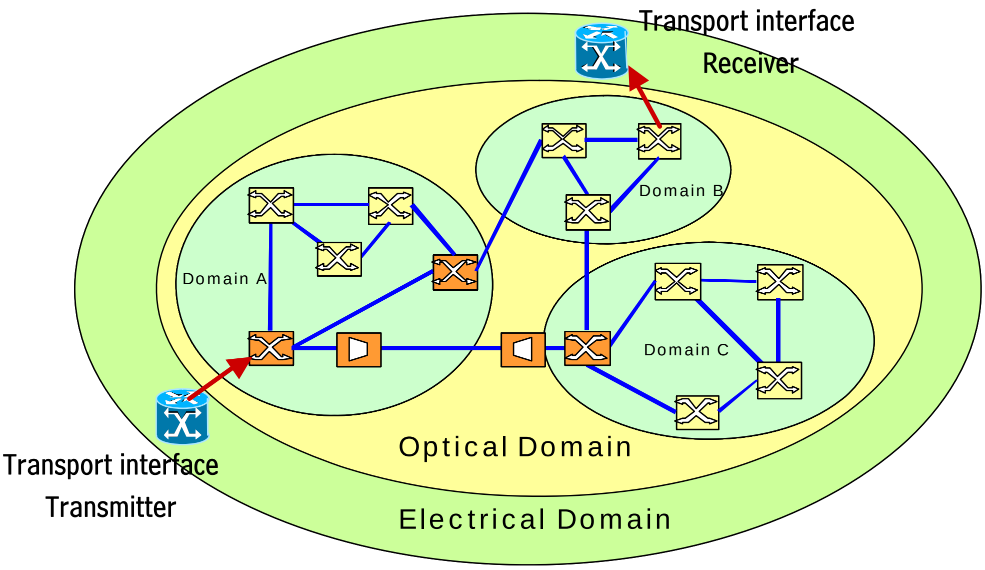


Figure 32 - Optical transparent network

Quality-of-Service (QoS) provisioning associated with service guarantees is an important asset for developing highly scalable "on-demand" networks. To provide acceptable QoS, wavelength routing algorithms (WRA) should associate effective routing algorithms with awareness of physical layer properties, taking under consideration physical layer impairments (PLI).

The following aspects will impact the design of the physical layer of the optical network and thus must be considered:

1. Optical transparency and translucency

A network is called optically transparent, if the transmission of the optical signal is independent from the specific characteristic (analogue or digital, modulation format, signal format, bit rate, …) of the signal, whereas in a translucent network the signal propagates in the optical domain as long as possible, and will be electrically converted in case of needed regeneration, channel dropping, wavelength conversion, etc. Figure 33 shows a translucent network, consisting of several transparent islands.

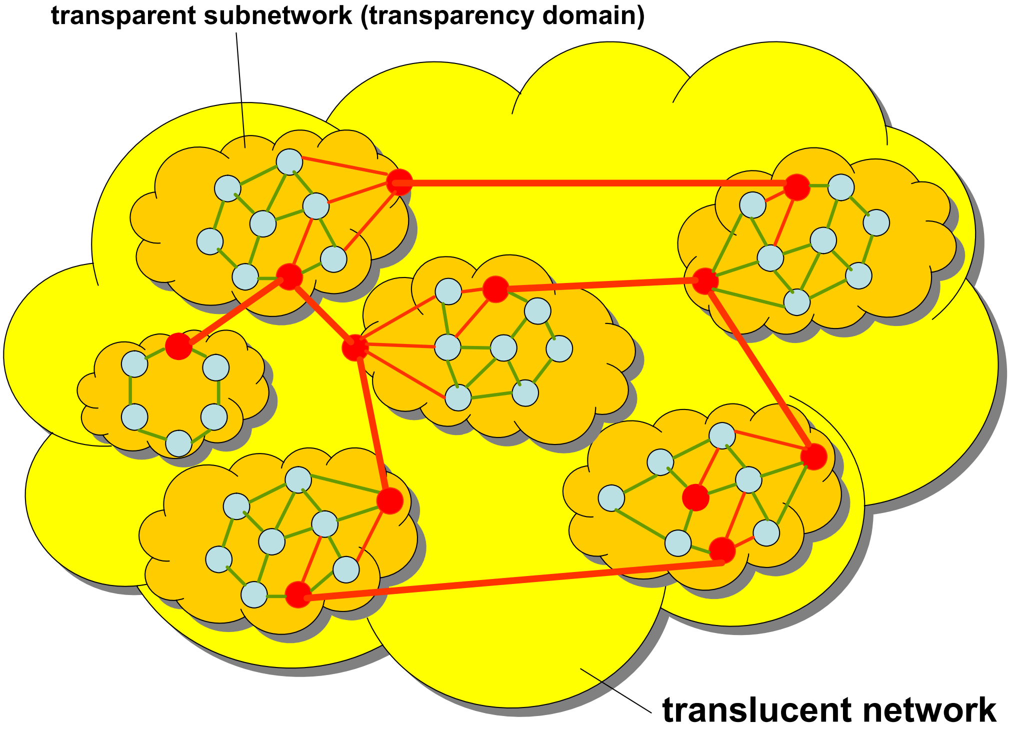


Figure 33 - Optical translucent network

2. Physical transmission impairments

The introduction of a transparent optical layer significantly changes the physical characteristics and the behaviour of the network. New requirements for the network design and the system equipment have to be worked on.

3. Network dynamics

Once a certain level of transparency is introduced into optical networks, switching in the optical layer will become a natural extension for such type of network. Then the optical network can provide greater flexibility when an automated process can efficiently organize the provisioning. Now the required network dynamic will define a new set of boundary conditions. Typical modes of operation can be distinguished:

- Provisioning by the management plane,
- Automated provisioning by the control plane (e.g. user/customer induced),
- Failure events (rapid change in configuration), and
- Recovery actions after failure events.

4. Physical building blocks / optical components

The following subsystems are of particular interest to support dynamic all-optical networks:
- Tunable Transmitters/Laser,
- Amplifier Transients (EDFA, Raman),
- (R, T)OADMs,
- Optical cross connects OXC,
- Optical Regenerators,
- Wavelength Converters,
- Adaptive Receivers, and
- Forward Error Correction (FEC).

5. Modulation Formats and physical constraints

Presently used modulation formats (like NRZ, RZ and CS-RZ) as well as new ones (e.g. Optical duobinary, DPSK, SSB, …) have to be assessed regarding advantages and drawbacks of their adoption in the envisaged transparent/hybrid network scenario.
In order to achieve optimum performance all aspects of optical transmission, such as loss and noise accumulation, chromatic dispersion management, polarization-mode dispersion effects, non linear mechanisms (self- and cross-phase modulation, four-wave mixing, …), cumulative filtering and cross-talk effects, must be considered and correctly modelled concerning their interaction with the given modulation format.

6. Optical monitoring

Reducing the number of O-E-O conversions within the optical network also reduces the possibility of monitoring the signal performance in the conventional way. In a transparent (sub)network, optical monitoring (often referred to as Optical Performance Monitoring, OPM) aims to extract the optical channel performance by measuring or estimating transmission parameters at different points in the network, see Figure 34, without any detailed knowledge about the light-path under test.

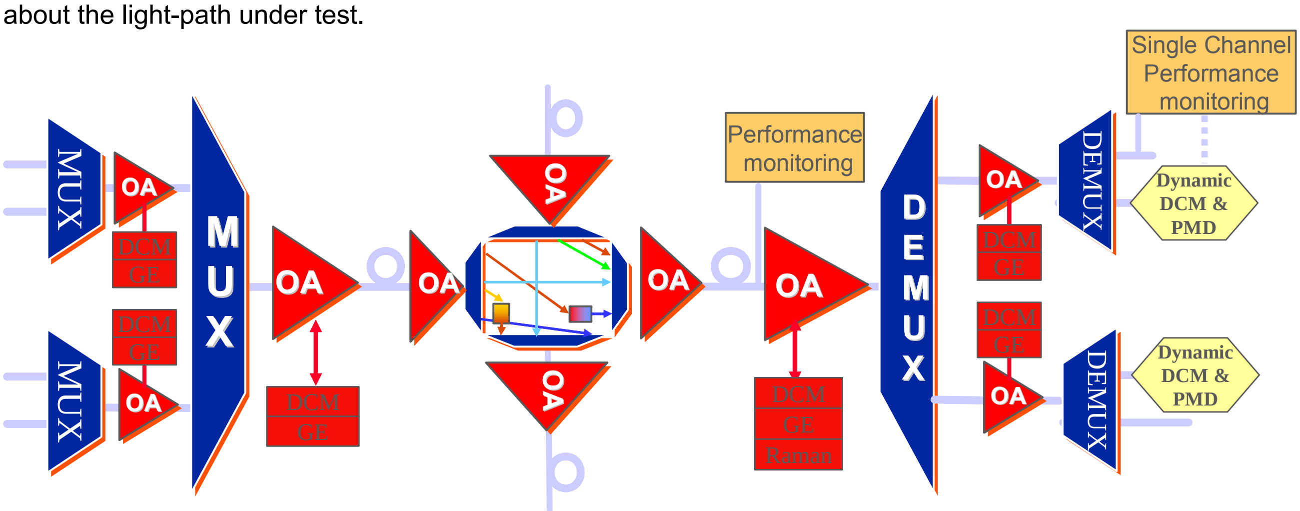


Figure 34 - Transmission system with optical monitoring and adaptive compensators

Finally, for a cost efficient implementation of these systems an integrated approach is desired, which allows to compare different solutions under realistic conditions.

3.5.2 Objectives

The overall objectives of WP5, transmission and physical aspects, were:

- To identify the main building blocks for the transmission, i.e., to identify the main building blocks for transmission in next generation flexible broadband optical networks, driven by the architectural demands of WP1
- To derive conclusions on the physical feasibility of dynamic transparent optical networks, i.e., to carry out a feasibility study of the physical aspects of dynamic transparent optical networks, in collaboration with WP1 for architectural and WP4 for control and management plane aspects
- To define design rules and optimum transport format for transparent transmission, i.e., to identify design rules for the physical layer of transparent optical networks and to derive the optimum transport format (bitrate, modulation, bursts) with respect to performance and cost impacting functionality for the different network segments, which will be used to develop efficient path computation algorithms taking into account transmission constraints.
- To evaluate path computation algorithms for dynamic network simulation, including physical constraints based routing, and to develop a detailed cost model for the components used in the network simulation, with the goal of being able to compare transparent approaches to opaque ones.
- To define transparent domains, in the meaning of how 'big' could or should a transparent domain be, and to perform a cost study to support the design of transparent domains and to compare O-E-O vs. all-optical transport networks.

3.5.3 Main activities

According to the objectives the work package has been organized in five major activity areas and sub-teams were build to investigate:

A. Generalized light path design
In a transparent network, the following system parameters and technologies are the key design factors for its physical layer:

- the number of nodes and in-line amplifiers and their sites,
- optical node technology, i.e. what types of OXC or OADM,
- what transmission technology to use: such as modulation format and equalisation, the fibre types and the dispersion management scheme,
- bit rate, wavelength spacing,
- signal power.

The approach adopted here starts with a first assessment of the targeted network topology with respect to the longest shortest path.

B. PMD channel model and compensation strategies
Although much research work has been spent on the topic of PMD, it must be considered as one important limiting factor in the design of dynamic, transparent optical networks, due to its stochastic and dynamic nature. Therefore a dedicated activity was assigned for this subject.

C. Optimized equipment placement (technology selection)
Starting from the result of the light path design, the network is equipped with the selected technology applying topology information and traffic assumptions (forecasts) for optimum equipment placement.

D. Dynamic path computation

After technology selection and equipment placement the resulting network is posed to dynamic changes in the traffic pattern. Different routing algorithms as well as network architectures will behave differently in terms of network performance criteria like utilization and blocking probability.

E. Cost aware partitioning into transparent domains considering optical monitoring requirements

In a final design stage an overall assessment of the achieved functionality against the expected cost (CAPEX and OPEX) is envisaged for the variety of potential options considered in the procedures described before. This investigation intends to take into account also control and management aspects and the partitioning of the network into transparent domains.

The latter two activities have started in the reporting period, and are ongoing in the second phase of the project.

3.5.4 Major results

A. Generalized light path design

- Longest shortest paths
We have developed a route search algorithm based on the "k Edge Disjoint Shortest Paths" algorithm. This algorithm finds the k routes between a pair of nodes that have no common links (can cross common nodes though), and the total cost[1] of these k routes is the minimum. Note that this set of paths may not contain the shortest path as when calculated in isolation, or any of the "m edge-disjoint shortest paths" when calculated for 1<m<k. This is because the objective is to minimise the total cost of the set of paths.
Understandably not all node pairs in a network will have k edge-disjoint routes when k is higher than 2. Therefore we have modified the algorithm by allowing a limited number of common links. Still some node pairs may not have k routes even with this relaxation, in which case we have taken a lower number of routes (hence we talk of "$k<k_0$ Edge-Disjoint Shortest Path with Edge-reuse"). The aim of this rough analysis is to find out a preliminary indication of the lengths of potential light-paths in a future transparent optical network to work out the best-suited optical technology to realise it.
We have defined a 'characteristic distance' for a network as the distance below which 90% of paths fall (including up to k disjoint paths for all node pairs). This ratio should mean that the network is too over-engineered, and of course there may need to be a few regenerators to deal with the very long paths.

Table 12 - Analysis results of potential light-paths in different networks

Network	k	Max. #Hops	Longest of the k Light-paths (km)	90% Length (km)	Ratio (%)
Pan-European	<5	11	5385	3357	62.3
	<4	10	4878	3313	67.9
DT	<5	13	1698	1254	73.9
	<4	13	1698	1192	70.2
BT Metro	<6	17	495	303	61.2
	<5	17	484	284	58.7
	<4	16	431	254	58.9
BT Core	<5	21	1109	687	61.9
	<4	20	1000	601	60.1
TiLab	<6	15	2878	1874	65.1
	<5	14	2477	1721	69.5
	<4	13	2265	1552	68.5

The analysis of the resulting light-paths distances is shown in Table 12. The first column indicates the analysed network. The second column shows the maximum number of Edge-Disjoint Shortest Paths with Edge-reuse that have been searched. The third column shows the highest number of hops of any found light-path that does not necessarily correspond to the longest light-path in terms of fibre length, which is shown in the fourth column. Having calculated the Cumulative Distribution Function (CDF) we have found the light-path length for which 90% of all light-paths are shorter. Finally, the last column shows the ratio of the 90% distance with respect the maximum light-path distance.
We see that the maximum distances are considerably longer than the 90% distance - although not double. The ratio of 90%/Max distance seems to be similar for all networks analysed (i.e. roughly between 60 and 70%). The DT reference network is slightly different as there are only a few nodes, so not many diverse paths. So we can see that there is quite a long tail to the distribution. **From this analysis we can draw a preliminary rule that says**

[1] Cost can be any metric such as fibre distance, number of hops, a mixture of those, etc.

that 90% of all reasonable light-paths are shorter than approximately around two thirds the maximum length for that specific network.
This result may be used as a starting rule design to derive the optical technology that would enable the specific network to become an operational all-optical network. Hence assuming we go for the 90% "characteristic distance", then we could have a procedure such as:

a. Do a light-path distance analysis on your network
b. Find the 90% distance
c. Choose an appropriate technology to give good transmission over this distance.

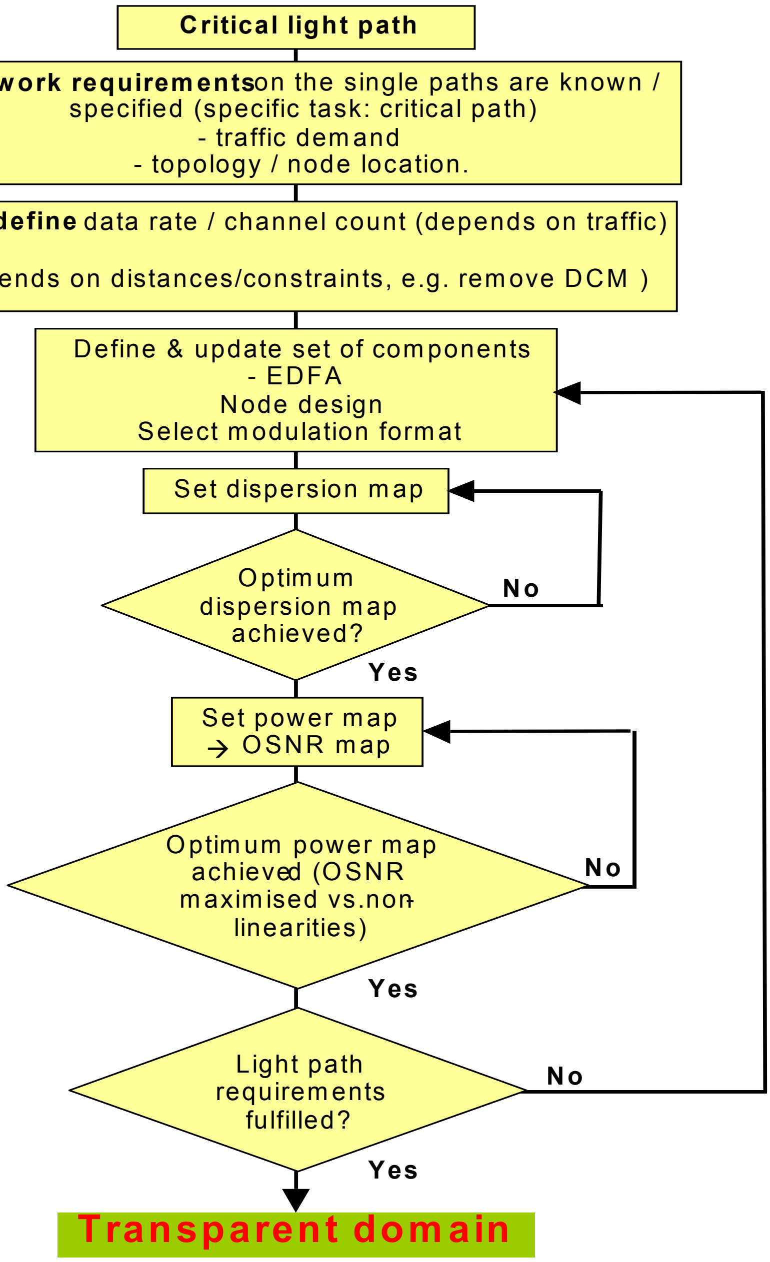


Figure 35 - Light path design procedure

- Optical path power budget
To evaluate the feasibility of an optical path a power budget based approach including physical impairments, like CD, PMD, non-lin., etc. is used. There are different types of optical

networks depending on the applications, as currently studied within Nobel WP5, 3 types of networks are considered: metro, medium haul and long haul core networks.

Table 13 - Optical path power budget

		Optical path:	
		Scenario/reference network	
		Total path length	
		Number of nodes	
		Signal bit rate	
		Total number of wavelengths	
		Wavelength range and spacing	
		Wavelength for the optical path	
		Fibre type/dispersion management	
		Modulation format	
		Electrical equalisation/optical equalisation	
A		**Baseline optical path performance in Q value:**	
	1	Optical noise effect due to amplification to compensate fibre loss and various losses in optical nodes	
	2	Extinction ratio	
	3	Receiver optical and electrical filtering	
B		**Propagation effects:**	
	1	Dispersion effects	
	2	Nonlinear effects: SPM	
		XPM	
		FWM	
		SRS	
		SBS	
	3	PMD effect	
C		**Optical Amplifier dynamics:**	
	1	Gain flatness	
	2	OA transients	
D		**Crosstalk:**	
	1	Crosstalk due to imperfect filtering	
	2	Static crosstalk due to optical switching	
	3	Dynamic crosstalk due to optical switching	
E		**Node filtering related effects:**	
	1	Filter cascading	
	2	Signal and filter wavelength misalighnment	
F		**Jitter**	
G		**Wavelength conversion or regeneration**	
H		**FEC improvement**	
I		**Required system margin**	
J		**Estimated optical path performance in Q**	
K		**Required optical path performance Q for a given BER target**	
L		**Optical path performance margin**	

Optical path performance (J)
= (Baseline performance A) – (Penalty B-F) – (Margin I) + (performance gain G-H)

When a network has been built, the above system designs are fixed. For a given network, an important question we need to answer is whether an optical path in the transparent network is physically feasible, i.e. whether a given service through the optical path would meet the required quality target, such as a bit error rate target. There are different transmission impairments in the transparent optical networks that cause degradations on the optical path performance depending on the type of networks and the transmission technologies employed. Their overall effect determines the feasibility of an optical path. Here we consider a power budget approach to include various aspects of the transmission in the transparent networks and assess whether a given optical path performance meets the requirements for an error free circuit and thus is physically feasible.

Table 13 gives the proposed power budget table. The first part is the main parameters for the optical path. In the power budget, we start from a baseline performance of a given optical path when considering only the amplifier noise effect due to the amplification required to compensate the fibre loss and the various losses in optical nodes. Then taking into consideration the penalties induced by various major transmission effects and performance gains due to the use of some transmission technology, a more realistic optical path performance is estimated as described below. By comparing this estimated performance with a pre- defined optical path performance requirement, the optical path margin is calculated. An optical path with negative margin or insufficient margin would be most likely not feasible.

B. PMD channel model and compensation strategies
Besides the systematic theoretical assessment of the PMD channel model (relevance of first-order vs. higher-order PMD) a consistent description of PMD compensation schemes for use in the optical path power budget based table has been developed. Two different compensation approaches, which are shown in Figure 36, have been evaluated experimentally.

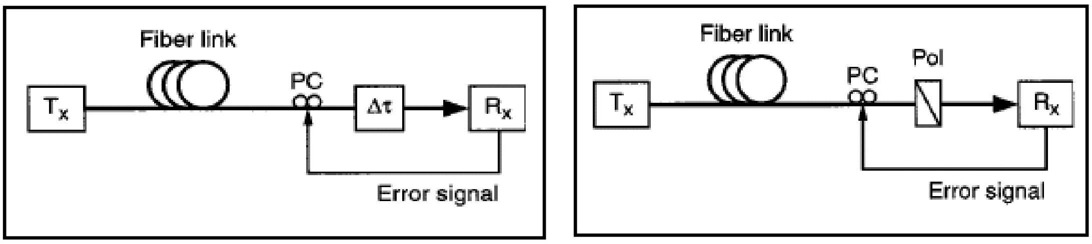


Figure 36 - Principal PMD compensation setups under consideration, wit hand without birefringent element.

Since PMD is considered critical for high bit rates, a 40Gbit/s setup using a single birefringent element was tested and a compensation range of about 4.5 ps mean PMD was demonstrated (Figure 37). For a 10Gbit/s system the approach with a simple polariser was evaluated, it was achieved to compensate add approximately 4.7 ps to the PMD tolerance.

