SEVENTH FRAMEWORK PROGRAMME

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Final Report on integration activities in the Virtual Centre of Excellence on Network Technologies and Engineering

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Abstract:

This report provides a summary of the results achieved by the joint activities during the entire BONE project in the VCE on Network Technologies and Engineering. The report presents an overview of the organization of the work and of the results achieved in the executive summary and more detailed information on the Joint Activities carried on in the VCE.

Keyword list: optical networks, traffic engineering, OBS, OPS, protection, restoration, Carrier Grade Ethernet, technology survey.

1. Clarification:

Nature of the Deliverable

R	Report
P	Prototype
D	Demonstrator
O	Other

Dissemination level of Deliverable:

PU	Public
PP	Restricted to other programme participants (including the Commission Services)
RE	Restricted to a group specified by the consortium (including the Commission Services)
CO	Confidential, only for members of the consortium (including the Commission Services)

Disclaimer

The information, documentation and figures available in this deliverable, is written by the BONE ("Building the Future Optical Network in Europe*) – project consortium under EC co-financing contract FP7-ICT-216863 and does not necessarily reflect the views of the European Commission*

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2. Executive Summary

This document summarizes the integration activities performed within the VCE on Network Technologies and Engineering.

2.1 Participation

149 researchers belonging to 42 partner institutions registered to WP11 in the BONE directory service. This is a measure of the general interest for the topics addressed by the WP. The involvement of partners and researchers is uneven, ranging from active participation to several joint activities to a more basic auditory participation.

The partners involved are UPC - BILKENT - TUW - SSSUP - UPCT - UAM - AIT - UCL - FPMs - PoliTO - GET - USWAN - UNIBO - CTTC - UNIMORE - Ericsson - KTH - UniRoma1 - UniRoma3 - BME - FUB - IT - AGH - UoP - TID - UC3M - FER - CORITEL - FT - UPVLC - UST-IKR - TUB - PoliMI - COM - UEssex - IBBT - WUT - UDE - TUE - RACTI - HWDE – TELENOR.

2.2 Joint research Activities (JAs)

The R&D effort in WP11 was devoted to run the JAs. All over 15 JAs were part of WP11, some ended at the end of the second year, some started during the second year and run till the end of the project and some run all ver the project duration. A description of objectives and findings of the JAs that were completed at the end of year 2 can be found in the WP11 second year Deliverable [D11.2]. The WP leader took care to avoid overlapping with JAs in other WPs and within the WP. For this reason some topics, that are indeed relevant for WP11, are not investigated. These topics are investigated in the framework of the TPs and WP11 will rely on the results produced there. Moreover it is worth reminding that, at least in the understanding of the WP leader according to his previous experience, a VCE does not have as major goal the steering of the direction of the research (more typical for a TP).

Table 1 shows title, participants and responsible person of the JAs that were completed during BONE. Some JAs were completed at the end of Y2 as indicated in the Status column. All the other JAs will be completed at the end of the project, more or less at the same time of the delivery of this document.

Activity #	Activity Title	Partners	Responsible	Status
1	Common Architecture/Hierarchy for integration of OCS, OBS, and OPS in a common transport plane	TUW, DTU, AGH, GET/ENST, PoliTO, UEssex	Gerald Franzl	**Completed Y2**
2	Comparative techno-economic network planning in OCS/OBS/OPS networks	UPCT, TID, UNIRM, FT, AGH	Pablo Pavon Marino	**Completed Y3**
3	Experimental tests of Carrier Ethernet techniques	FUB, UNIROMA3, UNIROMA1, UNIBO, UNIMORE, KTH, CORITEL	Francesco Matera	**Completed Y3**
4	Extension of the Flow-Aware Networking (FAN) architecture to the IP over WDM environment	GET/ENST, AaM, AGH	Victor Lopez Alvarez	**Completed Y3**
5	Network planning algorithms considering fault tolerance, security threats and periodic traffic patterns	FER, KTH, UPCT, IT, AIT, GET	Nina Skorin-Kapov	**Completed Y3**
6	On exploring Admission Control Mechanisms for OBS networks	UAM, UC3M, UniMORE	José Alberto Hernández	**Completed Y2**
7	PCE for Multi-domain Traffic Engineering	SSSUP, PoliMI	Filippo Cugini	**Completed Y3**
8	Resilience analysis of double rings with dual attachments	UAM, TID, AGH	José Alberto Hernández	**Completed Y2**
9	Traffic engineering and topology design in metro networks	SSSUP, GET/ENST	Isabella Cerruti	**Completed Y3**
10	Survey on OBS routing methods for OBS networks	UPC, IT	Mirek Klinkowski	**Completed Y2**
11	Effects of outdated control information on routing in optical networks	POLIMI, CTTC	Achille Pattavina	**Completed Y3**
12	NETBENCH "Benchmarking of network architectures for guaranteed service provisioning"	UoP, UEssex PoliTO, UniBO, GET, UAM, UC3M	Theofanis Orphanoudakis	**Completed Y3**
13	Adaptive Admission Control in Dynamic GMPLS Networks	UC3M, UPV	David Larrabeiti	**Completed Y3**
14	Server file-exchange in OBS networks	UAM, Uessex	Victor Lopez Alvarez	**Completed Y3**
15	Sharing of resources in GMPLS-controlled WSONs	CTTC, SSSUP, DTU	Raul Munoz	**Completed Y3 (from WP22)**