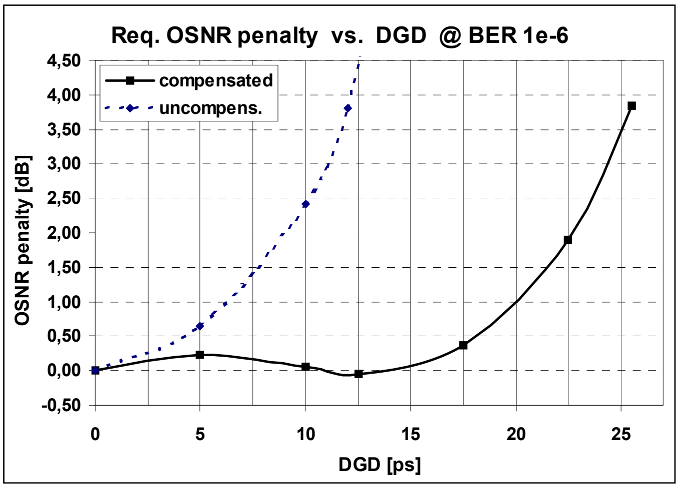


Figure 37 - PMDC results for 40 Gb/s with birefringent element

This approach is attractive, due to the fact that it does not add birefringence to the system and can be placed close to high PMD spans, in order to avoid accumulation of PMD induced signal distortion.

C. Optimized equipment placement (technology selection)

- Physical Layer Impairment (PLI) based routing

Dynamic transparent network planning and operation have been studied evaluating several different approaches. Routing and wavelength assignment (RWA) algorithms with different characteristics in terms of performances (in terms of computational complexity, resource/cost optimization, considered physical impairments) have been compared.

Network dimensioning with heuristic approach has been carried out on a reference network, for various traffic demand levels, including physical effects (ASE and PMD). Physical effects have also been considered applying a specific optimization algorithm (lessening the number of used fibers). Basing on the common cost-model elaborated by the CSG, total network cost for static traffic and for the considered optical switching options (patch panel, MEMS, Wavelength Selective Switch and Wavelength Blocker) have been computed and compared for scaling traffic demand levels, showing cost trends and performances trade-off. The heuristic RWA incorporated for PMD effect assessment the Q-factor penalty semi analytical evaluation developed within WP5: simulations with transponder with standard receiver and with electronic equalizer FFE5+DFE1 (modelled within WP5) have been compared, showing how the improved tolerance can provide benefits on network dimensioning, with different cases of PMD distributions in the network links. Network dimensioning examples with 40 Gb/s lightpaths have also been performed, to test a case where PMD effects become disruptive.

In order to evaluate how the network dimensioning is tolerant to traffic increase, incremental traffic simulations have provided indications about the average additional traffic load accepted in a reference network dimensioned for a certain level of static traffic, always considering ASE and PMD effects.

To extend the evaluation beyond a pure transparent networks, an extension of the RWA has been proposed, able to support network dimensioning with regenerators, optical PMD compensators and electrical equalizers, optimizing resource utilization with an heuristic approach.

Different approaches have been evaluated and compared for modelling PMD, in order to elaborate suitable methods to include PMD in physical constraint based routing.

Among them, a semi-analytical method for 10 Gb/s NRZ signals has been developed basing on the numerical modelling (including all-orders PMD, with wave plates approach, already started in Y2004) to obtain a Q-factor penalty for different mean DGD and outage probability values. The results, that can be summarized a form suitable for fast computation, have been applied to routing computation algorithms in the transparent optical networks.

Furthermore, a PLI-aware WRA is developed to address QoS. Its effectiveness is assessed by means of Blocking Probability (BP) and Load Balance (LB) for different path establishment algorithms.

In terms of PLI receiver noise, Amplified Spontaneous Emission (ASE) accumulation, Cross-Phase Modulation (XPM) and Four Wave Mixing (FWM) are taken into account and their collective impact on system performance is studied. This was evaluated via analytically calculating the Q-factor of the signal. Analytic methods are fast and allow application in a dynamic network. They are also upgradeable and can be used in a scalable network. Moreover, due to the flexibility of the algorithm, any of the physical parameters can be used as an optimization variable in order to assess its impact in performance degradation at system and network level.

Two path establishment algorithms were used for that purpose and were compared in that respect. Traditionally, the path establishment decision is based on the 'shortest-cost-path' routing algorithm and the cost can be defined accordingly. When a connection request appears, the shortest cost path is calculated. At this point, a connection is blocked only if there is no possible route between the nodes. In D26, path establishment was based on two different algorithms depending on the 'cost' to be optimised: a) shortest path (SP) and b) shortest widest path (SWP). As the name implies SP seeks the path between two nodes that spans the least fibre length. SWP seeks the path that has maximum continuous (adjacent) available wavelengths and thus is least congested. Because of the nature of nonlinearities, cross channel effects are enhanced when many channels occupy the fibre. The SWP is looking for the least occupied path and indirectly for the one where the noise stemming from nonlinearities is minimized. No wavelength conversion or regeneration was considered. Furthermore no protection scheme was investigated at this point.

The aim of the contribution was to present the routing engine and investigate the impact of the physical layer characteristics on the blocking performance when a specific algorithm is used. In order to understand the impact of the algorithm choice depending on the specifications of the physical layer we assume three different kinds of physical layer. The methodology is equivalent to the layered approach. Three types of physical layers depending on the 'excess' impairments were assumed. The first type is OSNR limited, the second is nonlinearity limited and the third type includes both types of impairments.

It was proven that the physical layer type impacts the selection of the PLI aware WRA routing algorithm. When nonlinearities are considerable, the load balancing offered by SWP offers a better physical performance, however when ASE is accumulated the SP algorithm is performing better. When PLI awareness is introduced the network performance is expectedly degraded but physical performance in guaranteed. However depending on the excess impairments and the type of network specific algorithms are preferred. For example it was shown here that SP algorithm is better for ASE limited networks but SWP for nonlinearity limited. So the choice of algorithm is based on the physical layer type.

- Simulation engines

A major result of this activity is the comparison of different simulation methods, that have been developed. Network planning involves complex calculations, since many parameters and constraints contribute to the planning problem, to achieve a cost-efficient and physically stable design. Because of this complexity, we propose different modelling and algorithmic approaches. Meanwhile, these approaches have been transformed into software tools which are now available and provided by several partners of WP5.

As the simulator engines are developed for quite different purposes with quite different assumptions and require different computational resources, it was decided to give a tabulated overview over the various simulator engines making a stringent comparison easier.

As a rough discrimination of tools it is reasonable to split them up into

- tools for the planning and installation phase where the equipment placing is optimized and
- tools for dynamic path computation taking physical constraint based routing into account, in order to allow the network to efficiently add and remove connection on

demand. Here algorithms are proposed to solve the path computation problem at various levels of detail.

As a performance metric for comparison of different solutions overall network cost has been introduced.

- Cost model
Based on the node architecture proposals from WP6 we defined a cost metric for the physical layer to be able to optimize the network design regarding the equipment costs, and especially to draw conclusions where a transparent network approach is advantageous against an opague one.
The cost values have been contributed by various partners, based on their own internal data, as well as educated estimates where detailed information was not available for less mature components. The values refer to CAPEX only and are normalised to the cost of a 10 Gbit/s transponder suitable for transmission over a reach of 750 km. This normalisation should help to reduce the variability of cost data between different partners, as this partially removes the issue of different vendor discounts offered to customers.
The detailed tables listing the relative costs of transmission and switching components can be found in the related deliverable.

- Equipment placement
The following results are based on the DT reference network and use the 2005-2007 traffic scenarios. Under non-optimised conditions, considering all network links equipped with either 40- or 80-channel systems and using these resources as effective as possible in terms of number of used wavelengths and path lengths, the overall network costs are as listed in Table 14.

Table 14 - Results of network planning for the different traffic matrices

Year	2005	2006	2007
Total network cost	1254	1648	2104
Total network cost, mixed transponders	1089	1426	1762
Number of used wavelengths	33	48	70
Average link load	55 %	39 %	60 %
Number of lightpaths	226	315	478
Number of lightpaths > 750 km	20	38	50
Longest path	986 km	1097 km	1124 km
Average path length	439 km	455 km	455 km

It can be seen that only a low percentage of the light paths in all scenarios are longer than 750 km, and thus giving the possibility to use cheaper transponder technology according to the cost table, which could lead to a significant cost reduction by allowing a mix of transponders with 750 km and 1500 km reach in the network. However, this results in a reduced flexibility when it comes to possible future reconfigurations and dynamic light path set-ups. This is an example of the tradeoff between cost and flexibility encountered when planning a network.
Applying one particular optimisation algorithm and using for example the 2006 traffic scenario, and additionally taking into account that keeping at least 10% of the available wavelengths free in order to increase flexibility, leads to an optimised topology as can be seen in Figure 38 - Topology for the 2006 scenario with 10% of the wavelengths free

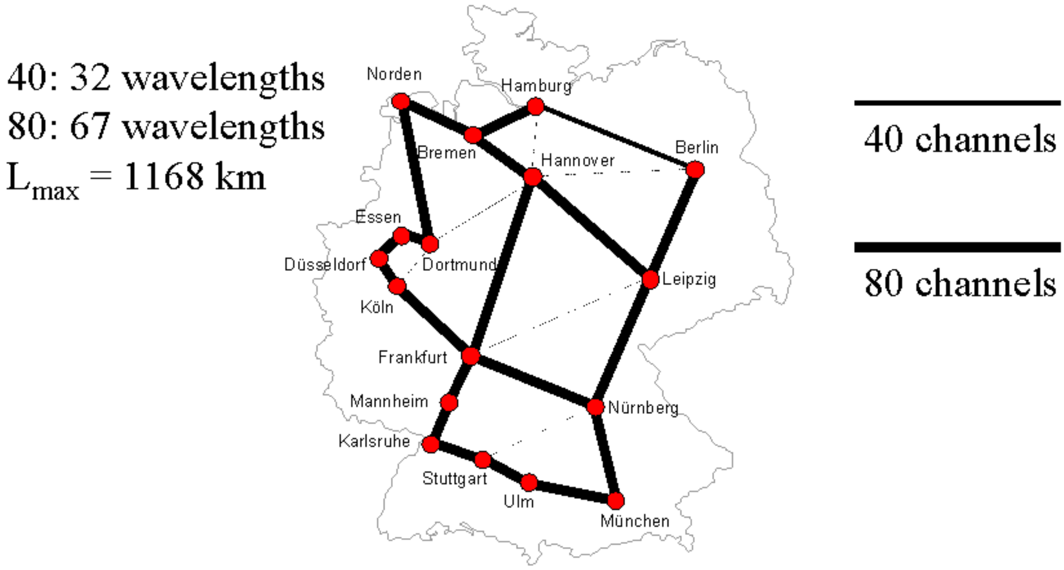


Figure 38 - Topology for the 2006 scenario with 10% of the wavelengths free

The network costs and statistics are presented in Table 15. For the cost values it is assumed that in the 2005 scenario, all links are equipped with 40-channel systems, while for the 2006 and 2007 scenarios, all links are equipped with 80-channel systems.

Table 15 - Results of network planning and optimisation for the different scenarios

Scenario	**2005 (opt)**	**2005 (10%)**	**2006 (opt)**	**2006 (10%)**	**2007 (opt)**	**2007 (10%)**
Total network cost	1150	1168	1454	1465	2001	2039
Total network cost, mixed transponders	991	1002	1266	1264	1660	1706
Number of used wavelengths	39	36	77	67	76	71
Average link load	72 %	67 %	64 %	62 %	72 %	67 %
Number of lightpaths	226	226	315	315	478	478
Number of lightpaths > 750 km	27	19	80	64	51	62
Longest path [km]	978	986	1168	1168	1092	1079
Average path length [km]	455	449	511	496	466	468

The relative cost difference between a cost-optimised solution and a solution where 10% of the wavelengths are kept free is in general very small. This implies that even when cost is the major concern the slightly higher price for extra flexibility is probably acceptable. In addition, the cost difference is reduced even further when a mix of different reach transponders is allowed, since the optimised solution requires more paths longer than 750 km.
Comparing the solutions when links are removed to the solutions for the full network we see that the cost savings that can be obtained by optimisation depends greatly on how much unused capacity exists for the full network, i.e. on the average link load. The largest cost reduction is obtained for the 2006 scenario where the average link load was low for the full network, since 80-channel systems were required even though the number of used wavelengths were only 48. In general it is clear that a trade-off exists between the cost and the flexibility of the network. Nevertheless, planning the network carefully is important in order to use resources as efficiently as possible, either to reduce cost or increase flexibility for future upgrades and dynamic reconfigurations.

D. Dynamic path computation

In dynamic networks, connections demand is a probabilistic process that has a connection inter-arrival time parameter and a connection duration parameter (holding time) after which the connection is released. The total number of connections in a network follows a stochastic process of setting-up and tearing-down a certain number of network connections during a finite period. This enables an analysis of the dynamics of the connection demands during the transitory phase (or upgrading phase where the demand dynamics have an overall growing average) and the steady-state phase (where the demand dynamics have a constant average). Although the traffic total volume in public networks on average has been shown to ever increase (but at a lower rate than during a pure transitory phase), considering the time scale enables the definition of the steady state regime: it can be defined as the state when the arrival rate is constant in a time-scale at least one order of magnitude longer than the mean duration of the connection.

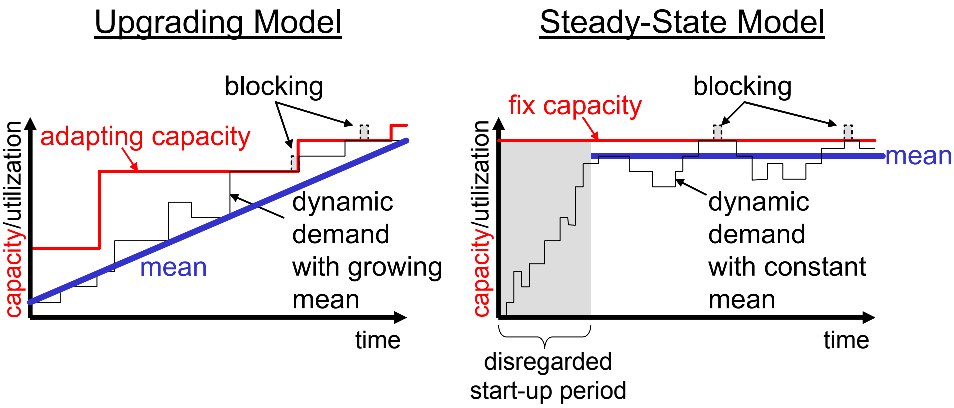


Figure 39 - The transitory (upgrading) model and the steady-state model

The steady-state model enables to evaluate algorithms without modelling the process of adapting capacity in the upgrading models, which is a complex operation process by itself. Thus we can concentrate on the evaluation of the path computation algorithms themselves, in a network with fix capacity. We can also assess the performance of future on-demand applications, where paths set up and tear down at an equivalent rate.

Therefore WP5 focuses on the steady state of a network and the blocking probability, as a measure impacting QoS, will be a function of the installed capacity and connections demand.
A flexible all-optical network has to support a number of feasible transparent paths between any two nodes generating or absorbing traffic. Clearly, the network will be more flexible as the number of feasible paths increases. However, there is a trade-off between network flexibility and network cost and therefore a balance should be found. The number of feasible paths crucially depends on the network topology and the strategy of the network operator.
A main objective in designing an all-optical network is to find not only network design rules, but also proper and efficient constraint routing algorithms that will ultimately be the ones used to determine which and how many transparent routes and paths are feasible in the network whilst still ensuring a cost-effective network.

- Routing engine

Besides the use of routing algorithms at network design time, to come to optimised network topologies, it is evident, that these algorithms need to be included into the network management system, to perform the wavelength routing in the network operation phase. A functional block diagram of such an inter-working is shown in Figure 40.

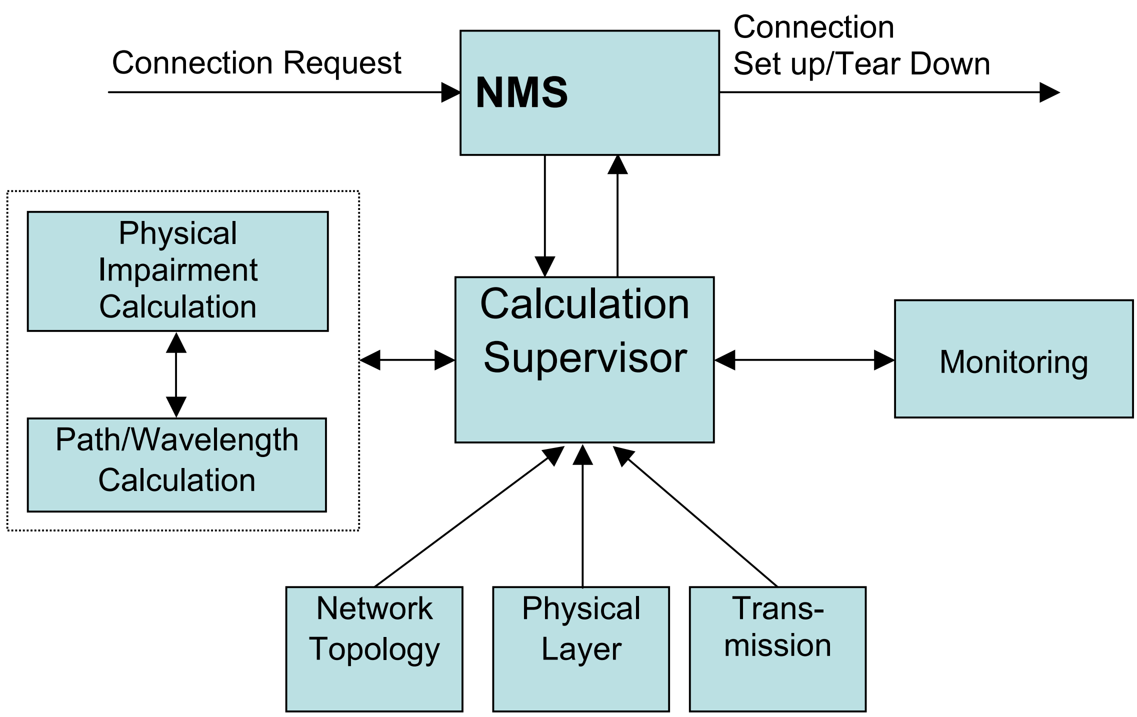


Figure 40 - Schematic of the routing engine

The requirements for the routing algorithms in the operation phase are significantly different from those at design time, especially with respect to calculation time. On the other hand results gained at design time can already be included into this system.
Within the work of WP5 an approach towards fast routing calculation has been developed, basically consisting of three steps: First, the wavelength-dependent transmission performance is assessed using a software tool for fast Q-factor calculation in transparent optical networks. Second, from the obtained Q-factors, linear constraints are derived for operationally simple use in dynamic path computation algorithms. Third, a dynamic path computation algorithm is modified to include the derived linear constraints and the results of this algorithm are compared in terms of blocking probability with other algorithms that do not consider physical constraints.
The results achieved suggest that feasible methods for constrained-based routing can be defined, being both operations-friendly and accurate enough to achieve low blocking.

E. Cost aware partitioning into transparent domains considering optical monitoring requirements
One major objective of WP5 has been to identify solutions and technologies for physical transmission in transparent optical networks, i.e.

- define and model the network elements of such structures for the physical network layer:
  - node architecture,
  - interfaces,
  - transmission formats;
- define optimisation criteria as input for network simulations,
- investigate the dynamic behaviour of those networks.

In particular, these studies lead to a substantial clarification of a network partition into generalised transparent islands. Practical and economical reasons exist at the outset, which naturally lean towards a network partition. They are the existence of different administrative domains (entities representing the extent of resources belonging to a single network player) and the operators’ needs to cope with different management domains (entities representing collections of managed objects grouped to meet organisational requirements according to geography, technology, policy or other structure). The stiffness of the original framework and the costs of network over-engineering have been eliminated thanks to a suitable hybrid node architecture, the network partitioning into different technology level areas, a clear definition of inner core network and the requirement of its transparent coverage. This evolved framework, based on multi-domain network management concepts, guarantees a flexible mix of technology levels and a better exploitation of transparency economies. If in specific cases no network partitioning criterion applies, the network itself is to be considered as a single transparent/translucent domain with one inner core diameter and a single technology choice. No issues of over-engineering rise in this case, since all subsets of the infrastructure would appear all the same (homogeneous network with uniform traffic).

Network partitioning is considered a future-proof approach, since it is in line with traffic increase forecasts, which are dominated not much by peer-to-peer services, but mostly broadcast services will be particularly important (e.g., for video applications). They will probably require a distributed set of servers, leaning again towards a traffic partition into different local areas, with a particularly efficient exploitation of cheaper optical technologies.

- Example for optical monitoring (OSNR Measurement)
In the area of performance monitoring experimental investigations have been performed on OSNR measurement (in collaboration with WP7).
The "true OSNR" measurement technique based on polarisation nulling is a very promising technology to obtain OSNR values in DWDM transmission systems even after optical add/drop operations. There are no real alternatives present at the moment able to perform “in-band” noise measurement. However, it does have limitations with respect to accuracy when effects are present which affect the polarisation state of the ASE noise. Further studies are required to determine the accuracy possible when using this technology in a specific system. For instance, the influence of the PDL of system components on the OSNR measurement accuracy could be simulated by a statistical approach of assuming many individual components which have a certain PDL and a certain ASE contribution, and random polarisation changes between these components. A maximum value for certain transmission experiments can be estimated. As a result, an estimation of the maximum error can be done based on the results presented in Figure 41.

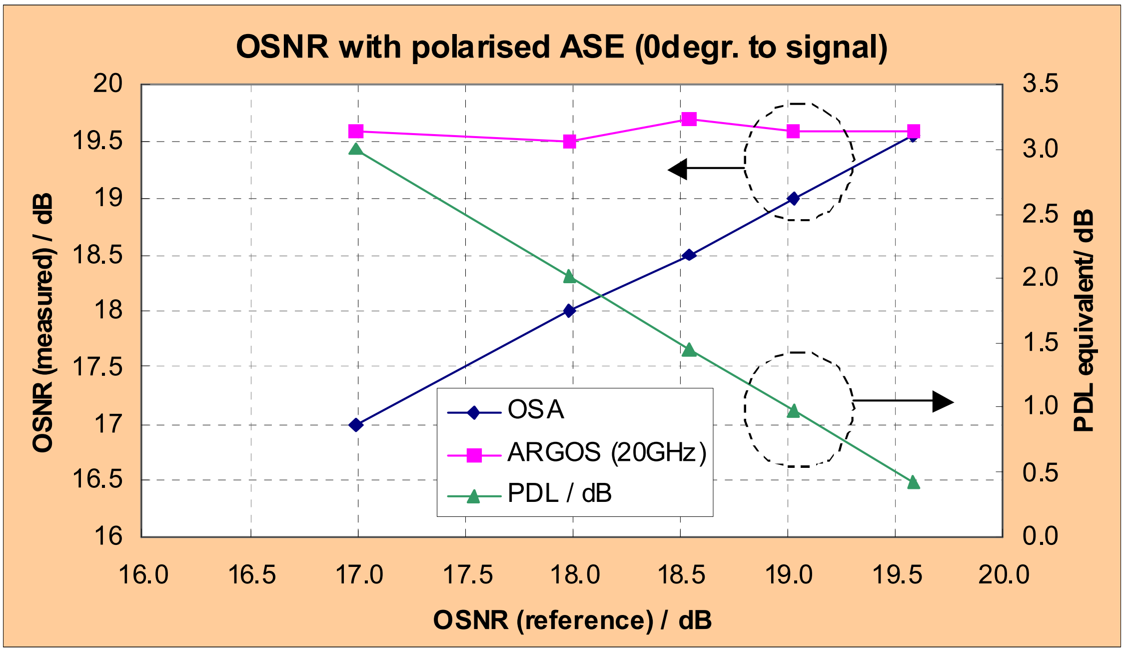


Figure 41 - Measurement results with partly polarised ASE. The polarised ASE fraction is in parallel to the signal polarisation. The "PDL equivalent" is the ratio of the polarised ASE to the un-polarized ASE in dB.

Although there are some problems to be solved concerning PMD and polarisation effects, the polarisation nulling method seems to be mature to be used as OSNR measurement equipment in optical networks. Since this technology has the potential to measure also the PMD this method could provide valuable information about the physical state of the individual wavelength within an optical network to the control plane.

3.6 WP6 Multi-service node architectures

3.6.1 Scope and state of the art

Fueled by the increasing Internet protocol (IP) traffic, the rollout of residential broadband and high-speed mobile services as well as the emerging demand for Ethernet-based private line and local area network (LAN) services, packet-oriented network traffic is continuously growing. To support the traffic growth, the prevalence of different packet-based services require for a packet-optimized transport layer which maintains the carrier-class OAM and resilience features traditional SDH offers. As network operators aim at improving their profitability by introducing new revenue generating services and managing their capital (CAPEX) and operational expenditures (OPEX), modular platform solutions are necessary. These reduce costs by an increased integration due to technology/layer convergence, lower power consumption/real estate and provide a simpler installation, operation and maintenance by extended plug-and-play features. The built-in scalability facilitates a future-proof growth in line with increasing traffic demands. Whilst private and business IP services are important in their own right, managed full- and fractional wavelength services, virtual private networks (VPNs) on layer 2 and the efficient transport of storage area network (SAN) protocols call for an independent transport infrastructure which is truly multi-service.

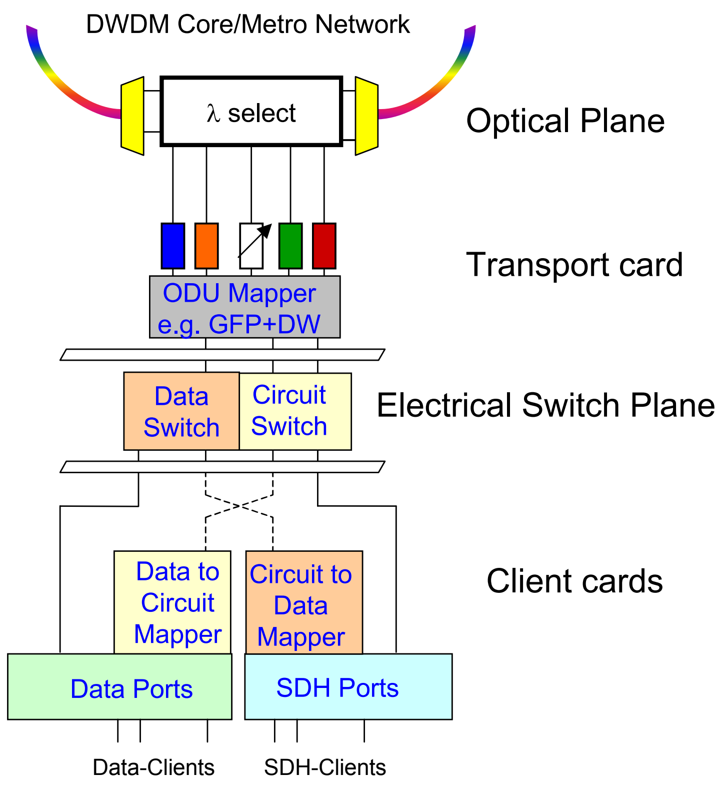


Figure 42 - Schematic view of the evolutionary node architecture

Today's metro and core networks predominantly use node architectures employing circuit switching in the electrical plane, on top of a static optical plane. In a typical network scenario, packet based data traffic is aggregated at the client interfaces and subsequently mapped into circuit switched transport technology and thus the client interface performs the appropriate data-over-SDH capabilities. Obviously these nodes are not capable to support future service demands, wherefore a node architecture evolution, capable to adapt to today's circuit to future's data centric traffic is necessary.

In the first evolutionary step of these node architectures (see Figure 42), hybrid switch planes including a circuit switch as well as a data switch plane will increase today's data aggregation and statistical multiplexing capabilities. In a further evolution towards a node architecture optimised for pre-dominantly data traffic, this node architecture can essentially migrate to a pure data switch plane, provided that the remaining problems such as carrier-class resilience and OAM features have been appropriately addressed. To be able to cope with traditional leased line services, the node architecture must include Circuit Emulating Services (CES). The evolution of these node architectures is indicated by the dashed lines from the mappers to the switches in Figure 42. As an example, today's state of the art technology to map packetised data into circuits is GFP. The produced circuit is consequently switched through the circuit switch. The hybrid node, in which both of the switching planes are available in parallel, will not use one of the client mappers (i.e. no "dashed" connections), whereas the node with only a data switch will need an SDH-to-data functionality.

Depending on client equipment and location, all these evolutionary steps of the network nodes will find their place in future networks - for example in network scenarios where the majority of the clients use traditional legacy equipment, next-generation SDH nodes might be implemented.

3.6.2 Objectives

Objective of WP6 was to define and investigate the multi-service/multi-layer nodes required to build such converged multi-service networks. WP6 had therefore the goal to break network level requirements down to implementation specific questions being addressed by the different activities in the workpackage. The workpackage translated network level aspects into requirements, specifications and prototype implementations for multi-service nodes on a system, subsystem and component level.

The main overall goals of WP6 were:

- to identify hybrid **multi-service**/multi-layer **node architectures** (including electrical packet layer – IP, electrical circuit layer – SDH/SONET/OTN, and advanced optical circuit layer – WDM including functionalities such as optical switching and wavelength conversion & regeneration) supporting the evolutionary network architectures resulting from WP 1;
- to evaluate and compare different node architectures with respect to parameters such as cost, performance, implementation complexity, switching granularities, scalability, balance between optics and electronics, active vs. passive configurations;
- to specify selected node architectures and implement selected functions on a laboratory prototype level (suited for demonstrations in WP 8) incorporating requirements from WP 1-5;
- to define requirements for **flexible client interfaces** and **adaptive transport interfaces** and to implement prototypes on a laboratory level;

3.6.3 Main activities

The main activities carried out by WP6 were reported in three deliverables: D8, D9 and D24.

- D8 "Specification of requirements for flexible client and adaptive transport interfaces". This deliverable included:
    - A high level description of the multi-layer/multi-service nodes, including an evolutionary development adapted to the network scenarios developed in WP1.
    - Definition of the functional requirements of the nodes.
    - An implementation example for the medium-/longterm-scenario.
    - A description of a commodity node as benchmark.
    - Definition of general interface requirements such as supported services, CP, MP, FCAPS and OAM functions, resilience, TE, needed protocol stacks.

    - Specific flexible client interface requirements such as supported protocols, bitrates, and transmission distances.
    - Specific adaptive transport interface requirements such as supported protocols, bitrates, transmission distances, adaptive receiver concepts, tolerance to transmission impairments and modulation formats.
- D9 "Specification of hybrid multi-service/multi-layer node architectures”. This deliverable included:
    - Mapping of network modes, services and related requirements from WP1 to node architectures supporting these.
    - Specification and comparison of data- and circuit switches covering the electrical and optical layers.
    - Implementation examples for respective line cards and switch cores.
    - Detailed implementation specification for a G.709 frame switch.
    - Discussion of resilience strategies for multi-layer nodes.
    - Detailed comparison of optical cross connect architectures.
    - Prospective studies on:
        - Realisation options for MEMS based OXC architectures.
        - Wavelength converters as building blocks for augmenting the optical layer functionality.
        - A nodal building block for optical power transient suppression.
        - Concepts for clock distribution and clock domain assignments in asynchronous frame switches.
        - Automatic bandwidth control for a dynamic SDH layer.
- D24 "Intermediate prototype implementation of selected node and interface functions”. This deliverable included:
    - A general definition of network modes and a description of their relationship with network services
    - A detailed technical and economic study of optical bypass architectures
    - Carrier class resilience and OAM strategies for packet-based network services
    - Further investigations on Automatic Bandwidth Control (ABC)
    - An implementation oriented study of the architecture of a Frame Aggregation Unit (FAU).
    - Discussion on optical 3 R regenerator architectures
    - A new theoretical model specifically developed to describe the transmission of DQPSK signals with co-propagating OOK and DQPSK channels.
    - The development and test of a Frame Aggregation Unit (FAU) for a G.709 frameswitch architecture, which can be used as a client interface board
    - A prototype unit for demonstration of a novel optical power transient suppression scheme in transparent optical networks and the experimental verification of the new concept
    - Transport interface prototypes for DPSK and DQPSK modulation and related tests, specifically targeting 40 Gb/s data rate

- o A transport interface prototype at 10 Gb/s incorporating a Maximum Likelihood Sequence Estimator in conjunction with cost-effective dispersion-tolerant modulation schemes and related tests
- o Experimental analyses on new architectures for optical regenerators and optical clock recovery schemes
- o 40 Gb/s tuneable dispersion compensator tests

In addition, further prototyping and trial activities accomplished after release of D24 were reported in D23 of WP3 and D35 of WP8.

3.6.4 Major results

In the first year of the project, WP6 formed the framework by introducing the scope of the workpackage and the terminology used. As such, it constituted the foundation and reference for all further work being carried out in WP6. Further on it analysed and defined multi-service/multi-layer node architectures that can meet the challenges of emerging data-centric networks and respond to the requirements defined by the network-level workpackages. Specifically WP6 provided the requirements for flexible client and adaptive transport interfaces for the multi-layer/multi-service nodes of a NOBEL network and outlined functional requirements of multi-layer/multi-service node architectures.

Based on the technical achievements in the first year of the project, in the second year WP6 concentrated on investigating and detailing the implementation options for the multi-service/multi-layer nodes and their respective interfaces, that corresponded to the specifications provided in the first year.

The following sections will summarize these results.

3.6.4.1 Network modes

Required to address the long-term architectures and visions of network operators, the achievements included a description of the architectural considerations that are important when designing a multi-layer/multi-service node as described by NOBEL WP6. It was described how such a multi-layer/multi-service node could fit into a converged network architecture vision and detailed how QoS and protection and resiliency could be provided. This is an important requirement on the design of a multi-layer/multi-service node because the multi-layer/multi-service node architecture will be critical to achieving the ambition of operators (especially incumbents) to rationalise their current portfolio of network platforms and converge them onto a single network platform capable of delivering a full portfolio of services.

A properly specified and well constrained co-ps mode would be ideally be used to multiplex several higher layer network link connections onto a single lower layer co-cs trail while guaranteeing the QoS metrics demanded by higher layers and services. A co-ps mode capable of emulating CBR co-cs trails would offer network operators a significant amount of flexibility in their network and the design of a particular multi-layer/multi-service node. The co-ps mode could also be used to statistically multiplex several client layers (or applications) onto a co-ps trail which in turn may be multiplexed onto a co-cs trail. Such statistical multiplexing allows operators to gain significant statistical gains within their network by requiring them to deploy less bandwidth than would otherwise be necessary.

Harmonisation between client and server layer protection mechanisms is required in a multi-layer/multi-service node because protection mechanisms (especially the timers used before triggering a protection event) in one layer network in the network stack may impact other layer networks in the same network stack. If the protection mechanisms in the client layer are triggered too fast then short breaks or short faults in the server layer, which the server layer could repair itself, will trigger unnecessary protection events in the affected client layer. Therefore, in general, protection should be performed fastest at the bottom of the network stack (the duct) and slowest at top of the network stack (the application/service itself) in order to avoid unnecessary protection events being triggered.

Conclusions from this work include the necessity for the multi-layer/multi-service node described by WP6 to support a co-ps layer that is able to allow operators to statisically multiplex high layer clients whilst also providing guaranteed bandwidth of QoS. Such a multi-layer/multi-service node must also be capable of harmonising the protection mechanisms used at each layer that it implements so that it is capable of triggering protection at the most appropriate and cost effective layer.

3.6.4.2 Implementation Aspects for Resilience on the Packet Layer

Without additional resilience mechanisms, circuit-oriented/packet switched networks suffer from a lack of quality of service with respect to new services. Circuit-oriented/circuit-switched networks such as SDH networks are known for delivering a very high quality for a long time. So, learning from SDH became obvious for packed based Ethernet/MPLS networks. In order to achieve a similar level of resilience and network availability, well known SDH protection mechanisms have been examined and proposed for their introduction into Ethernet/MPLS-based packet networks. SDH protection mechanisms (MSP, SNCP and MSSPRing) offer switching times of about 50 ms. WP6 analysed content and status of the ongoing standardisation activities in Ethernet/MPLS resilience and OAM. It mapped MPLS-based resilience mechanisms to their SDH counterparts. As also the OAM functionality required for fault isolation and communication is absent in native MPLS networks, MPLS OAM packets have been introduced to provide the missing functionality.

In particular, Connectivity Verification (CV), Fast Failure Detection (FFD), Forward Defect Indication (FDI) and Backward Defect Indication (BDI) packets are needed for defect identification and alarm suppression rules. OAM techniques have to be applied end to end on a per LSP basis as well as the layering concept of ITU-T Recommendation G.805 has to be taken into account. Client/Server relationships have to be obeyed to build LSP sub networks. Server Signal Fails (SSF) are used to inform the client layer of some defect of its server layer, e.g. for alarm suppression and consequent action constraints.

With respect to SDH, two types of protection switching architectures (1+1 and 1:1) have been mapped to label switched path MPLS networks, another one (1+1 packet protection) has been developed from scratch. OAM packets (CV/FFD) are used to detect defects of the working and protection path. In order to achieve a reasonable availability, the protection path has to be monitored all the time as well.
Two restoration mechanisms have been examined, LSP Restoration and Fast Re-Route (FRR). They both guarantee reliable networks according to their specific reality and requirements. LSP Restoration is a method of global repair. The result was that with using an alternative LSP tunnel (either pre-established or established on demand) global repair of some link or node fault is very easy. FRR has to be the choice, if due to higher timing requirements local repair is needed.

Of course, best use of available network resources is if 1:1 protection schemes are implemented. In order to achieve dual ended switching a protocol for it has to be defined. It is suggested to use the K1/K2 protocol of the SDH multiplex section protection for it. So, this protocol hast to be transported using the LSP OAM packets for it. The advantage is, that this protocol is widely used and therefore very well tested.

Packet 1+1 path protection provides a new packet level protection service. It provides a very fast recovering from any failure instantaneously and transparently, but the price for it is a sophisticated and complex algorithm to be implemented. So, in terms of restoration time, this can be characterised as an instantaneous recovery from a failure since there is no need to detect, notify and switch to a protection path explicitly.

3.6.4.3 Optical plane & adaptive transport interfaces

Optical bypass architectures

Several specific aspects of optical bypass architectures were analysed. The architectures which were investigated span multi-fibre junction node based on commercially available components, multi-granular (fibre, waveband, wavelength) cross-connects able to cope with an increased traffic demand in the future and modular broadcast & select architectures incorporating wavelength conversion to prevent blocking in network scenarios with increased dynamic on the optical layer.

Multi-granular optical plane architectures

On one hand, the use of dense wavelength division multiplexing (DWDM) offers efficient transport of several Terabit/s per single fibre. The high level of aggregation, on the other hand, increases the amount of processing effort for access to a single piece of information, e.g. an IP packet. The tremendous difference in information density between the fibre and packet granularity levels calls for an efficient and flexible integrated optical network switching architecture. Strategies on this issue include optical bypass and the introduction of additional intermediate granularity levels, e.g. wavebands, optical bursts.

Multi-granular switching tries to prevent serious waste of bandwidth as a potential result of mismatched granularity between large and fixed wavelength channels and traffic flows. In addition, multi-granular switching aims at increasing the limited scalability of wavelength-routed networks.

The concept of a multi-granular OXC allows to handle different granularities simultaneously. In addition to the usual granularity levels of fibre and wavelength channel an intermediate level of wavebands has been introduced. For waveband switching (WBS) several wavelengths are grouped together and switched as an entity whenever possible. Whereas the main advantage of the optical bypass is that the electronic switch or router can be reduced in size, because it has to process only a part of the traffic, the purpose of multi-granular OXCs is, to reduce the overall size of the bypass cross-connect in order to further reduce cost. In general it is cost efficient, when as much traffic as possible is switched on the coarser granularity. The optimisation of multi-granular nodes depends on the traffic characteristics, network topology, and MG-OXC node architecture

Three different multi-granular OXC architectures without λ-conversion have been compared with respect to a complexity function, based essentially on component count. A simple transparent OXC without wavelength conversion switching only on wavelength level was chosen as reference.

Two main architectures have been identified. These are the single-layer multi-granular OXC and the hierarchical multi-granular OXC.

In the single-layer MG-OXC (SL-MG-OXC) architecture the incoming traffic flow is divided into two streams to the wavelength (λ) and waveband (WB) level, and switched on the wavelength and waveband level respectively. At each layer local traffic can be added or dropped.

In the hierarchical MG-OXC (H-MG-OXC) architecture all incoming traffic flows into the waveband (WB) switch, a part of this traffic is handed over to the wavelength switch, where it is processed and passed back to the WB-layer switch. Local traffic is added or dropped at each layer for this architecture too.

The hierarchical structure was further differentiated in an architecture in which each wavelength de/multiplexer only operates in a single waveband, and in a more flexible architecture in which cyclic de/multiplexers are used which are capable to in all or several wavebands.

Besides the detailed results, the main outcome can be exemplified, by comparing the 3 OXC architectures on the basis of three typical node characteristics (Gain is essentially defined as percentage of reduction of component count):

For an <u>“Add/drop node”</u> (80% add/drop capacity at the λ-level and 20% switching capacity at the WB-level) the gain is small ($\leq$10%) for SL-MG-OXC and H-MG-OXC architectures. The H-MG-OXC with cyclic MUX is more complex compared to the reference architecture. These poor values are explained with the low degree of waveband switching combined with the additional overhead of multi-granular architectures compared to the single layer approach of the reference architecture.

For a "Standard node" (50% add/drop capacity at the λ-level and 50% switching capacity at the WB-level) a moderate gain can be achieved for the SL-MG-OXC, and the H-MG-OXC architecture, but for the H-MG-OXC/ with cyclic MUX architecture either gain or loss can result, depending on the switch fabric size.

For the "Transit node" (20% add/drop capacity at the λ-level and 80% switching capacity at the WB-level) the gain is substantial for all architectures (up to 75% for the H-MG-OXC), caused by the large amount of waveband switching. For the H-MG-OXC with cyclic MUX the gain is somewhat smaller, but this is compensated by the increased flexibility.

As hierarchical multi-granular concepts seem to offer limited scalability, NOBEL also considers a specific non-hierarchical approach to still benefit from the advantages multi-granular architectures can offer while achieving high scalability. The basic proposed node architecture is based on two cyclic NxN (N the number of fibre ports) AWGs and N*M (M the number of wavelengths per fibre) wavelength converters providing optical bypass, waveband add/drop for core-metro connectivity, and wavelength add/drop functions. These functions are addressed in more detail below.

Optical bypass

This function is a corollary of the ability to one-to-one switch any input fibre (or waveband) to its complementary output fibre (or waveband) by applying the wavelength converters involved as O-O regenerators only, i.e. "conversion" to the same wavelength.

Core-metro connectivity

Application of waveband filters or full (de)multiplexers enables direct access to individual wavebands. Metro networks can then be connected via one or more wavebands to the core network. This allows for a more efficient allocation of fibre resources. In addition, "local" traffic between metro networks connected to the same core node can be supported at a waveband granularity level as well, and combined with waveband grooming this will save on processing costs.

Add/drop functions

The add/drop ports created by application of wavelength (de)multiplexers can be used in many ways. In essence, any combination of optical and electrical switching, routing functions, and O-E-O regeneration can be considered. Depending on the network dimension, O-E-O regeneration might be required at certain core nodes to patch up the optical signals that have already bypassed the maximum cascadeable number of nodes.

Modular broadcast & select OXC architectures

A crucial step in enabling transparent optical networks is the assessment of cost-effectiveness of optical switching architectures. The cost of an OXC depends on the number of switching elements to be used i.e. on the particular architecture and the corresponding switching technology should there be different reconfiguration speeds to choose from.

The essence of the adopted approach here is that because it is recognized that the highest degree of modularity is requested in order to curb the introductory cost, all migration steps should be pre-planned thoroughly and studied well in advance. It is of paramount importance to ensure continuity and compatibility through successive migration steps. This secures that neither physical layer nor networking performance degradation would occur when successive steps are introduced.

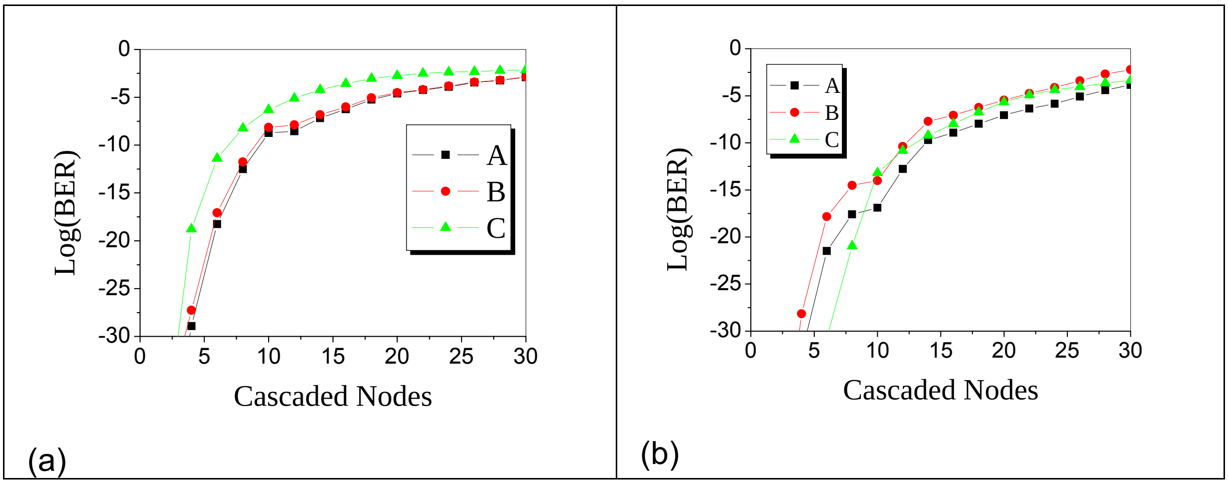


Figure 43 - The BER curves v. number of nodes for two different technologies of O-E-O WCs, parameterised for the three configurations of the wavelength conversion module.