Table I. List of WP11 Joint activities

A brief summary of the topics addressed by the JAs is presented in the following.

2.2.1 Optical Burst and Packet Switching

OBS and OPS are rather mature research topics and the JAs devoted to this area were mainly of review type.

A JA was devoted to a survey on routing methods in OBS. It started from the awareness that in the literature very few works try to put together and classify the great variety of routing strategies that have been proposed for OBS networks. The study showed that both linear and non-linear optimization methods deal effectively with the routing problem in OBS networks, but also outlined that proposed methods are designed in particular for networks with a full wavelength conversion capability while it must be noticed that few routing solutions are intended for wavelength conversion-less networks. This observation may stimulate further research.

The problem of admission control in OBS was also investigated by proposing the Random Packet Assembly Admission Control mechanism (or RPAAC), a policy which is designed to drop packets at the border OBS nodes when the network load exceeds a certain threshold. RPAAC includes a monitoring stage whereby all network links are examined, the traffic flows causing excess traffic per link are identified. This information is sent back to the border nodes, which adjust the admission control probability for each individual flow. This study shows that RPAAC is capable of maintaining the load levels within acceptable performance levels.

Three JAs considered both OBS and OPS. Two aimed at establishing some benchmarking strategy to compare different optical switching technologies. The former aims at a cost/performance comparison between OBS/OPS mesh networks, by defining a reference network scenario and by defining the major cost/performance parameters to be considered. The latter wants to define a reliable benchmarking scenario to compare optical circuit, burst and packet switching in terms of CAPEX and OPEX, with specific reference to the capability of providing dynamic resource allocation and/or guaranteed end-to-end performance. Issues that are considered relevant include: topology definition, node functionality, realistic traffic models, control plane issues, integration between access and core and node architectures for multi-service traffic scenarios. Work is still ongoing to provide a comprehensive evaluation of the different aspects considered.

Finally a JA studied options to integrate all three optical switching paradigms (OCS, OBS, and OPS) in a single transport plane. It mainly analysed the issue of deploying a GMPLS controlled OBS network, outlining that a full integration will imply some extensions to the MPLS protocol and additional overhead to control the massive requests for resources allocation of OBS.

2.2.2 Protection and restoration

This is a well-investigated topic and the JAs in this area tackled problems arising in real implementation of the protection/restoration strategies.

A JA extended previous works related to the impact of delayed control information on the network. The investigation analyzed the performance loss over three different dimensions: (1) the value of control delay; (2) the routing strategy adopted (namely, unprotected, dedicated path protected and shared path protected); (3) the conversion capabilities (the wavelength convertible case will be referred as Virtual Wavelength Path, VWP, as opposite to the not wavelength convertible case referred to as Wavelength Path, WP). This work was also extended with the experimental evaluation of the impact of the outdated information in the ADRENALINE testbed.

Another JA, starting from the consideration that ring topologies for MANs are typically not protected against multiple failures, proposed an evolutionary path towards meshed topologies based on Double Ring with Dual Attachment (DRDA). The JA evaluated the reliability and availability metrics of DRDA topologies following the well-known pre-configured protection cycles (p-cycles) approach as their main recovery mechanism. The proposed analytical tools evaluate: (1) the repairing times that a network operator must guarantee to achieve a given service availability; (2) the service availability offered by different size DRDA topologies and their implications in adding new nodes in the inner and outer rings; (3) the service availability with respect to the amount of backup capacity dedicated to recover from failures.