Towards this objective a modular architecture was proposed during the first year of the project. This starts with a basic broadcast and select architecture that can be enhanced by additional modules to include limited wavelength conversion and finally to evolve into a fully reconfigurable switch. To evaluate these architectures, several simulations were performed, using analytical and numerical methods, of numerous combinations of modules and components. Specifically, different OOO and OEO technologies were examined for several variants of the modular architecture, and several configurations, in terms of number of wavelengths and OXC ports, for each variant. The results were compared in order to evaluate the number of OXC that can be cascaded for each case and thus estimate its utility. As an example, a subset of the obtained results for one of the architectures is shown in Figure 43 - .

Today, it is well established that the values of both the local and the total dispersion of a given link, strongly influence the strength of the fibre non-linearities. Therefore, with suitably chosen values, the system performance bounces between dispersion limited and nonlinearity limited. In point-to-point links, this dispersion management is performed either at the transmitting or at the receiving end by means of all-optical devices (e.g. Fibre Bragg Gratings, FBG) or electronic systems (modulation format, electronic equalizers etc). However, these techniques could not simply be extended in multi-hop, multi-link all-optical networks.

For this purpose, a modification of the basic modular architecture described earlier was proposed, that not only switches wavelength channels between input/output fibres but it is also able to perform the corresponding adjustments to the dispersion values in order to reduce the effect of nonlinearities in multi-hop links. This allows operating a given system at higher channel power, which in turn improves the performance of OSNR limited systems. This is done separately for each channel, to account for the individual transmission conditions that a channel will have met when transported via different paths through a transparent optical network.

Multi fibre junction nodes: a cost analysis

A detailed cost comparison, taking into account the complete architectures has been carried out by comparing three different architectures:

- A patch panel architecture with a static optical plane
- A broadcast & select architecture based on wavelength blockers
- A broadcast & select architecture incorporating Wavelength-Selective-Switches

The two latter ones offer an automatically reconfigurable optical plane and hence offer benefits in operational expenditures (OPEX) compared to a simple patch panel, as e.g. remote control, optical restoration etc. could be applied. As OPEX benefits are generally difficult to quantify, D24 focused on benefits in capital expenditure (CAPEX). However, it should be noted that as OPEX in typical networks can well equal 5 times the CAPEX, architectures which are slightly worse in CAPEX may still be advantageous when the total cost of ownership including OPEX is considered. Further assumptions used in the cost comparison have been a 50 % add-drop-ratio and a fixed configuration of each node architecture with respect to the nodal degree (i.e. number of fibre pairs at the node). To make the nodes suitable for core networks facilitating

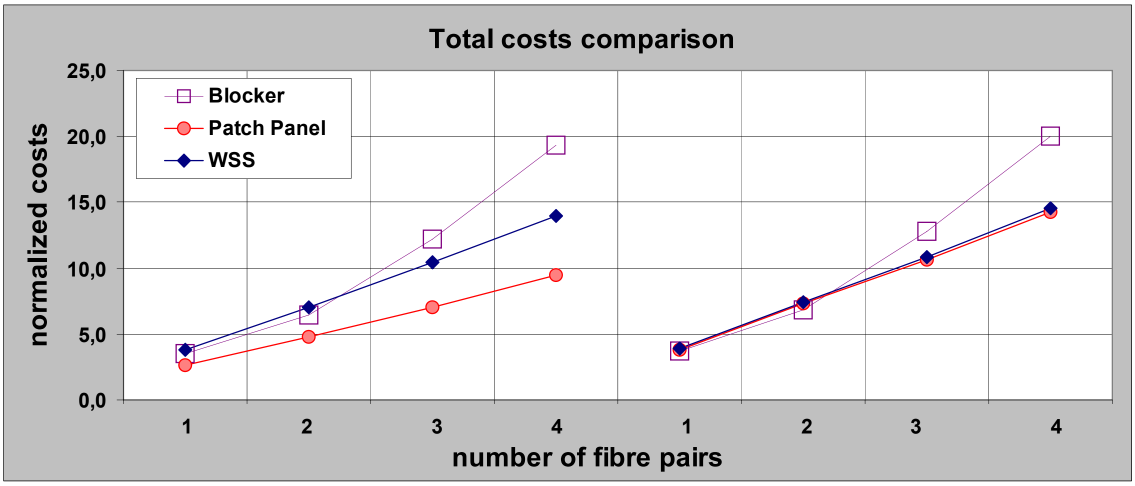


Figure 44 - Total cost comparison showing the scalability, for fibre pairs growing from 2 to 4, plotted for 8 channels (left side) and 40 channels (right side).

transparent transmission over extended long-haul distances, a per channel power levelling function was assumed to be present in each node.

Figure 44 - shows the cost comparison (costs normalized to the costs of a wavelength blocker) of the three architectures for two system capacity utilizations: a low capacity system with only 8 channels per fibre (left side) and a system with 40 channels per fibre (right side). It can be seen that in case of the low capacity system, the patch panel architecture offers the most cost effective optical bypass solution (i.e. lowest first-in costs). At 40 channels the cost advantaged of the patch panel solution shrinks compared to the more sophisticated blocker and WSS based architectures, not considering any additional OPEX benefit these latter architectures exhibit. The blocker based architecture is well suited for OADM nodes with a fibre degree of 2. The WSS architecture is more advantageous at higher fibre degrees due to the fact that the wavelength selective switch costs grow linearly with the fibre degree whereas they grow quadratically for the wavelength blockers.

Selective node functions enabling transparent optical networks

Key optical subsystems were proposed and demonstrated within WP6. They are particularly related to the transparent optical node that is envisaged in medium and long-term scenarios. These subsystems are:

1. **a novel type of optical signal regenerator**: it can be implemented in the node to reshape the signal with no further OEO conversion, it is protocol-agnostic, intrinsically stable (i.e. requires no interferometric balance), not polarization dependent, and furthermore could be potentially realized into a single chip
2. **a novel scheme for the stabilization of the node optical amplifiers**; it is needed to prevent the dramatic propagation of link faults throughout a transparent optical network; it does not affect the structure of the amplifiers, neither decrease their gain; it has been demonstrated using commonly available low-cost components;
3. **implementation of a 40 Gbit/s receiver including a tuneable dispersion compensator** (TDC); a TDC is needed for various modulation formats at 40 Gbit/s in order to compensate for dispersion variations with temperature and, furthermore, in a reconfigurable network, when the accumulated dispersion changes depending on the

signal path, which means that a TDC might be needed even at lower bitrates. The TDC used for the implementation was based on a temperature controlled fiber Bragg grating.

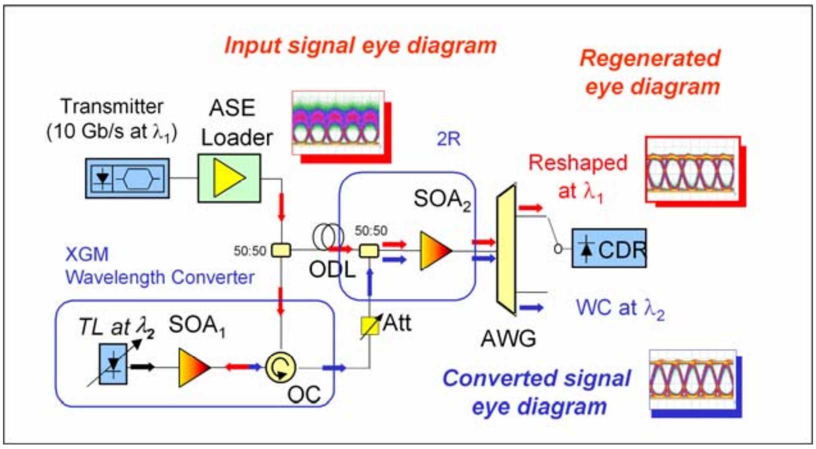


Figure 45 - Scheme for all-optical reshaping of the signal. Eye diagrams refer to input signal, output signal at the original wavelength and wavelength-converted signal.

The signal **optical regenerator** implements optical reshaping (2R) and it is realised by combining nonlinear gain modulation effects into two Semiconductor Optical Amplifiers (SOAs). The scheme is illustrated in Figure 45 . Here a noisy signal is intentionally produced by adding ASE noise over a 10 Gb/s signal. This signal is split in two parts. A first part is used to produce an inverted copy, by countepropagating Cross Gain Modulation in a SOA (namely SOA1, in the lower left corner). The other part of the input signal is then sent to a second SOA (SOA2, in the center of the figure), where it experiences all-optical reshaping. This last effect can only be obtained if in SOA2 the input signal propagates together with its inverted copy, i.e. the one produced in the first stage, and if these two signals have comparable delay, so that at SOA2 input a roughly constant power is obtained. The scheme offers intrinsic stability, as it is not polarisation sensitive neither requires sub-wavelnegth stability (as in any interferometric scheme). It provides reshaping without changing the original wavelength, which is not usual for 2R regenerators, and, as a further possible option, also produces a high quality additional wavelength-converted signal (at λ_2).

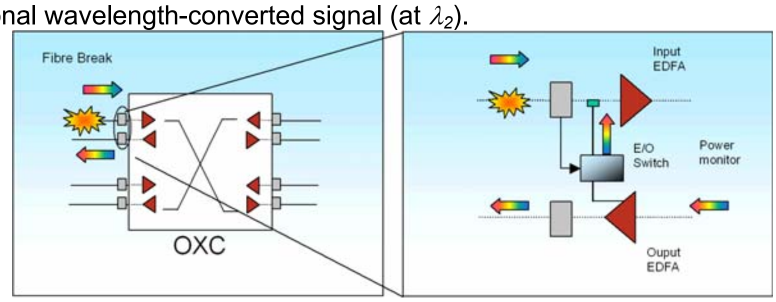


Figure 46 - Scheme of the stabilization technique based on channel replacement

The **optical amplifier stabilization** is obtained by cost-effective means that exploit the bidirectional symmetry of the circuit-switched lightpaths (Figure 46 -). Input/output ports are paired according to this symmetry, so that as traffic suddenly drops at one input port (due to a fibre cut), a small power fraction of the counterpropagating traffic is redirected to the input port to replace the missing channels. This stabilises all survived lightpaths in the network, even the disjoint ones. The replacement circuitry was developed in the project, set-up in the laboratory and tested in a complex experiment emulating a network scenario with several nodes. The results show that the technique indeed is a viable and cost effective option compared to more complex stabilisation schemes and has a number of unique advantages:. It does not reduce the gain of the amplifiers in normal operation, it does not requires complex electronics and is the only solution that prevents spectral reconfiguration effects.

The **receiver incorporating the TDC** was used in a set of field transmission experiments at 40 Gbit/s. The target of the experiments was to verify and compare the performance of the Alternate-Phase Return-to-Zero (APRZ) and the Carrier Suppressed Return to Zero (CSRZ) modulation formats through a fibre link designed for transmission at 10 Gbit/s.
In order to automatically control a TDC, a method for obtaining a feedback signal by detecting the accumulated dispersion is needed. It was investigated, both by simulations and experiments, methods for obtaining a feedback signal based on filtering out different spectral components of the received signal. As algorithms for controlling the TDC based on the described feedback signals depend on properties of the transmitter such as the modulation format, it was proposed a method for using the TDC to gain information about the modulation format and to decide how to control the TDC.

In addition to the experimental and implementation work, a theoretical study on the impact on system performance of group delay ripple (GDR) in fiber gratings was carried out, resulting in the proposal of a newproposed figure-of-merit for these devices. The figure-of-merit allows for a simple method to predict the signal degrading effect of the grating.

Implementation related results on robust transport interfaces

Transparent optical networks are requiring highly robust interfaces to linear and nonlinear transmission impairments like e.g. OSNR degradations, chromatic dispersion (CD), self-phase-modulation (SPM) and cross-phase-modulation (XPM). Robustness can be achieved either by e.g. electronic equalizers, forward error correction (FEC) schemes, pre-distortion at the transmitter or by sophisticated modulation formats, less sensible to transmission impairments as today's state-of-the-art formats NRZ and RZ. The relatively cheap electronics for equalizers are attractive realisations especially for metro systems with limited transparency, but electronic compensation often has the drawback that speed limitation don't allow the application of these techniques for high speed transmission systems at 40 Gb/s or beyond. These high speed system will be realised in core-networks, where it will be often the case that existing systems at e.g. 10 Gb/s will have to be upgraded to higher bitrates without changes of the infrastructure like e.g. MUX's/DEMUX's or dispersion compensation schemes. Therefore both, adaptive transport interfaces with equalizers and/or sophisticated modulation formats are needed for the network nodes supporting the infrastructure of future networks, which are aligned to the NOBEL vision.

This section summarizes the results and realisations of interface prototypes, both incorporating advanced modulation formats or electronic equalizers.

With respect to modulation formats two kinds of prototypes have been realized: a 10 Gbaud (NRZ/RZ)-DPSK (selectable) and RZ-DQPSK interface, where the latter has been upgraded to 20 Gbaud (see Figure 47). With the (NRZ/RZ)-DPSK interface performance tests have been carried out including back-to-back sensitivity, PMD and dispersion tolerance. Here the RZ-DPSK interface has shown the expected higher performance compared to NRZ-DPSK. With respect to the RZ-DQPSK interface a detailed set-up description has been given and the inherent stability issues have been discussed.

Figure 47 - Photos of the assembled 21.5 Gbaud RZ-DQPSK transmitter and receiver

Since there is no optimal modulation format for all applications and conditions, the mixed operation of phase and intensity modulation formats is an important option for an optimized system approach as well as for migration scenarios. It has therefore been analysed experimentally how co-propagating OOK modulated channels influence DPSK and DQPSK channels. From the studies it can be concluded that the phase modulated signals can experience a severe performance degradation due to XPM by the OOK-neighbours. To analyse this effect further a new theoretical model was developed. Results generated with the mode are shown in Figure 48 - in comparison with experimental results. It can be seen that the theoretical model agrees very well with the experimental results and therefore allows an accurate estimation of the performance of systems with mixed modulation formats.

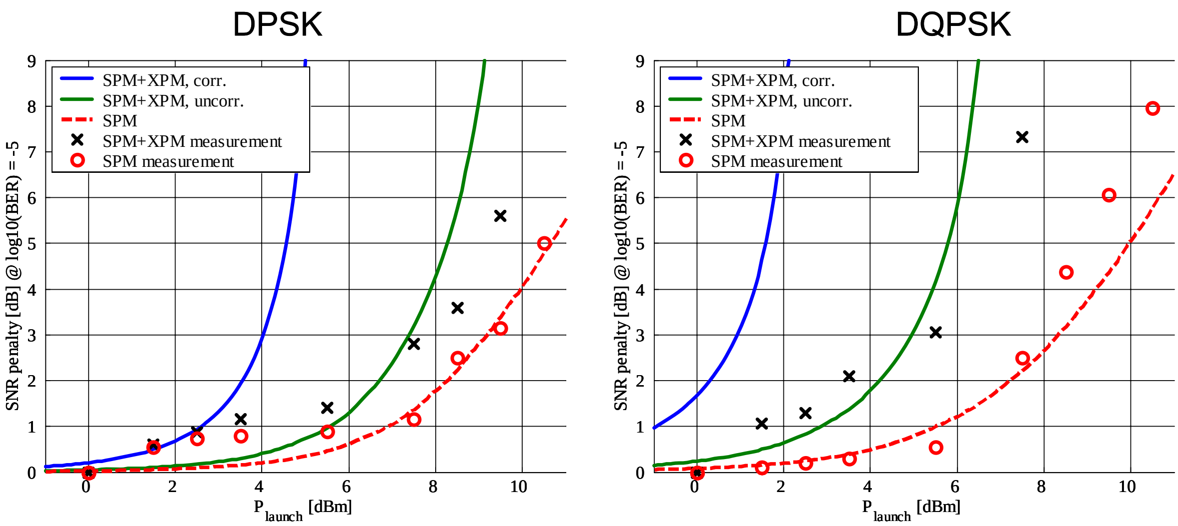


Figure 48 - Comparison of experiments and simulations for 10 Gbaud DPSK and DQPSK channels in a DWDM system with 10 Gb/s IM neighbours

An adaptive transport interface prototype incorporating a Maximum Likelihood Sequence Estimator (MLSE) has also been developed and tested. The performance improvement for several modulation formats has been verified. Namely NRZ, Optical Duobinary transmitters (ODB) have been compared with respect to their dispersion tolerance with receivers with and without and MLSE. In both cases a significant improvement of about 1000 ps/nm of dispersion tolerance was found. Specifically the ODB modulation format, with a transmission distance of 250 km without any dispersion compensation, has shown its suitability for cost-effective applications in metro/regional optical networks.

Cost effective transport platforms for metro regional networks will be a special focus of the research activities in phase 2 of NOBEL starting 2006. Although sophisticated modulation formats like DQPSK or ODB show, a significantly increased tolerance to transmission impairments compared to the today standard NRZ-format, they have the drawback of complex and costly transmitter and sometimes also receiver set-ups. Generally these transmitter techniques require, as for long-haul NRZ transmitters, costly external modulators which in addition don't allow optimized footprint solutions for the systems, leading to non cost optimized solutions for optical systems at 10 Gb/s. To overcome these drawbacks directly modulated lasers or lasers with integrated electro-absorption modulators are attractive candidates in future optical networks.

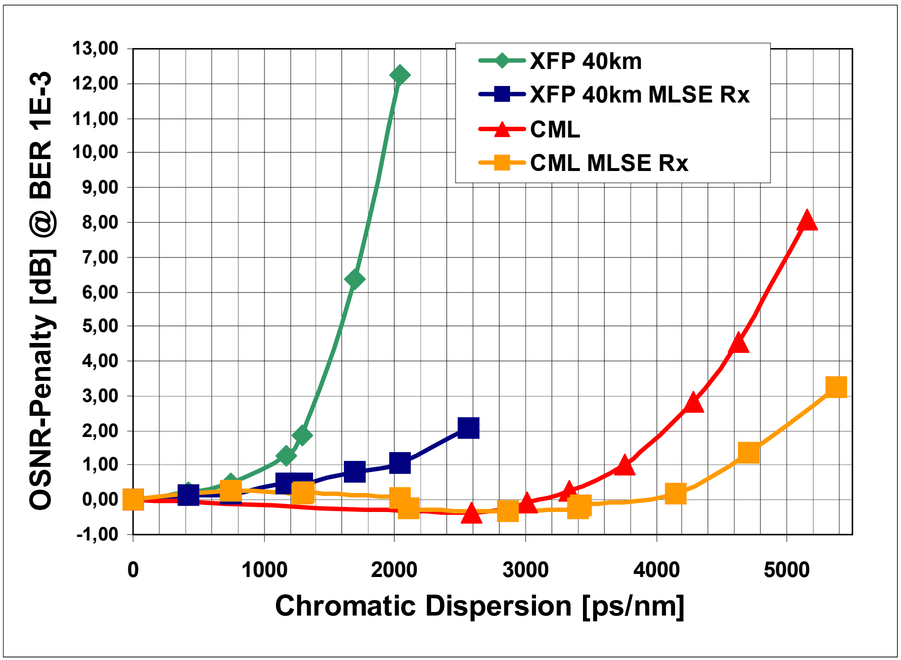


Figure 49 - Dispersion tolerance of “cheap” MZ modulator-less transmitters with MLSE

Figure 49 - shows first measurements carried out with a standard 40 km XFP module and a Chirped Managed Laser (CML) and receivers with and without a MLSE. Also here the chromatic dispersion tolerance is significantly improved by the MLSE and for the CML a superior transmission distance of about 300 km has been achieved, without any dispersion compensation fiber. Optimizing the footprint e.g. by building XFP modules with integrated CML and MLSE, but also the evaluation of other solutions, like e.g. pre-distortion techniques and equalizer techniques will be part of the work of the next phase of the project for enabling cost effective metro/regional optical transport platforms in the future.

3.6.4.4 Electrical plane & flexible client interfaces

Finally we present result related to the electrical plane and flexible client interfaces of the multi-layer/multi-service node architecture. In the transport layer framework of the G.709 Frame Switch architecture a prototype of the Frame Aggregation Unit, a key component was developed, produced and validated by laboratory tests. Constraints of the future transport network service of automatic bandwidth adaptation were identified, the impact of system parameters was evaluated and application scenarios were selected.

G.709 Frame Switch Architecture

Based on the detailed theoretical investigations of the G.709 Frame Switch architecture in WP3 a hardware prototype of one of the key components, the Frame Aggregation Unit (FAU), was realised under the umbrella of WP6. The basic idea of this concept is to aggregate client packets into equally sized containers at core network ingress. This is performed in a so called Frame Aggregation Unit. As a container format the G.709 frame was chosen. The frames then are forwarded to a Frame Switch where, in contrast to current ITU-T G.709 standard, each individual G.709 frame is switched.

The main requirements of the FAU are: Firstly, it has to classify the frames according to destination address and service class. Secondly, the FAU will aggregate homogenous classes of service into each frame and last but not least, it has to forward the frames. Any switching functions for both client packets and G.709 frames are performed either on router side or within the G.709 Frame Switch itself.

According to these requirements the FAU has to fit the following functions:

- Termination of Gigabit Ethernet client signals
- Termination of 10Gigabit Ethernet client signals
- Classification of client packets into destination and service classes
- Buffering of packets
- Mapping of packets into ODU2 structure
- Termination of OTU2 streams

To fulfil the functionality the individual components were selected carefully. As an example, a XILINX FPGA was chosen due to its flexibility and our long experience with this technology. During the definition phase the Virtex-IIPro technology was state-of-the-art and was selected therefore.

At a first glance the number of circuits is relatively low and the layout seems to be simple. But the PCB design was very challenging due to the high pin count in conjunction with high restrictions for the geometry of the traces. Especially, this became very critical for the FPGA/RAM interface. Furthermore, the transmission lines between the FPGA and the optical Gigabit Ethernet interfaces are difficult to design, too, due to the data rates in the gigabit range.

There were a various layout restrictions which could only be handled in a close co-operation among circuit and layout designer but nevertheless, manual routing was required. Of course, there are some automatic tools on the market to do this partly, but this would lead to expensive investments in tools and still some manual refinement would be needed. With detailed planning and accurate dimensioning / tracing we were able to meet all requirements.

The board size is 233 x 280 mm according to the Double-Europe-Format. Blind holes as well as buried vias were used due to the requirements given by both impedance controlled lines and the multitude of lines.

Figure 50 shows the front view of the final board. The FPGA is located underneath the fan, the memory module resides above the FPGA, power supply is arranged down to the right and the Ethernet interfaces are shown at left hand side. The backside of the board mainly contains the G.709 interfaces (one interface is partly visible at top left above the first Ethernet interface).

In summary, we have successfully designed, build and tested a hardware prototype of one of the key components, namely the FAU, of the G.709 Frame Switching concept. All building blocks were integrated on a single test board and an error-free operation of the key building blocks could be demonstrated.

But the design and manufacturing of such a board is still very complex making the board expensive. Hence, advanced solutions have to be investigated in the future. One of the drawbacks of this solution is the necessity to demultiplex most of the incoming signals due to the limited processing speed of the used components resulting in a huge amount of parallel busses which have to be routed across the board.

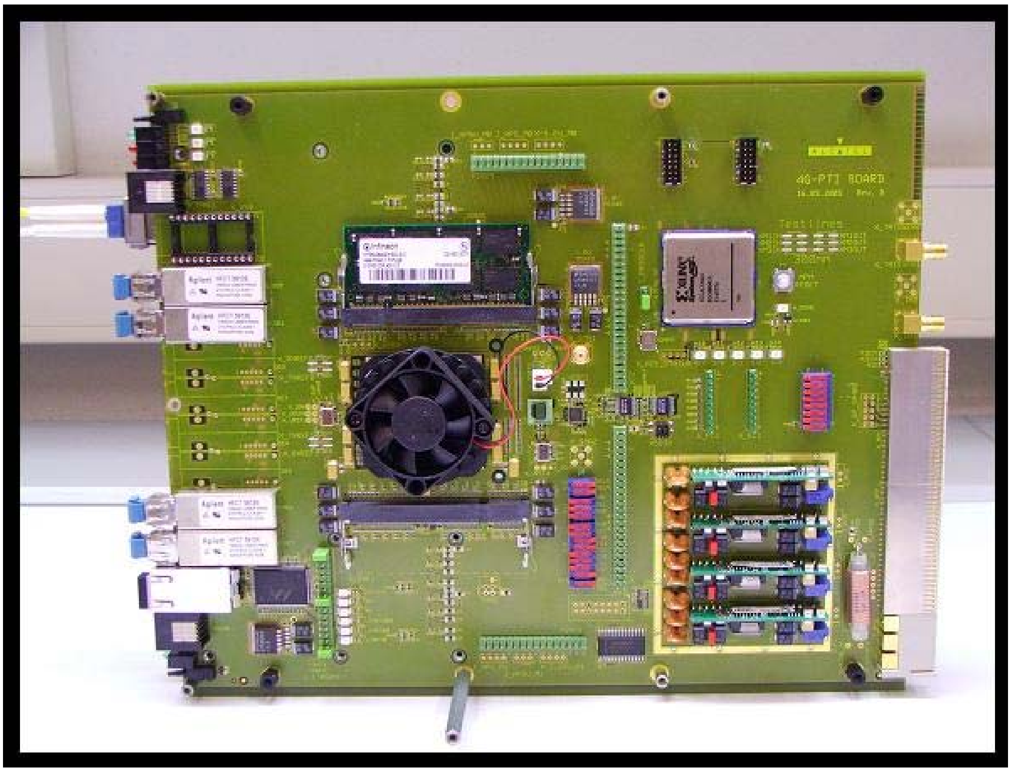


Figure 50 - Front view of the Hardware Prototype of the FAU

Also work was started on the serialisation of the parallel interfaces on the board and on the use of standardised backpanel equipment in order to reduce the complexity of the current board and with it the hardware cost. This will avoid the multiplexer/demultiplexer modules and high speed busses, which are hard to handle and limit the amount of very fast data interfaces up to now.

New FPGA modules offer the possibility to handle data rates up to 10GBit/s. Due to a complex integrated termination circuitry with adaptive pre-emphasis in the transmit path and equalisation in the receiver path, the external effort is reduced to a comparatively simple differential line. It is assumed that this bitrate can be handled with usual board materials like e.g. FR4, with special attention to well defined impedance matching and careful routing without vias, corners etc.

Another point of interest is the use of standardised backpanel equipment like the ATCA system. This offers the application of commercially available hardware like controllers, power supplies and control boards and the availability of well defined high speed connections up to 3 GBit/s across the backpanel.

To verify the advantages of the above mentioned concept in NOBEL 2, it is intended in a first step to develop a testboard with an appropriate FPGA, ATCA interfaces, and a high speed infrastructure to test the data transmission up to 10 GBit/s across the board and via the backpanel.

Bandwidth adaptation in NG SDH/WDM networks

The feasibility of dynamic bandwidth adaptation in SDH/WDM transport networks with next generation SDH features such as VCAT and LCAS (s. Figure 51) was studied in detail. The aim of the bandwidth adaptation service is to adapt network capacity to the current traffic state in a cost efficient way, while maintaining a high quality of service level. The impact of network traffic characteristics as well as system parameters under several technological restrictions were analysed. As a reference scenario, the case of static overprovisioning was considered.

First the critical aspects and requirements for dynamic bandwidth adaptation in transport networks to cope with dynamic data traffic patterns were identified. Second, the impact of the following traffic, timing and granularity parameters on quality of transport service were quantified:

- Traffic burstiness defined as relation of individual flow rate to aggregate traffic mean
- Measurement interval
- Bandwidth adaptation frequency, control interval
- Granularity of adaptation, virtual container size

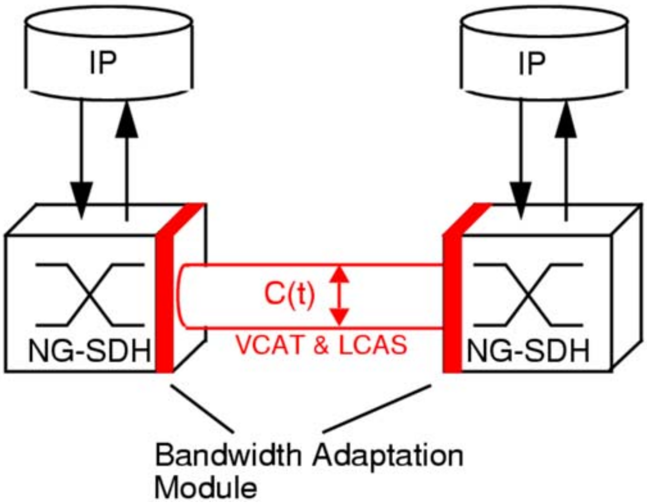


Figure 51 - Dynamic bandwidth adaptation in NG-SDH networks

In the studies aggregate traffic using an M/Pareto fluid flow model and three controllers of different complexity for bandwidth estimation was used. Principal effects of dynamic provisioning in transport networks were shown. Dynamic bandwidth adaptation is not suitable for a stationary highly bursty data traffic. Only, for smaller burstiness, higher performance improvements compared to the static case can be gained. Additionally it was shown that additional delays due to set-up and signalling have minor impact on the performance than the basic measurement interval. As a final step the static scenario of overprovisioning with the introduced approach was compared. It was found, that bandwidth efficiency can be gained in the mean. Using the same amount of bandwidth as in the static reference scenario a better quality of transport service was achieved and while keeping the transport service quality fixed, less bandwidth is needed in the mean to gain the same service quality with the chosen approach. It is supposed, when the traffic is instationary, e.g. following a daily shape, the estimators can adapt to those changes, while the static case cannot. In these scenarios the bandwidth efficiency gain is expected to be much larger.

3.7 WP7 Enabling Technologies and Components

3.7.1 Scope and state of the art

Transport networks based on DWDM technology are the backbone of today's communication systems. Their bandwidth is sold to carriers or end customers, nowadays mostly in the form of SDH/SONET connections. Carriers in turn retail this bandwidth to end-customers or other carriers/retailers.

New optical communication systems offer the possibility to selectively add or drop groups of wavelengths in pure optical nodes in between the end points of the transmission link. Purely optical nodes enabling the realisation of real meshed, transparent, optical networks are the next step of evolution of optical networks. The vision is to generate a packet network based on optical technologies. The different evolutional steps for the next generations of optical networks have been described in the NOBEL network scenarios for short term, medium term, long term, and extended long term by WP1.

Although re-wiring by hand is not necessary any more when optical switches have been introduced, intense planning has to precede any switching event. According rules and planning tools have been developed with in NOBEL WP5. In operation, network management has to comprise intelligent software to assign the routes and to setup respective light paths, e.g. with generalised multi protocol label switching (GMPLS). In addition to today's management plane (MP) which is mainly used to configure the network elements (NE) there probably will be an additional control plane (CP) to fulfil these transport related management tasks. To benefit from the advantages of dynamically reconfigurable optical networks, optical transport networks (OTNs) have to facilitate physically robust and flexible broadband data transmission. The according requirements are established within NOBEL WP4.

The results from WP7 provide the requirements on the different building blocks of optical networks and evaluate different available or upcoming technologies concerning their ability to fulfil these requirements.

3.7.2 Objectives

The overall goals of WP7 were:

- Identifying the majority of the main building blocks for (transparent) optical networks
- Assessment of several existing and emerging technologies
- Requirements definition for some of the advanced components for future networks
- Establishing a list of components to be standardized for interoperability
- Determined the technology improvements necessary for burst and packet oriented optical networks

3.7.3 Main activities

The initial phase of the activities addressed the identification of main building blocks for optical networks. Requirements for these subsystems and components in a transparent dynamic network were mainly derived from deliverable D3 (WP5). Evaluations of emerging technologies enabling Optical Burst Switching are carried out basing on requirements coming from D4 (WP3). Inputs from D8 and D9 (WP6) at the functional level have been also considered to address further investigations. From these deliverables and independent evaluations within WP7 the main building blocks and technical requirements for future optical networks have been extracted.

We identified three steps for three different levels of transparent optical networks, first, meshed optical networks, second, additional needs for interoperability, and third, for horizon three step of optical burst and packet switched networks.

Assessments are carried out comparing performances of available and proposed products with requirements relevant to various functions (transmitter/receivers, signal rerouting and optical monitoring) of a dynamic network.
Concepts and architectures for subsystems/optical functions have been investigated in order to identify most suitable solutions. International standards (such as ITU-T recommendation G.697 defining OPM measures) have been considered.
WP7 have started a market scan for currently available technologies regarding main building blocks, also contacting non-European suppliers to assess Europe's competitiveness in specific innovative enabling technologies.
The most promising components were evaluated in more detail, by simulations, experiments, and theoretical investigations, depending on the availability and status of the technologies (from ready to buy component to devices in concept phase).
In order to achieve cost effective networks, not only the technical aspects of the components and sub-systems has to be evaluated but also economic aspects have to be taken into account. Therefore, together with WP5 and WP2 an activity has been started which focus on the cost comparison of different levels of transparency. The according results are presented in WP5.

3.7.4 Major results

The main achievements of WP7 in the second year of the project have been:

- Identifying the majority of the main building blocks for (transparent) optical networks
- Complement of the list of requirements for the different components and sub-systems necessary to enable the networks according to the scenarios established by WP1 and further defined by WP3-6.
- Provisioning of a detailed market scan: many components commercially available today have been identified and are described according to their product sheet. Also, the underlying technologies are briefly presented.
- Technology scan from scientific and technological publications. Identification of interesting technologies and, if available comparison of different technologies suitable for the same purpose.
- A selection of very promising technologies or available components have been experimentally tested and rated.
- A techno-economic evaluation of several technologies has been summarised in a table.

3.7.4.1 Main building blocks for transparent optical networks

In this section we give a brief overview on the main building blocks identified within the WP7 and the NOBEL consortium to be important for future (transparent/translucent) optical networks. We identified three steps for three different levels of transparent optical networks, first, meshed optical networks, second, additional needs for interoperability, and third, for horizon three step of optical burst and packet switched networks.
Assessments are carried out comparing performances of available and proposed products with requirements relevant to various functions (transmitter/receivers, signal rerouting and optical monitoring) of a dynamic network.
Concepts and architectures for subsystems/optical functions have been investigated in order to identify most suitable solutions. International standards (such as ITU-T recommendation G.697 defining OPM measures) have been considered.
WP7 have started a market scan for currently available technologies regarding main building blocks, also contacting non-European suppliers to assess Europe's competitiveness in specific innovative enabling technologies.
The following list summarises the achieved results:

- Identified the majority of the main building blocks for (transparent) optical networks

For meshed transparent networks, following devices have to be evaluated:

- Adaptive Transmitter and Receiver
    - Tunable laser,
    - Tunable filter
    - compensators (PMD and CD)
    - Equalizer (optical or electronic)
- Amplifier solutions reducing the problem of transients due to switching
- Reconfigurable optical add-drop multiplexer (ROADM) and cross connects (OXC)
- Optical performance monitoring (OPM) and signal quality analysis
- Regenerators – optical or OEO regenerator pools?
- Wavelength converter
- Forward Error Correction (FEC)
- Equalizer

- In order to obtain interoperability in transparent optical networks, standards have to be established for (only a selection of the major issues is given – see also WP5):
    - Modulation and FEC formats
    - Dispersion maps, i.e. range of the accumulated dispersion value at a node
    - Agreement how to ensure proper signal (signal quality analysis and OPM)
    - Control for optical amplifier and other crucial equipment (amplifier transients and spectral properties for changes of the channel count)
- Going towards packet or burst based switching in the optical domain, further requirements occur
    - *Fast* tunable laser and filters
    - *Fast* optical switching
    - All optical regeneration
    - Burst mode receiver
    - Optical buffering
    - Optical label processing
- Resilience and Protection strategies which avoid error propagation

3.7.4.2 Technology and Component Evaluation

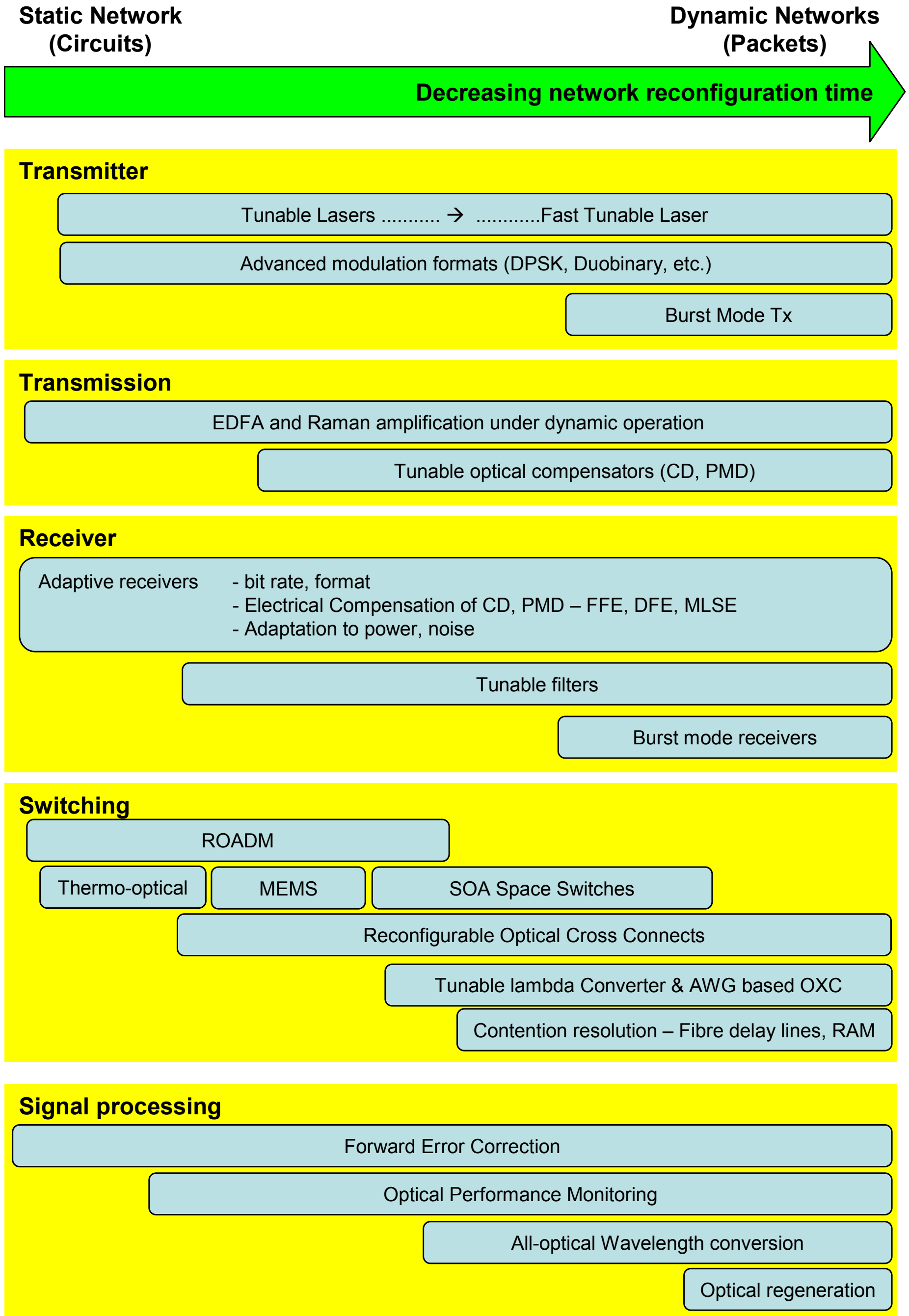


Figure 52 - Technological steps for the NOBEL evolutionary optical network vision

The short and medium term network scenarios are mainly described in terms of evolution of higher level protocols and enhancement of the data awareness also at lower level in the short term scenario and native Ethernet implementation in medium term scenario (see WP1). From the optical transmission point of view, we consider that the short term network scenario maintains current trends, in terms of adoption of technologies lowering network operators' investments (CAPEX) and operational (OPEX) expenses, while for the medium and long term we consider that the implementation of automated provisioning, routing and restoration will start. In the long term scenario we consider the wide adoption of dynamic transparent routing, while optical burst switching (or one of the several alternative concepts worked out within WP3 within the project) is envisaged in the extended long term scenario.

Thus we mainly focused in evaluation of technologies for performances and costs for short/medium term, evaluating technologies enabling new functionalities, for instance dynamic routing in the long term. Technologies enabling extended long term scenario applications are still at research level and survey/assessment of concepts and solutions has been performed.

Considering optical technologies the effort has been focused on a collection of requirements coming from different WPs, internal elaboration, an extensive market and technology scan to assess current products and survey of advanced technologies fitting in network scenario requirements. Starting from inputs from various Nobel WPs dealing with node architecture and network transmission, and from analysis of market and emerging trend, we have considered in our work some of the key optical modules and carried out technological assessment of different solutions basing both on public results and on experiments carried out by Nobel partners in their labs. The activities for the individual key components as identified within the first period are described briefly below.

3.7.4.3 Summary of the evaluated technologies

Tunable Lasers

Tuneable/reconfigurable modules (tunable lasers, ROADM and some tuneable filter technologies) evaluations have been refined for applications in the short term (inventory and planning savings), medium and long term (remote provisioning/reconfiguration, network restoration, dynamic transparent routing); specific experimental activities have been performed.

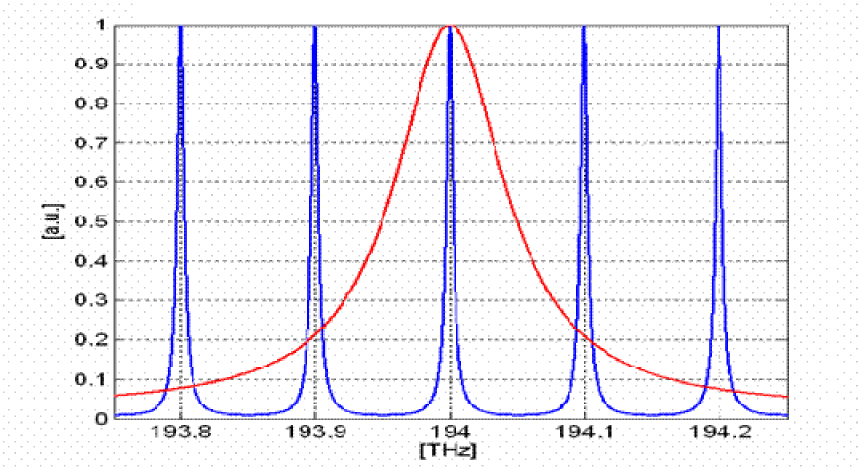


Figure 53 - ECL laser: The blue line (narrow spectra) is the spectral response of the cavity etalon, the red one (broad spectrum) is the tuneable mirror transfer function selecting one channel

Suitable technologies for widely tuneable lasers in the different network scenario are analysed in D20 and summarised in D34. Technologies/products for cost-effective substitution of fixed sources in the short term have been evaluated and compared. In the short term network scenario tuneable lasers are required for integration in 10 Gb/s transponders (low power consumption, simple control) and solutions in line with requirements have been identified. An assessment of the characteristics suitable for medium/long term scenarios has also been carried out, also with experimental activities focused on switching time (fast network reconfiguration requires a tuning time on the order of milli-seconds) and optical performance evaluation.

This activity led to the identification of viable solutions for more stringent requirements, especially in terms of switching time: besides multisection DBR (very fast inherent switching time), tuneable ECLs can be considered as a viable solution for medium term if the nature of the tuning element will allow msec-scale switching time (as e.g. LC-based ECLs). Integrability issues have been considered as an important factor for cost-effective solutions.

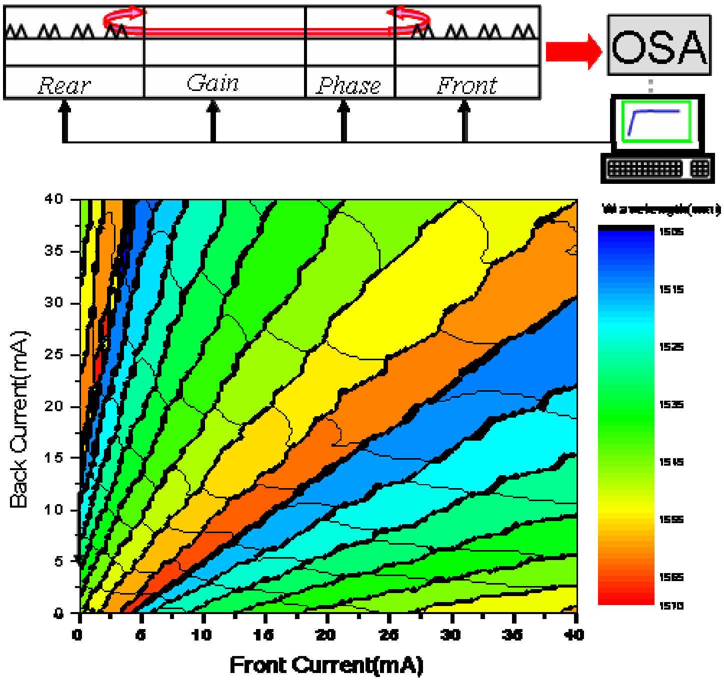


Figure 54 - Experimental set-up for tuneable laser characterisation and measured tuning map

Reconfigurable Optical Add-Drop Multiplexer (ROADM)

In recent years Reconfigurable OADM (ROADM) architectures have been proposed in order to automate the network management and to adapt the network to changing loads. For ROADM modules, an extended set of requirements has been considered, segmented for the various network scenarios and network segments, identifying a set of viable technologies. Available and proposed technologies implementing the different ROADM architectures have been evaluated, together with a technological assessment of basic building blocks required and the possible integration at subsystem level. In this context also the results from the IST-project PLATON (OADM using planar waveguide technology) have been reviewed and reported.

Planar light-wave circuit (PLC) platforms have been studied, together with technologies for Wavelength Blocker (WB) and Wavelength Selective Switch (WSS), especially for medium/long term scenario, where support for optical switching in mesh networks will be required. Experimental activities have been performed on specific solutions for ROADMs.

PLC based ROADM with architectures based on mux/demux and switches are seen as suitable solutions reaching technological maturity, potentially with low cost and high integration, especially in the metro-core area, since the technology is progressing and traditional limitations are going to be overcome: dimensions and power consumption are decreasing with upcoming new materials, specific technological solutions and new switch structures, East-West separated architectures and colourless ports are available, the latter allowing for larger optical switches. Moreover, these architectures have in principle the benefit of having a single wavelength access (signal level equalization and monitoring).

The interest for components for ROADM nodes with high capacity and more demanding applications has been focused on WB and WSS because of their good performances and network-level features (scalability with off-ring upgrades, reduced filtering effect for improved cascadeability). Proposed technologies to implement WBs have been evaluated, mainly based on Diffractive MEMS, liquid crystals or PLC approaches.

WSSs are more adapted to implement higher order nodes and have a high scalability. Specific solutions to achieve high number of colourless drop ports in WSSs have been investigated: PLC-based platforms, free-space optics and hybrid technologies where the wavelengths are separated in PLCs and the switching is done with free-space optics, which seems to be a very promising approach.

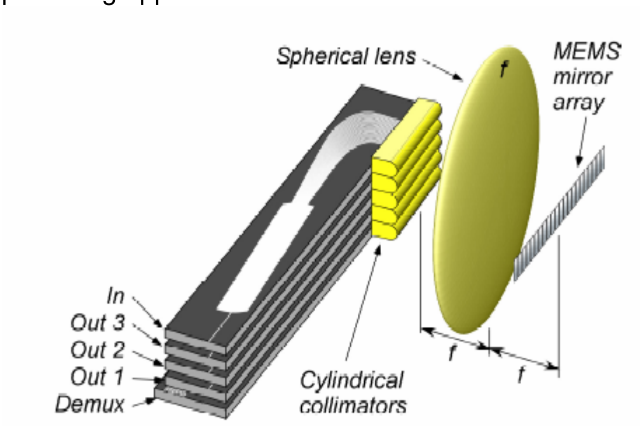


Figure 55 - WSS from Lucent [ECOC2005 Th3.6.4]

PLC-based nanotechnology might be a basis for tuneable devices matching the medium/long term network scenario requirements in terms of an increased network flexibility (single and multi-wavelengths switching in msecs). Therefore, samples of this technology have been chosen to be tested within this WP. Adoption of nanostructures to implement several tuneable filters into a single chip is a promising approach for future implementation (possibility to implement filters with good spectral characteristics, potential low-cost technology, tuning time of few msecs) even if technological improvements are needed to reach target performances.

Tunable Filter

Tunable filters have been investigated, considering requirements from various potential applications to implement several functions, such as signal routing, ROADM, ASE suppression in tuneable receivers, channel selectors for optical performance monitoring (OPM). Beside the evaluation of suitable technologies for integrated solutions, experimental activities on tuneable filters structures have been carried out. Based on the extensive study performed in the first period of the project on tuneable filter technologies, evaluations have been refined and updated. Recent demonstrations on diffraction grating MEMS show good spectral characteristics and the possibility to be integrated in a standard butterfly 10 Gb/s receiver, both for tuneable receivers and for implementing basic OSA functionality for OPM. Micro-rings are interesting, due to their compactness (High Index Contrast technologies). Ring-based structures have also been tested.

Here, the major challenge is to select the proper technological platform to implement high index contrast devices (major options evaluated are Si_3N_4, SiON and Silicon-rich-nitride), with a good trade-off between dimension, free spectral range (FSR), losses, manufacturability.

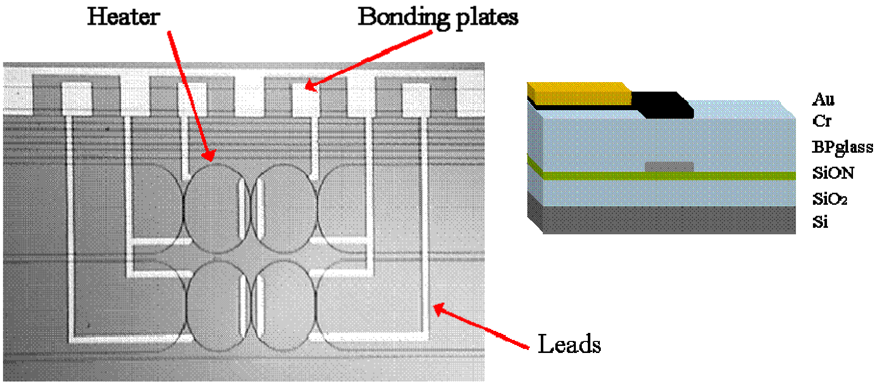


Figure 56 - Ring-based tuneable filters in High-Index Contrast

Polarisation Mode Dispersion Compensation (PMDC)

Two different approaches to compensate for PMD have been investigated. The first setup comprises of a polarisation controller together with a simple polariser. A detailed description of the theory of this setup can be found in the NOBEL deliverable D3 of WP5. This setup has been tested with a 10 Gb/s as well as a 40 Gb/s system. The second setup comprises of a polarisation controller together with a birefringent element, here a polarisation maintaining fibre. This setup has been tested with the 40 Gb/s system.
Compensating for PMD with a simple polariser shows good improvement for the 10 Gb/s NRZ signal, whereas for the 40 Gb/s DPSK signal the approach with the birefringent element should be used. The main issue of both approaches is the speed of the polarisation controller, which can follow the speed of the used polarisation scramblers (scan rates up to 8), but real system behaviour is assumed to be much faster.

Optical Performance or Parameter Monitoring (OPM)

The OPM activity within WP7 was twofold, on one hand a suitable solution for the short/medium term network scenarios has been searched, on the other hand, concepts have been developed which are capable to control the compensation or equalisation of various distortions especially for the extended long term scenario.
For the first issue different technologies have been evaluated, such as traditional optical spectrum analysis (OSA), Amplitude Sampling, variable decision circuit, and polarisation nulling. For today's WDM systems performance analysers based on OSA technology are available. Due to the multiplexer, demultiplexers and other filters a major problem in WDM systems is to obtain the "in-band" OSNR. We tested a commercially available product in which the polarisation nulling method is applied capable to detect the in-band OSNR. In addition this method has the potential to measure the current PMD value, a parameter of very high interest for all operators of long-haul optical transmission systems. From the experiments it can be concluded that this technology is mature to measure the OSNR in WDM-system if no significant polarisation dependent loss (PDL) is present. For PDL equivalent values of more then 1 dB this method cannot be used to obtain meaningful OSNR values. For system application the measurement speed of the device under test should to be improved; the PMD measurement implemented is not yet applicable.

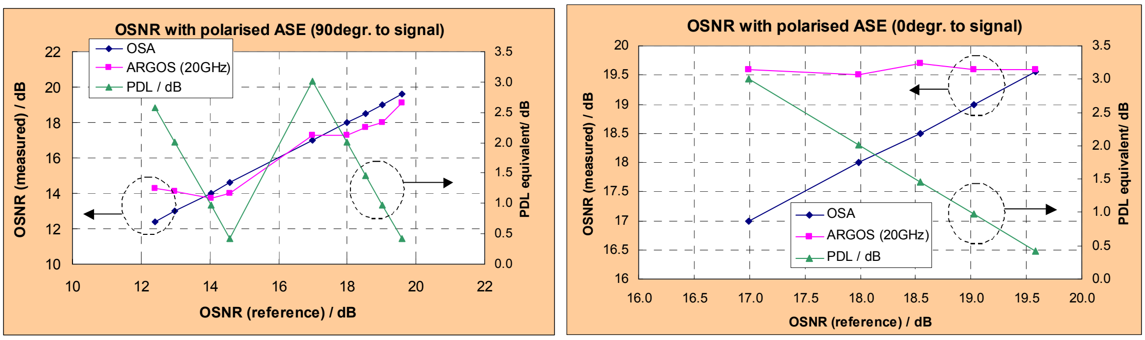


Figure 57 - Measurement results with partly polarised ASE. The "PDL equivalent" is the ratio of the polarised ASE to the unpolarised ASE in dB. Left: The polarised ASE fraction is perpendicular to the signal polarisation. Right: The polarised ASE fraction is in parallel to the signal polarisation

Second, a new method for performance monitoring of multi-channel 40 Gb/s systems for dynamically reconfigurable burst networks has been developed. The method is based on RF spectrum analysis and is capable to measure the power and chromatic dispersion of the incoming signal. Due to the multi-channel functionality this method has potential to be very cost-effective.

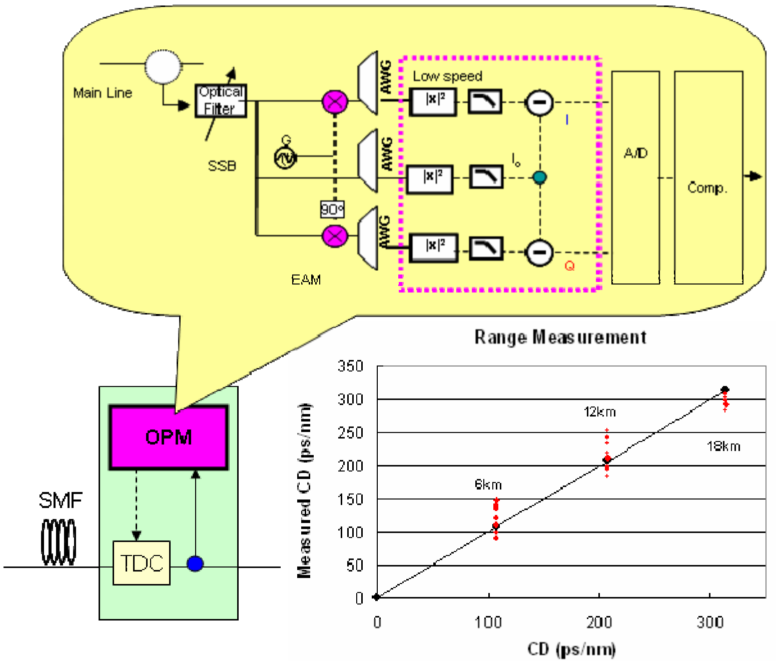


Figure 58 - Multi-channel Chromatic Dispersion monitoring scheme for dynamic networks. The range and accuracy of this technique is indicated in the plot

So far, the prototype established within the project has been characterised to have a detection range of the chromatic dispersion of 312 ps/nm for 40 Gb/s, a response time in the order of a microsecond, and is insensitive to first order PMD. In collaboration with WP5 this prototype has been tested together with a tunable dispersion compensation module (Virtual Imaged Phased Array). A tuning range of 300 ps/nm has been achieved and an accuracy of about 10 ps/nm.

All-Optical Wavelength Converter and Regenerator

All-optical wavelength converter and regenerators will be interesting for the long or extended long term scenarios to reduce the blocking probability in all-optical networks. If flexible and cost-effective technologies can be found OEO conversion can be avoided to reach this goal.

An all-optical wavelength converter and regenerator based on a nonlinear semiconductor optical amplifier (SOA) has been used in all-optical regeneration experiments at 10 and 40 Gb/s. The optical regeneration experiments seek to evaluate the performance of cascaded all-optical regeneration in transmission systems, using a recirculating loop transmission test-bed, with respect to signal degradations such as accumulated OSNR and nonlinear distortions. The regenerative scheme is based on optically induced cross phase modulation (XPM) in the nonlinear SOA.

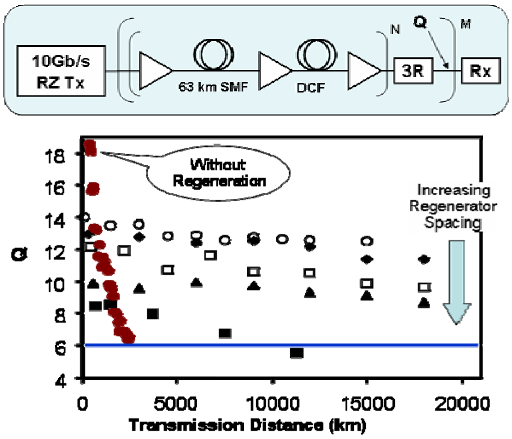


Figure 59 - Performance evaluation of cascaded all optical regenerators

From the activity an increased operating tolerance of an optical transmission system at 40 Gb/s when using an SOA based regenerator at the receiver in the presence of nonlinear and OSNR limited signal propagation was demonstrated. Both noise accumulation and nonlinear optical distortions were improved and resulted in an improvement in the power margin of 6.5 dB. The optimal regenerator spacing in an OSNR limited transmission system at 10 Gb/s using SOA based 3R all-optical regenerators was determined experimentally. The SOA transfer function and the assessment of the potential of the SOA devices for regeneration was determined by measuring the optically induced refractive index shift in SOAs using a spectrographic measurement technique.

Integratability and Cost-effectiveness of components evaluated

Components and modules have been evaluated for applications in short / medium / long term scenario according to the following considerations: for the short term network scenario (2005-2008) requirements are following current trends, in terms of technologies lowering network operator investments and operational expenses; in the medium term (2008-2010) due to implementation of automated provisioning, routing and restoration and initial adoption of dynamic transparent routing, still technology for performances and costs, but also technologies enabling new functionalities, in the medium term (dynamic routing); in the long/extended long term scenario technologies currently at research level, enabling OBS applications.

Cost evaluation of Components and Sub-Systems

Application	Company providing product (or dev. status)	Applied Technology	Technology Complexity	Possible Degree of Integration	Estimated cost position			comment
					RS	RW	CVR	
OPM	Teralink, Argos x01	Polarisation Nulling	Medium	Can be delivered as module, e.g. MSA300	€€	€€	€	- Comparable price position as “traditional” OSA technology, - Slower per channel information
RF monitoring	(Research)	RF spectrum analysis	Medium		€€	€		Details have to be tested in later development status low RW expected due to multi-wavelength application
Widely tuneable lasers (short term)	JDS-Agility	SGDBR	Medium	Laser+modulator feasible for short reach challenging for LH reach	€	€€	NA	Control to be simplified for integration into 10Gb/s transponders
Widely tuneable lasers (short term)	Coherent-Iolon, Intel, …	ECL	Low/Medium	Hybrid integration of laser and modulator	€	€€	NA	Performances varies depending on type of mirror element
Widely tuneable lasers (short term)	Santur, Furukawa, …	DFB array	Low/Medium	Laser+modulator integration feasible with on-chip combiners	€	€€	NA	Performances varies depending on on-chip or off-chip combiner solutions
Widely tuneable lasers (medium term)	soon Available / (Engineering)	Multisection DBR or ECL (liquid crystal based)	Medium	In principle possible for DBR, hybrid for ECL	€	€€	€€	Assuming required switching time around 10 msec
Widely tuneable lasers (long/ext term)	(Research	Multisection DBR	Medium/High	In principle possible	€	€€	€€	Require methods to reduce switching crosstalk for sub-msec tuning time
ROADM (short/medium term)	JDS, Dupont, ...	PLC-based integration of mux/demux and switches	Medium	Possible, technology improvements needed	€	€	NA	Mainly suitable for metro solutions
ROADM (medium term)	(Engineering)	WSS	Medium/High	Free-space or hybrid free-space/PLC	€€	€	€€	Hybrid solutions seems more promising
Tuneable filters for monitoring	Coherent-Iolon / Engineering	MEMS-tunable grating filter	Medium	Hybrid integration	€€	€	€	Integration with 10 Gb/s APD in butterfly package demonstrated

Application	Company providing product (or dev. status)	Applied Technology	Technology Complexity	Possible Degree of Integration	Estimated cost position			comment
					RS	RW	CVR	
Tuneable filters for monitoring	Aegis / Engineering	Thin-Film Filters	Low/Medium	Integrated with photodiode packages	€	€	€	Single cavity available. Improvement expected with multicavity design
Tuneable filters for signal rerouting	Research/Engineering	Microrings	Medium/High	High integration	€	€	€	Several materials/platforms under investigation. Performances/technology tradeoff
Tuneable dispersion compensators	Teraxion, Alnair, …) / Engineering	FBG	Medium	Non suitable for integration	€€€	€€	€	GDR control issues possible savings in the power budged -> simpler EDFAs
Tuneable dispersion compensators	(Research / Engineering)	Microring-based all-pass filters	Medium/High	Silica PLC integration	€€	€	€	Advantages over GT etalons due to fast tuning
Electronic CD equaliser (medium term)	CoreOptics, ... (Engineering)	FFE+DFE, VE, pre-distorsion	Medium	Development of ADC in SiGe BiCMOS for MLSE at 10Gb/s	€	€	€	FFE+DFE is the only demonstrated at 40 Gb/s up to now
Optical PMD Compensation	(Research)	Polarisation scrambling (fast pol. scramblers)	Medium	$LiNbO_3$ based polarisation controller	€€	€€€	€	Multi-channel solution required for 40 Gb/s

RS=relative to other solutions with approx. same applicability
RW=relative cost to a total cost of a wavelength
CVR=cost-value ratio for transparent optical networks
€ = cheap
€€ = Average
€€€ = Expensive

3.8 WP8 Integrated test bed and related experimental activities

3.8.1 Scope and state of the art

The realization of experiments for the demonstration of new advanced functionalities in a Pan-European environment requires a detailed analysis of the available functionalities in different locations and a careful evaluation of potential interconnection alternatives: NOBEL WP8 made a first step towards this objective that will be completed during the extension of the NOBEL Project.

The starting point for the realization of the WP8 experiments was the results of the activities carried out in the other NOBEL WPs (network studies, control plane functionality evolution, prototype development, etc.). Therefore, all the executed experiments are in-line with the NOBEL Project main purpose of investigating and assessing experimentally innovative network solutions and technologies for intelligent and flexible optical networks. Furthermore, the set of experiments to be realised have been defined keeping into account the status and the possible enhancements of the already developed test beds made available to the NOBEL Project.

The executed experiments can be divided in four general categories: transmission tests, validation of control plane functionalities, verification of control plane performances and, finally, experiments related to traffic measurements and to the interconnection of access and metro networks.

Moreover, WP8 organised also two public demonstrations executed during the workshop “Optical transport networks for next generation broadband services” jointly organised by the NOBEL and MUPBED IST projects.

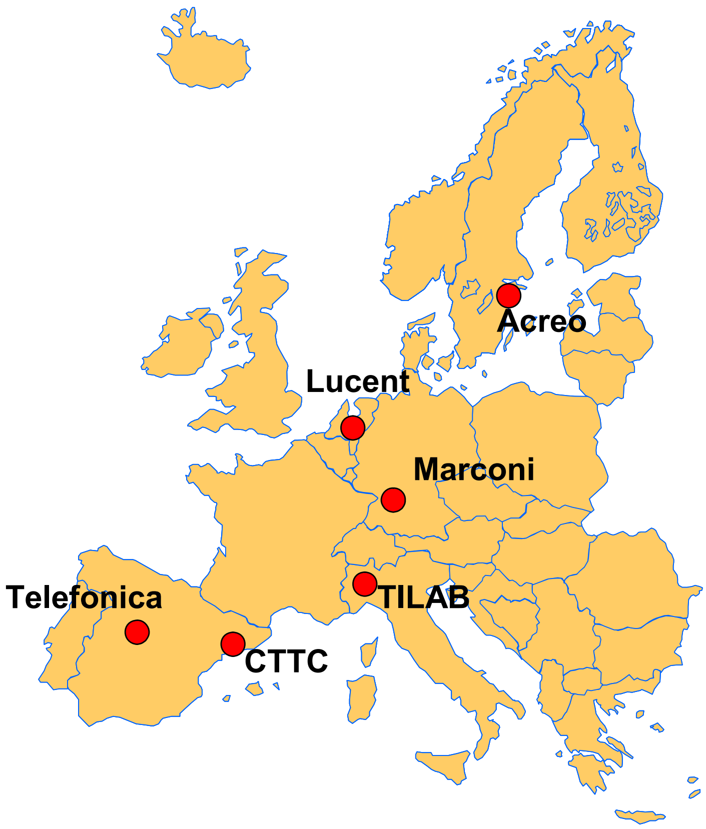


Figure 60 - NOBEL test bed and laboratories used for the experiments

3.8.2 Objectives

The overall goals of WP8 were:

- to study the feasibility of an integrated field trial for example interconnecting (already existing, or under development) test beds with the NOBEL test-bed;
- to complete the integration in laboratory test beds of equipment, subsystems and emulators leveraging existing test beds previously developed;
- to design the experiment to be executed configurations and the required systems (equipment, subsystems and emulators) for their realization in strict cooperation with the other NOBEL Workpackages and keeping into account the existing and available test beds;
- to execute the defined experiments and analyse their results.

3.8.3 Main activities

The WP work can be divided in the following activities: design of the NOBEL test beds, feasibility analysis of a field trial, integration of the NOBEL test bed, realisation of experiments and analysis of the results.

The first activity to be done was the definition of the experiment configurations and of the required systems (equipment, subsystems and emulators) for their realisation, keeping into account the existing and available test bed(s) (e.g. the IST LION, ACREO and the EMPIRICO test beds). This activity requires a strict cooperation with the other WPs (e.g. WP1 for network scenarios, WP4 for management/control, WP5 for transmission aspects, WP6 for multi/service nodes) where the new functionalities are defined, specified and the systems are realised.

Furthermore the feasibility analysis of an integrated field trial has been carried out in order to evaluate experimental activities that could be realised in cooperation with other Projects (e.g. IST MUPBED).

Then, the implemented equipment, subsystems and emulators have been integrated in the NOBEL test beds, the designed experiments have been executed and their results discussed.

3.8.4 Major results

As previously described, all the experiments executed in WP8 have been defined selecting specific topics in cooperation with the other workpackages and are line with the NOBEL main purpose of investigating and assessing experimentally innovative network solutions and technologies for intelligent and flexible optical networks.

The experiments can be divided in four general categories: transmission tests, validation of control plane functionalities, verification of control plane performances and, finally, experiments related to traffic measurements and to the interconnection of access and metro networks.

Transmission experiments

Experimental performance of key optical components

In the last decade, the tremendous increase in traffic has motivated the search for methods to increase the bandwidth of fibers, especially for those already deployed in SDH networks due to the need to save investments and the current economic situation in the telecommunications sector. In this direction, wavelength multiplexing is a technology that allows the bandwidth upgrade of existing fibers. Apart from WDM, the current most relevant advances in optical networking technologies are reconfigurable OADMs, programmable OXCs, optical fibres, optical amplifier, tuneable lasers and photoreceivers. With the fulfilment of the demands for increased functionality of the IP layer, such as the addition of traffic engineering and QoS capabilities, it is becoming feasible to construct IP directly over WDM, and to eliminate opto-electronic conversions in the core nodes. This is the result of the recent networking trend in reducing the number of layers, driven primarily by the convergence of network technologies to IP, which implies reducing costs significantly. Hence, the transition of IP/WDM is becoming a viable choice for network operators.

It is NOBEL's view that all-optical (transparent) networks are the future for data communications, due to their great advantages: a unique capability where only the two end-point transceivers need to understand the

format, protocol and data rate of the data transmitted; low latency across the network; and reduced network element costs due to lack of electronic conversions. A crucial issue for service provisioning in transparent networks is quality of service (QoS). As WDM becomes a mature technology and its technology-related problems are tackled successfully, the support of different optical quality levels between a single source destination pair arises as the following step to achieve QoS comparable to or even better than SDH networks. The first step towards assuring QoS in transparent transport networks is to characterize the performance of key optical components along lightpaths.
The objective of the NOBEL WP8 experiment “Experimental performance of key optical components” is the evaluation of the particular characteristics of optical components that compose the transport plane of the CTTC test bed, described in [D7], as well as their interaction with the control and management planes. The first phase of the experiment was to characterize the subsystems on which the OADMs of the CTTC test bed, as well as the fiber links and transponders. For each of these elements, several performance parameters were measured, such as switching delays, insertion losses, BER or attenuation. The second phase of the experiment was to measure the performance of the OADMs, which are based on AWGs, optical and MEMS switches, and to estimate end-to-end performance of a longest-span lightpath through simulation with the settings of the CTTC test bed, including optical amplifiers. Such performance was measured in the form of OSNR and optical channel power at the receiving end.
The lasers used in the CTTC test bed have high frequency stability (□3 GHz), side-mode suppression ratio (35 dB) and OSNR at the transmitter (30 dB/0.1 nm). The fiber links have an attenuation slightly below the typical for SMF (average 0.193 dB/km). The switching delays obtained from optical and MEMS switches are below 25 msec, although interfacing with control and management planes adds extra delay; the worst case is the TL1 interface of the MEMS switches used as a distribution stage of the OADM, which can add up to 20 msec to the switching delay from request to full response. The insertion losses of the OADM architecture are rather high, especially in the protection mode but can be easily compensated with optical amplification; they range from 14.96 to 24.74 dB for add-out and in-out without protection and from 36.2 to 43.37 dB for the same schemes in protection mode.
When simulating lightpaths in the CTTC test bed with optical amplifiers at inputs and outputs of each OADM (14 dB gain at input and 25 dB gain at output), the optical power received is above the sensitivity of the photoreceiver (over –30 dBm) and the OSNR obtained at the receiving end is over 7 dB, that is more than sufficient for the targeted BERs (a Q factor of 7 corresponding to a BER of 10-12) for a 2.5 Gbit/s channel, with a 36 GHz optical filter at the receiver end; this value corresponds to a 12 dB/0.1 nm OSNR, to which a slight margin due to physical constraints (dispersion, nonlinearities) must be added.

Evaluation of the APRZ modulation format for high-speed transmission

The alternate-phase return-to-zero (APRZ) modulation format has been shown in several simulation studies and experiments to have very good non-linear tolerance and it is therefore a promising candidate for 40-Gbps transmission. An APRZ signal is an RZ signal in which the phase of neighbouring bits alternates between two values. This phase alternation reduces the impact of intra-channel four-wave mixing (IFWM) by causing IFWM contributions coming from different pulse combinations to interfere destructively.
The main objectives of the experiment were to test ARPZ in an installed system, outside the controlled laboratory environment, as well as to test the upgrade feasibility of an installed 10-Gb/s transmission link to 40 Gb/s. In particular the experiment assessed the impact of non-linear effects, dispersion, and filtering.
In the experiment, the APRZ transmitter was implemented as a short-pulse RZ transmitter followed by a phase modulator driven by a V□/2 peak-to-peak, 20-GHz clock signal. At the receiver side receiver sensitivity at BER=10^{-5} is measured, which would allow for error-free recovery with standard forward-error correction. The transmission distance is 820 km on standard single-mode fibre (SSMF). At the intermediate nodes, in-line dispersion compensation is accomplished by means of dispersion compensating fibre (DCF) modules, and re-amplification is accomplished by means of erbium-doped fibre amplifiers (EDFA). The installed system is dispersion under-compensated, and in order to operate at 40 Gb/s, though, full dispersion compensation is needed. Therefore extra DCF is inserted at the transmitter, and a tuneable dispersion compensator (TDC) at the receiver (per-channel compensation is going to be a system requirement at Gb/s). Optimum pre-compensation is used.
First, the impact of non-linear effects is evaluated in the unfiltered scenario (the wavelength multiplexer and de-multiplexers were just removed from the installed system). It was found that for launch-power into the SSMF above 6 dBm, where non-linear impairments become the limiting factor, APRZ achieves a considerable improvement in receiver sensitivity over RZ (see Figure 61). Next, 40-Gb/s transmission was

analysed on the complete system, including the multiplexer (75 GHz) and de-multiplexer (50 GHz). The receiver sensitivity for back-to-back in this case was found to be substantially unchanged compared to the unfiltered scenario. This does not mean that filtering won't impact transmission performance. Indeed, filtering will broaden the pulses being launched on the link, therefore making them less tolerant to non-linear impairments. And in fact the experimental results confirm this: non-linear effects are now dominating RZ transmission already at 3 dBm launch power, and make transmission not viable at 5 dBm (see Figure 61). Applying phase modulation reduces the impact of non-linear effects significantly, and a 4-dB sensitivity improvement is achieved, as well as a wider range of launch power, which allows for a certain stability margin (which can be translated in e.g. into transmission over longer spans). This, besides confirming the superior non-linear tolerance of APRZ, shows that 40 Gb/s transmission on installed systems designed for 10 Gb/s is viable. Finally, APRZ's dispersion tolerance is assessed by tuning the TDC away from optimal dispersion, and a one-order degradation in BER was observed for +/-20 ps/nm, similar to RZ transmission.

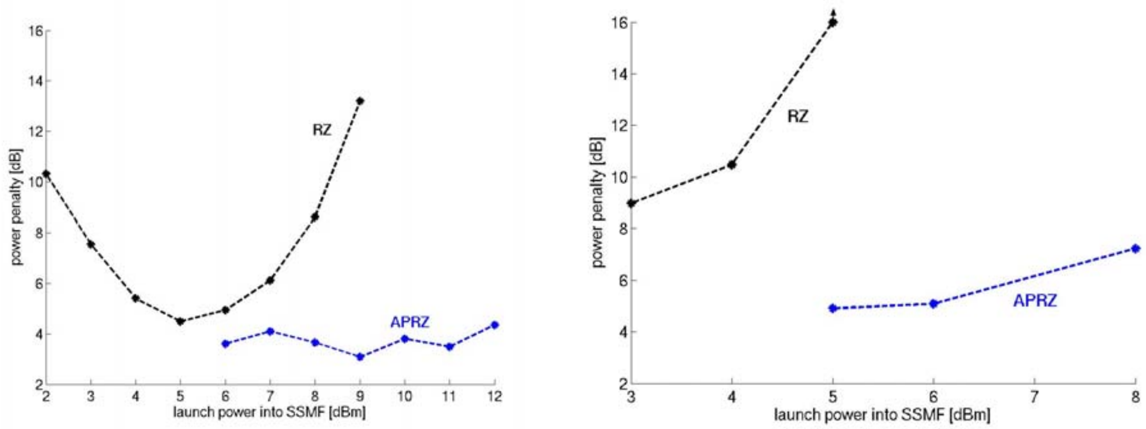


Figure 61 - Power penalty versus launch power into the SSMF for RZ and APRZ transmission over the 820-km link, without (left), and with (right) multiplexer and demultiplexer.

PMD mitigation of 40-Gb/s CSRZ transmission over 820 km

In this experiment a PMD-mitigator developed outside the NOBEL project is evaluated. The PMD-mitigator used here was based on a fixed DGD-line, which was set to 5.12 ps. The feedback system of the PMD-mitigator was based on spectral analysis of the frequency band from 38 GHz to 42 GHz of the detected electrical signal.

The experiment consists in comparing BER over long time, with and without the PMD-mitigator, using the CSRZ modulation format at 40 Gb/s. The tests were performed on Acreo's test bed (Swedish Broadband Testbed) over the 820-km WDM link between the cities of Stockholm and Hudiksvall, whose average PMD-level was measured to 4.5 ps (RMS), and the DGD-correlation to ~3 hours. The figures below present the statistical distribution of BER values measured for 40-Gb/s CSRZ transmission on the link with and without the compensator.

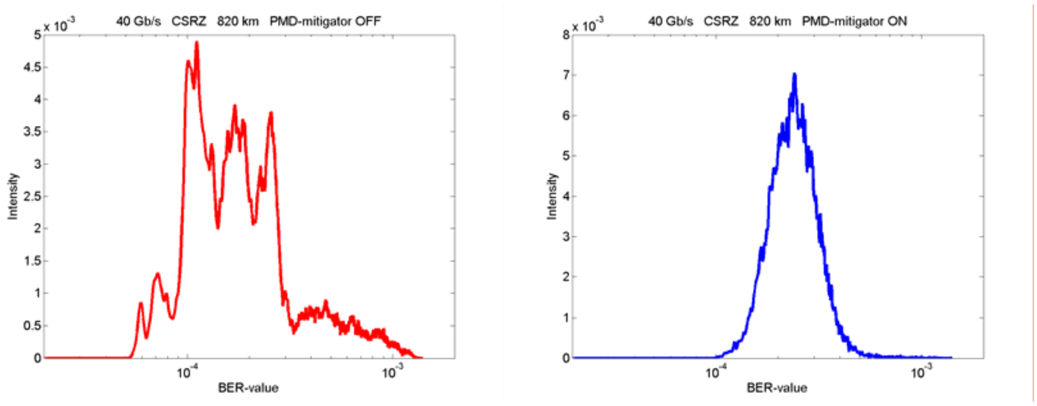


Figure 62 - Statistics of BER-values of the PMD-mitigated 40 Gb/s test-bed transmission, without (left) and with (right) mitigator

From the figures it can be seen that the performance of the system was improved by using the PMD-mitigator. It reduces the time period when the system operates with high error probability, i.e. $>5\cdot10^{-4}$, which is believed to be caused by temporarily high DGD-values. These BER-levels are critical since they are close to the EFEC-limit.

However, for low BER-values, which are here interpreted as low DGD-values, the PMD-mitigator had difficulties to align its own static PMD-vector in an optimal direction. This behaviour is explained by the fact that the transmission link is thought to be limited by ASE-noise, as well as intra-band noise during normal operation premises. The noise-level obscures the spectral analysis used to create the feedback signal for optimising the direction of the PMD-vector. The general conclusion, however, is that the PMD-mitigator improved the performance of the 40 Gb/s link.

Experimental results on 21.5 Gbaud (43 Gb/s) RZ-DQPSK interface prototypes

This work was based on the 21.5 Gbaud DQPSK interface prototypes developed and preliminary tested under the framework of WP6 and reported in deliverable D24 and is therefore an extension of the work carried out in WP6. In contrast to previous results published on this topic, the test bed experiments performed under the umbrella of WP8 concentrated on an operation in a typical terrestrial network environment where neither Raman amplifiers nor optical phase compensators or phase conjugators were present.

In the following the DWDM test bed experiments to evaluate the 21.5 Gbaud RZ-DQPSK transmission performance over a 660 km multi-span link are briefly summarized. Both single channel and multi-channel operation with neighbouring on-off keyed (OOK) channels at 10.7 Gb/s were investigated. Beside demonstration of a successful transmission, the investigation of the impact of nonlinear phase noise, both due to Gordon-Mollenauer noise and cross-phase modulation, was a focus of the experiments.

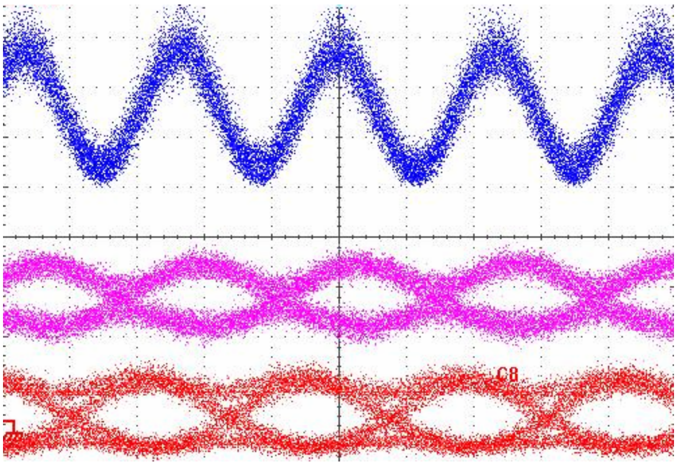


Figure 63 - Back-to-back eye pattern of RZ-DQPSK transmit signal and received I- and Q-component after interferometer and balanced detectors

Three different transmitter set-ups were investigated: a) a single 21.5 Gbaud RZ-DQPSK channel, b) an RZ-DQPSK channel with two 10.7 Gb/s neighbours at each side spaced 50 GHz apart and c) an RZ-DQPSK channel with two 10.7 Gb/s neighbours at each side spaced 100 GHz apart from the RZ-DQPSK channel. The four 10.7 Gb/ channels consisted of two full-band tuneable transponder modules at ±50 GHz and two externally modulated lasers with fixed wavelengths at ±100 GHz distance to the DQPSK-channel. Assuming an FEC threshold of Q = 10 dB to obtain a corrected bit error ratio better than 10^{-15}, all three transmit configurations clearly demonstrated error free operation after FEC with more than 3 dB Q-margin (see Figure 64). Expectedly, the single channel case was the best case measured. In the single channel experiment there was no noticeable decrease in performance due to nonlinear effects for launch powers as high as 4 dBm. The results of the multi-channel experiments got close to the single channel results at low launch powers where the optical amplifier noise is the main source of impairments (linear regime). As the launch power increases, the performance of configurations with OOK neighbours degrade more rapidly, because cross-phase modulation (XPM) sets in. The 50 GHz configuration suffers more from XPM than the 100 GHz configuration because XPM is more severe at lower channel spacings. Allowing for 0.5 dB XPM penalty in the investigated scenario, the maximum launch powers were 0 and 2 dBm for 50 and 100 GHz channel spacing, respectively. It was shown that with a careful optimisation of the back-to-back setup, as would be done for a commercial product, a noticeable improvement in performance could be achieved, which in turn would further increase margins or could extend the transmission distance. The realised optimised performance is to our knowledge the best back-to-back curve for RZ-DQPSK at 21.5 Gbaud reported so far.

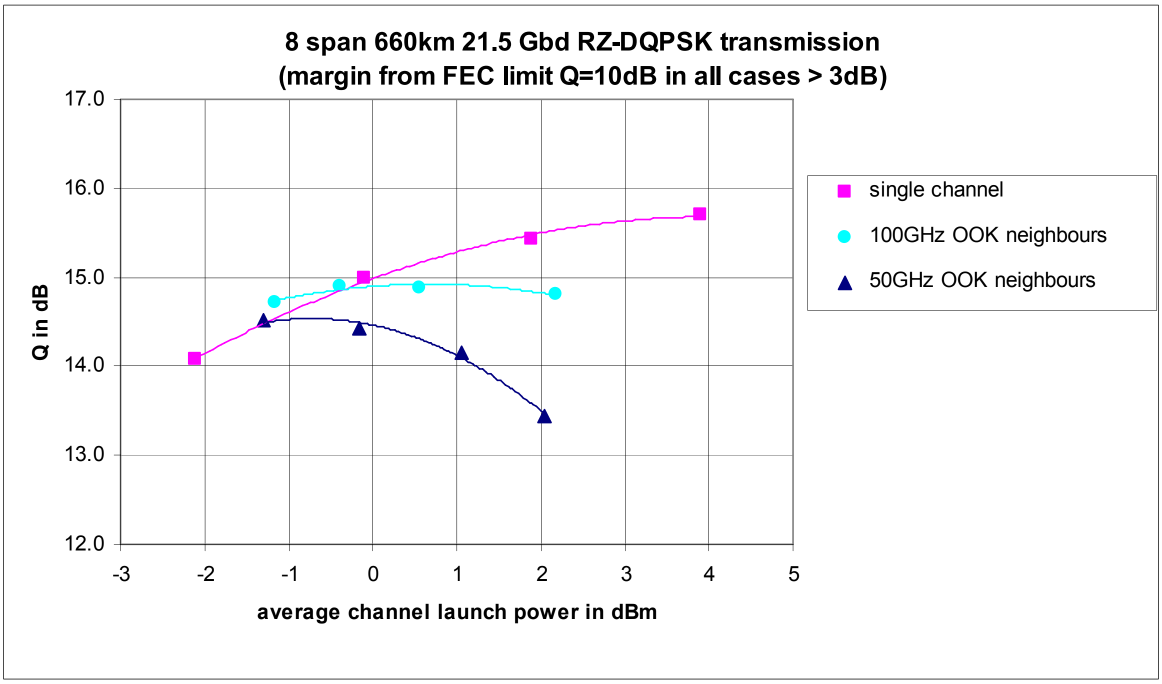


Figure 64 - Q factor vs. average per-channel launch power for the three transmitter configurations

Control plane functional experiments

Multi-layer connections setup

The objective of this activity was to demonstrate the realization of an end-to-end connection between two IP networks passing through two SDH domains interconnected via a transparent optical network. The IP networks were connected to the SDH domains by UNI interface; the same type of interface was used to connect the SDH domains to the optical network, see Figure 65. Therefore the clients of the IP layer provided UNI-C interfaces and the OXCs of the photonic layer UNI-N interfaces. The nodes of the SDH layer were able to handle UNI-C, UNI-N and I-NNI interfaces simultaneously. The Control Planes of the layers were interconnected via Ethernet. For the transport plane STM-1 and STM-16 interfaces were used. STM-1 connected the IP clients to the SDH layer and STM-16 connected the SDH layer with the photonic layer.

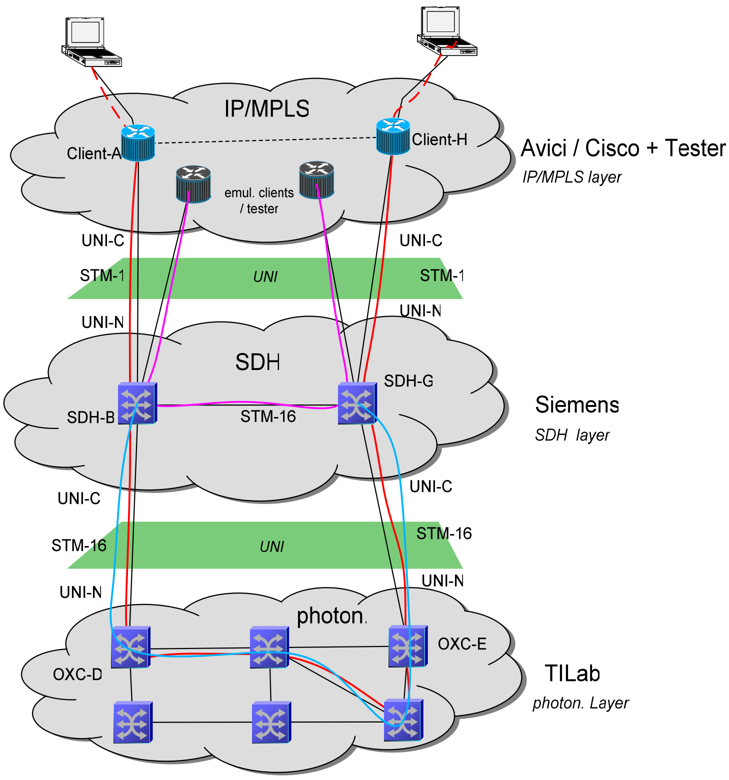


Figure 65 - Multi-layer connection setup (Cisco, Siemens, TILAB)

During testing the control plane functionality two experiments were carried out, involving devices and prototypes provided by Cisco, TILAB and Siemens. In the first experiment an IP client triggered the connection setup and tear down across the SDH layer to another IP client. In the second experiment the connection setup were triggered by the automatic LSP controller of the ingress node of the SDH layer and the connection were established across the photonic layer.

The correct functionality of the connection setup was checked by monitoring the RSVP signalling messages using the Ethereal network traffic analyzer. The transport plane connectivity across all three layers was tested by means of traffic generators and video stream application.

The interworking between Siemens, TILAB and Cisco equipment could be successfully demonstrated during the Nobel/Mupbed workshop in November 2005 at Turin.

Multi-layer, multi-domain virtual SPC – Joint test with the IST Project MUPBED

The objective of this experiment was to show the possible usage of the E-NNI interface for interconnecting photonic and SDH domains. It involves four domains made up by devices from three vendors interconnected by means of E-NNI interfaces. One of the domains has switching capability at fibre level and is made of six prototype photonics cross-connects developed by TILAB. The other three domains have SDH switching capabilities. Two domains are located at TILAB premises in Turin while the other two are in Berlin, at T-Systems premises.

The SDH devices used for the experiment are configured in the same way as they were during the OIF worldwide interoperability demo, held in June 2005 [OIF]. Both TILAB and T-Systems, together with other five carriers, participated in this event hosting the devices from different vendors. The equipment within a single location were interconnected both at data plane and control plane level. Figure 66 represents the network configuration and the LSP associated to the SPC created for the experiment.

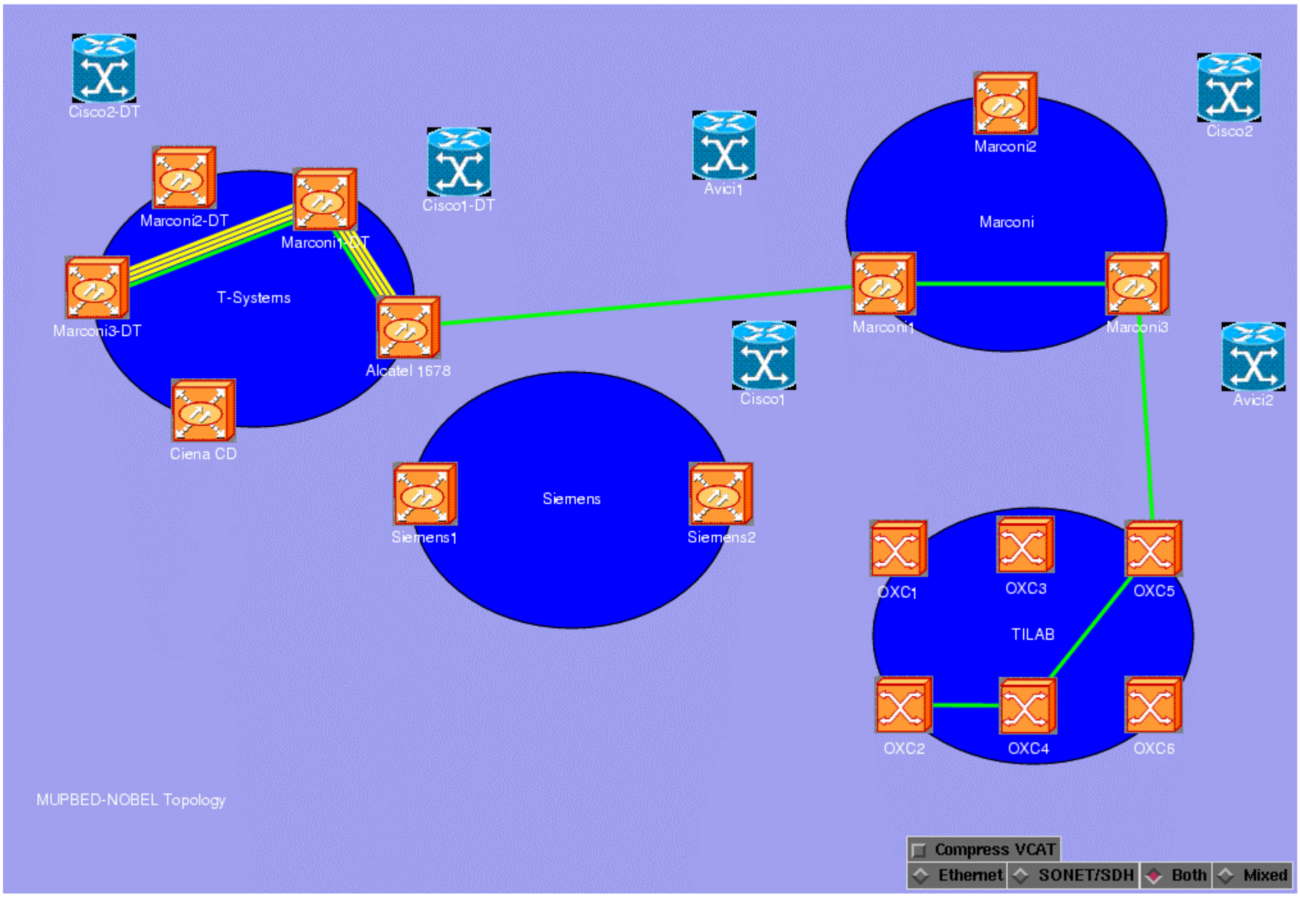


Figure 66 - SPC representation (green line) obtained by using the topology display software by Clearpond Technologies

This network configuration has been successfully demonstrated during the NOBEL/MUPBED joint workshop in November 2005 at Turin.

Control plane performance experiments

Experimental performance of GMPLS provisioning on all-optical ring-based MAN for SLA verification

This experiment is split in the following phases:

- Integration of control (GMPLS) and management (based on eXtendable Markup Language, XML, and Simple Network Management Protocol, SNMP) in a transparent intelligent DWDM network in order to perform dynamic provisioning of both SPCs and SCs [G.8080] using GMPLS, XML and SNMP. To examine the support of SPCs by means of temporary SCs, we model dynamic traffic as indicated in the table. Performance evaluation shows that the GMPLS control plane of the CTTC testbed is capable of performing automated provisioning of SPCs and SCs with service unavailability lower than 10-2 for γ>0.6 (SPC) and γ>0.85 (SC) when the total offered SC load is 50% of the total SPC, and γ>0.4 (for SPC) and γ>0.45 (for SC) when the total offered SC load is 10% of the total SPC load. It can be also inferred that the differences between uniform and hot-spot traffic are minor as the load decreases.

Parameter	Description	Expression	Default value in experiments
N	Number of nodes	–	9
λ_{SPC}	SPC mean arrival rate	–	Varies with γ
$1/\mu_{SPC}$	SPC mean holding time	–	100s
λ_{SC}	SC mean arrival rate	–	Varies with β
$1/\mu_{SC}$	SC mean holding time	$\alpha \times (1/\mu_{SPC})$	10s
ρ_{SPC}	SPC traffic load	$\lambda_{SPC} \times (1/\mu_{SPC})$	Ranges from 1 to 5 Er
ρ_{SC}	SC traffic load	$\lambda_{SC} \times (1/\mu_{SC})$	Ranges from 0.1 to 2.5 Er
ρ	Total traffic load	$\rho_{SPC} + \rho_{SC}$	Ranges from 1.1 to 7.5 Er
γ	Ratio of $1/\lambda_{SPC}$ and $1/\mu_{SPC}$	$1/\lambda_{SPC} = \gamma \times 1/\mu_{SPC}$	0.2 0.4 0.6 0.8 1
α	Ratio of $1/\mu_{SPC}$ and $1/\mu_{SC}$	$1/\mu_{SC} = \alpha \times 1/\mu_{SPC}$	0.1
β	Ratio of $1/\mu_{SC}$ and $1/\lambda_{SC}$	$1/\lambda_{SC} = \beta \times 1/\mu_{SC}$	$2 \times \gamma, 10 \times \gamma$
h	Probability that connection request is destined for hot-spot	–	$uniform$, 0.5

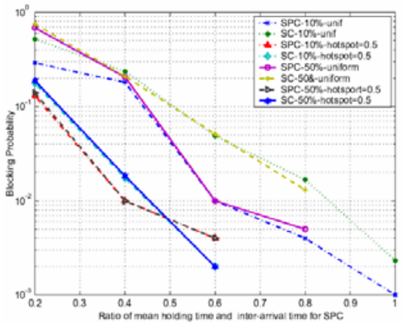


Figure 67 - Dynamic traffic model (left) and blocking probability for SPCs and SCs (right)

- Evaluation of the GMPLS RSVP signalling protocol of the CTTC test bed when provisioning optical connections generated by UNI-enabled clients emulated by a broadband tester, considering different dynamic traffic patters. SC traffic demand can follow both an uniform and a non-uniform scheme. The traffic model used in this experiment is complemented with real data from the Acreo test bed. In order to investigate the influence of non-uniform traffic load on the light-path blocking probability, the load between each node pair is given by:

$$\delta_{sd} = \frac{1/\mu}{1/\lambda_{sd} + (2X - 1)\varsigma}$$

where X is a uniformly distributed random value between 0.0 and 1.0 and ς is the non-uniformity factor. When $\varsigma = 0$, δ_{sd} becomes the uniform load.

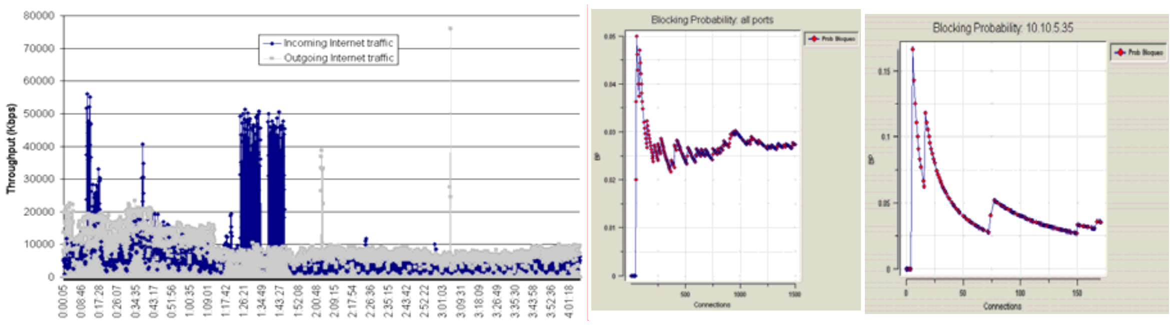


Figure 68 - Internet traffic in Acreo's Hudiksvall aggregation node and simulated blocking probability

- Evaluation of the impact of IP control channel parameters (Bandwidth, Packet delay and packet loss) on several GMPLS RSVP signalling schemes (e.g. bundle, summary refresh, reliable delivery).

Experimental performance of GMPLS fault management on all-optical ring-based MAN for SLA verification

Most of current metropolitan area networks are based upon fiber-ring architectures, as evidenced by the proliferation of multi-level SONET (SDH) rings. Given this large, entrenched base of ring topologies and the extensive experience operators have gained in operating SONET ring networks, it seems logical to plan for a migration to equivalent dynamic optical ring architectures based upon recent advances in optical networking technologies such as WDM, reconfigurable OADMs and OXCs, capable of providing high-bandwidth, end-to-end optical connections. On the other hand, network operators have become well-accustomed to the fast, timely recovery capabilities provided by SONET automatic protection switching (APS) that can achieve service recovery within 50ms after a fault event. Thus, these features must be kept in the new optical ring architectures. This experiment propose enhanced GMPLS recovery schemes for OMS and OCH fault management in Rings in order to provide service recovery within 50ms (SONET-like) after the fault event. Performance evaluation, in terms of recovery time, has been carried out in the ADRENALINE testbed.

Experimental GMPLS fault management for OMS transport ring networks
Experimental tests in ADRENALINE testbed with three nodes have shown that optical protection delay, that is, the time during which the working lightpaths do not have service is about 45ms, which is comparable to the SONET recovery levels. This delay also complies with the service level specifications considered within the NOBEL project for emergency and conversational services. An estimation of the control restoration delay has been obtained through pings each 100ms. Results shows that the control plane is out-of-service only around 2100ms, due to the elimination of the OSPF-TE HELLO messages used for detecting faults in the network.

Experimental GMPLS fault management for OCh transport ring networks
Experimental tests in ADRENALINE testbed with nine nodes have shown that optical protection delay is about 100ms, taking into account that switching time of TL1-based R-OADMs are about 70ms. The control plane is out-of-service only around 5s.

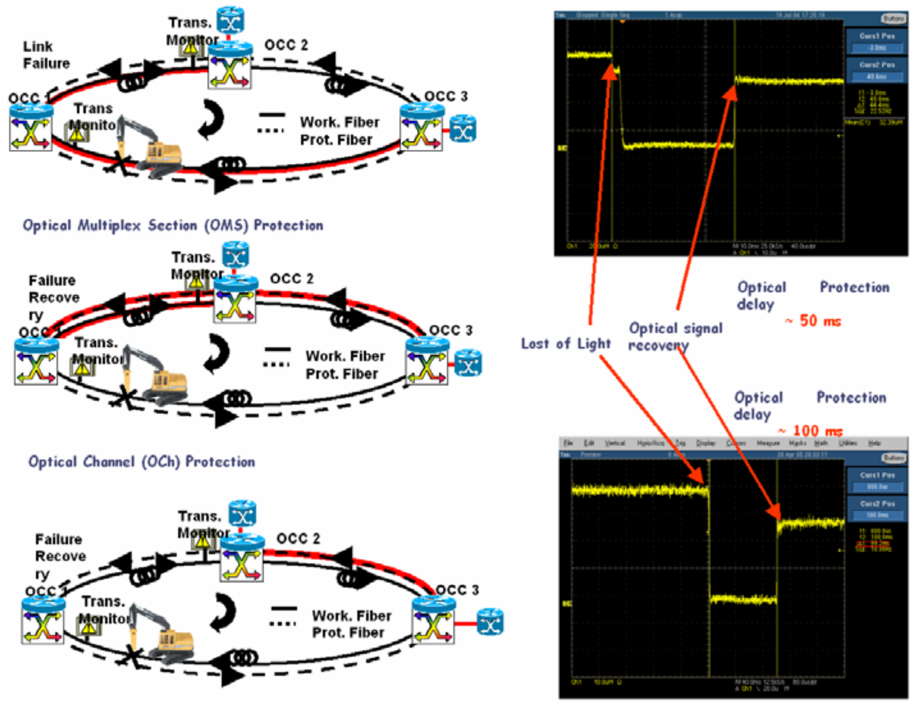


Figure 69 - Examples of optical protection delay measurements

GMPLS performance tests
This section describes conclusions derived from the experiments performed by the Lucent Enhanced GMPLS Emulator (eGEM) with respect to the path setup in the ASON/GMPLS optical control plane.
The first conclusion concerning the effect of the Link State Advertisement (LSA) on the path provisioning is that the setup time for a fixed number of hops is nearly constant, expect in the region where the LSA messages are exchanged between the neighbouring nodes, which correspond with jumps in the setup time. This is because the CPU has to process all the LSA messages to update the local database with status of the used available bandwidth in all the links in the network. Moreover, the LSA threshold is set to 50%, so the first peak occurs at connection 32, second at 48 etc.
Beside the effect of the LSA flooding, the number of hops in a path has also an effect on the setup time; this effect is expressed in the increasing of the setup time when the number of hops is increased, according the performed experiments we can conclude that the path setup time is nearly linear with the number of hops.
Another aspect of the performed experiments is the investigation of the effect of the LSA tuning on the path setup time. In this respect, we conclude that the mean path setup time decreases exponentially from LSA 0% till LSA 20%, after that the decrease of the setup time is nearly constant. It is to be noted, that the

behaviour of the mean path setup time with regards to the LSA threshold is nearly independent of the number of hops that take part in the routing.
It is important to note that the results obtained from the experiments are quite accurate; this is achieved by distributing the emulator nodes over different workstations (SUN) with the equal configuration. Further, the experiments are repeated a number of times in such way that the confidence level is kept above 95%.

Failure management, protection and restoration tests
Basic alarm processing management tests were performed and tested through node and link resets. In addition, innovative protection and restoration techniques featured by means of a distributed GMPLS control plane was analysed and verified, in single and multiple failure scenarios. Thereafter, a comparative analysis of different protection and restoration schemes has been performed in order to identify and characterize the different resilience mechanisms. Finally, validation and performance tests were carried out on LSP setup, protection and restoration topics.
These tests have been performed by means of the different resilience alternatives provided by TID's simulator. The test bed is based on six SDH GMPLS-enabled node emulators controlled by a network manager, implementing a proprietary control plane based on the standardized protocols OSPF and RSVP.
Setup and restoration times were collected for manually and automatically LSPs creation. Due to the fact that they have been taken on a simulator, it is not reliable to consider them as those expected in a real network, Nevertheless, the qualitative results can be taken into account for comparing the different approaches.
Next graphs show setup and recovery times for all types of protection and restoration schemes and also for all LSPs capacities:

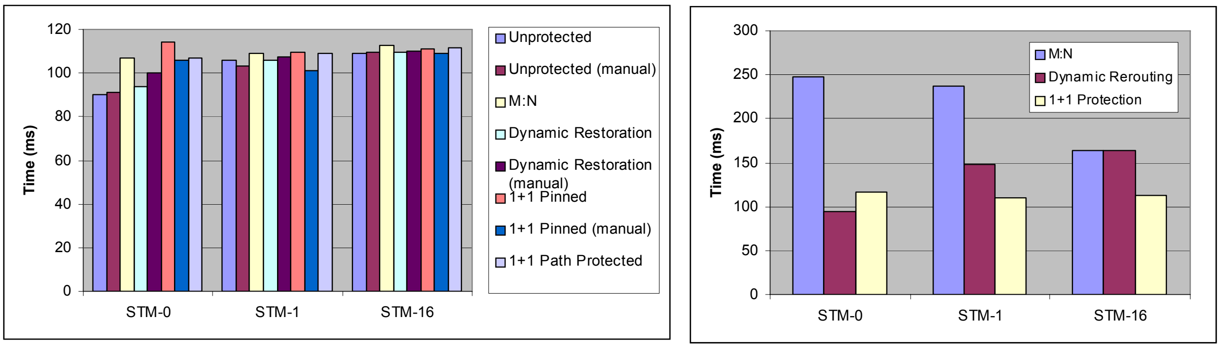


Figure 70 - Setup and recovery times

A comparative analysis of the setup times for a set of LSPs with different recovery mechanisms and different granularities shows the following:

- Setup time does not significantly change depending on the recovery mechanisms. Nevertheless, it is shown that protection and shared restoration approaches perform slightly worse than dynamic restoration or unprotected connections. These higher times (about 15 ms or a 30% increase) are due to the inherent added complexity in the establishment or selection of backup resources.
- While LSP capacity increases, setup time slightly increases too. This fact is based on the complexity of the routing algorithm used by the simulator for great granularities, and does not show further interest. The emulator is a "functional" emulator and it is not necessarily representative of actual network performance.
- 1+1 protection recovery time has proven to be constant, and similar to the setup. In this case, this time comprises the switch to the backup path.
- Restoration times are in general slightly higher to the setup times for a typical LSP. In addition, as the granularity increases the amount of resources necessary to redirect the traffic also increases. This issue significantly increments the recovery time for coarse granularities. Thus, the more restrictive the network status is, the worst performance the restoration process will show.

- On the contrary, M:N recovery times for lower granularity are much greater than those for coarser granularities. The path calculation time decreases as the number of pre-calculated resources to be chosen is reduced. Therefore, the more restrictive the network status is, the best performance (compared to other schemas) will be achieved by M:N recovery. This facts would require further study.

Interworking and traffic measurements

Investigation of interconnection aspects between broadband access networks and metropolitan networks – implementation and verification of a VPLS

This experiment aims at setting-up a Virtual-Private LAN Service (VPLS) connecting three geographically separated Ethernet LANs though Acreo's testbed. The test includes verification of basic functionality of the service, such as forwarding and MAC-address learning. Emulation of network services over an IP backbone network is a topic that currently attracts a lot of attention since it may enable a network convergence on the IP layer.

An important motivation for the work is that the resulting VPLS implementation may serve as a platform for future investigations where e.g. the level of QoS the emulated LAN supports in varying situations may be investigated.

In a VPLS a customer edge (CE) device is connected to the provider edge (PE) via an attachment circuit (AC). The provider edge is related to other PEs participating in the same VPLS instance by pseudowires (PW). The pseudowire is carried in a tunnel between the PEs (e.g. GRE, IPsec or MPLS LSP). A PE is in general connected to several PWs. The procedures for determining how a frame should be forwarded are called forwarder.

In Acreo's testbed the tunnel between the PE routers is realised by an MPLS LSP. The functionality of VPLS is split in control plane and data plane functionality. The controlplane functionality includes auto-discovery of new members of the VPLS and the set-up and tear-down of PWs for the inclusion and removal of VPLS members. The VPLS controlplane signalling is implemented with BGP extended communities.

The forwarding and encapsulation are dataplane functionalities. The forwarder is capable of MAC address learning, i.e. associating MAC addresses with logical ports. This functionality has been verified. When the PE receives a frame with unknown destination MAC address, this frame is forwarded on all ports. The encapsulation implemented is standard PW encapsulation.

The intention is to have a minimum of three members of the VPLS instance. However, so far we have only been able to implement two participating client networks. The functionality in the current status of the implementation is that of a Virtual Private Wire Service.

Traffic measurements

The Acreo real user end-to-end multi-service test bed provides a perfect environment to understand more about broadband user behaviour and to learn more about the traffic mix present in today's and tomorrows multi-service networks. This knowledge is crucial to be able to plan the architecture in open networks with many service providers where some of the services put high demands on quality of service.

In this measurement, internet traffic from about 70 households is analyzed. A traffic measurement system, Netintact's Packetlogic has been used for the evaluations. Packetlogic acts as a combined firewall/traffic shaper/statistics collector, which is transparent to the traffic passing through it. The traffic is separated on protocol/ application/ ip address/ ip network. All known applications such as http, ftp, kazaa, bit torrent, direct connect, gnutella etc… are recognized, independently of which port number is used. This is crucial today, since more and more applications are "clever" in using any open ports to transmit data.

The access technology in the residential areas in this test is Ethernet, and the specific equipment is Ericsson ELN (Ethernet Local Node). The households are supplied with Fast Ethernet (100 Mb/s) over multimode fibre. The internet service is rate limited to 25 Mb/s per ip address to the end user and all households in the test bed share a 24 Mb/s connection towards the Internet.

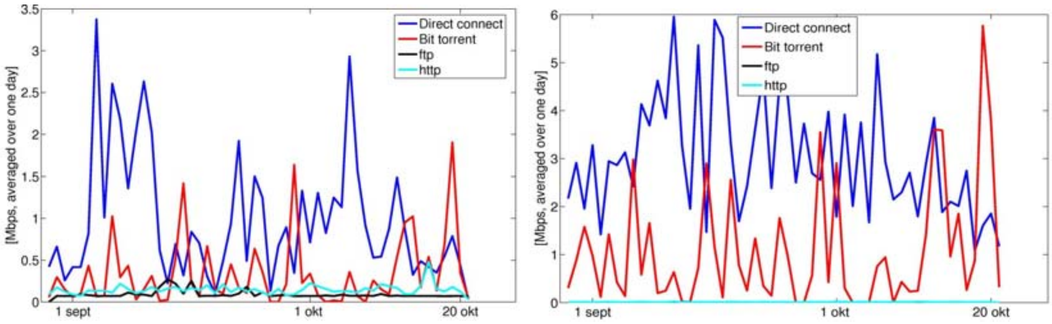


Figure 71 - Daily average downlink traffic by service for the most bandwidth demanding services, downlink (left), and uplink (right). Bit torrent and Direct Connect are peer-to-peer applications

The measurement shows that the bandwidth usage is dominated by peer-to peer traffic and that the uplink traffic is larger than the downlink traffic (see the figures above). The latter fact is probably due to the large and symmetric bandwidth enjoyed by the test-bed users. We have also observed that roughly 5-15 % of the users are dominating the bandwidth in this test. Only internet traffic was taken into account in this study. Otherwise IPTV would have been one of the most demanding services.

4 Conclusions

In conclusion, it can be stated that the NOBEL project has fully achieved its technical objectives producing a comprehensive vision of the transport networks evolution in the next years.

This vision is the result of the interplay between Network Operators requirements and technology capabilities foreseen by equipment manufacturers. It encompasses the long term designs of research centres and Universities as well.

The NOBEL technical results represent a detailed reference frame for the development of effective evolution strategies for all European countries, strongly enhancing the coherence of all efforts devoted to the construction of the Information Society.