2.2.3 Experimental

A JA was devoted to the experimental demonstration of techniques for core and metro networks. The experimental activities focused on the routing processes that are migrating from layer 3, where Carrier Ethernet will play a key role. Specific studies addressed techniques for full Carrier Ethernet solution: VPLS, MPLS-TP, IEEE 802.1ad (Q in Q), IEEE 802.1ah (MAC in MAC) and PBB-TE, taking into account topics of protection, restoration, traffic engineering, congestion resolution and resource allocation, especially for architectures based on GMPLS control plane.

Experimental activities were implemented, to test transport solutions based on Carrier Ethernet. The experiments focused on the use of VPLS.

The experiments confirmed that VPLS offers already the features required by WAN transport services based on Ethernet:

- can be used to control the QoS in access networks with a limited bandwidth (e.g. in xDSL, in PON networks etc.);
- is compatible with novel optical technologies such as all optical wavelength conversion, which was tested based on Four Wave mixing in DS fibre, showing that no signal degradation was introduced;
- it is possible to use MPLS restoration and protection techniques in VPLS, in particular, Fast Reroute and Standby Secondary Path in VPLS were implemented demonstrating that VPLS allows restoration times under 50 ms, with performances comparable to SDH/SONET with VPLS FRR performing better than VPLS SSP;
- WDM GbE transmissions can be used on long distance and a link span up to 350 km was demonstrated by using all optical amplifiers.

2.2.4 Network planning and traffic engineering

A number of joint activities were devoted to network planning and traffic engineering improvements of knows results and new emerging techniques were achieved and developed.

Flow-Aware Networking (FAN) represents an interesting approach to traffic engineering, which may permit network operators to overcome some of the issues posed by packet-based schemes. A JA was devoted to FAN with the goal to apply the flow based approach to the IP over WDM traffic engineering problem. Such JA used a technique called *Multilayer Flow-Aware Networking* (MFAN) that exploits the capability of the optical layer to solve congestion arising at the IP layer. In particular, when a multi-layer node detects congestion at the IP layer, additional resources are requested to the optical layer by establishing new lightpaths according to three different policies based on the flow age or activity level. The performances of such policies are compared under TCP and UDP traffic resulting in different trade-offs. Recent developments include the introduction of a recovery mechanism, which exploits both IP and optical layers in case of link/node failures, and the definition of an effective and fair admission control policy called *Enhanced Flushing Mechanism with Priorities (EFMP)*.

Another JA investigated a novel optical network planning approach that takes into account device faults and physical-layer attacks in a comprehensive way during the Routing and Wavelength Assignment phase. As a result a useful fault/attack prevention tool that reduces the potential attack consequences without the need for expensive specialized equipment. In particular, the algorithms that choose how to route and assign wavelengths to lightpaths are designed with the goal of minimizing the *Lightpath Attack Radius* (LAR), i.e. the possible service disruption caused by out-of-band crosstalk attacks. Recent developments in this direction include the definition of new objectives for minimizing the *Propagating Crosstalk Attack Radius (PCAR)* that takes into account also intra-channel crosstalk attacks and their detrimental propagating effects.

Traffic engineering in multi-domain network environments is still an open issue, due to the limited inter-domain visibility of network topology and resource availability. Although solutions to this problem based on the *Path Computation Element* (PCE) architecture have been recently proposed, such as the *Backward Recursive PCE-based Computation* (BRPC), limited work has been done in understanding how to extend current inter-domain routing protocols, i.e. BGP, in order to take advantage of the potential benefits of the PCE-based procedures. A JA investigated this issue and proposed *Hierarchical BGP* (HBGP) as a path-vector protocol dedicated to collect network views, from a limited number of authorized domains, with the goal of pre-computing the optimal sequence of domains to be traversed toward the destination. Different schemes to apply the proposed HBGP-PCE architecture have been defined and analyzed through simulation. In addition, a network test-bed based on HBGP-PCE has been implemented using commercial equipment.

A JA was devoted to traffic engineering in WDM optical MANs with ring topology, where each node is equipped with a single tunable transmitter and multiple fixed-wavelength receivers. An optimization study for topology design aimed at reducing the cost due to receivers and wavelengths is presented, showing significant results in terms of channel sharing capability and cost reduction were achieved with respect to existing ring architectures. In the third year the study focused on evaluating the stability conditions arising from the packet switched nature of the ring. Stability conditions were derived and included in the optimization problem, leading to a minimum-cost stable design of the optical packet-switched ring.

A further JA deals with Admission Control (AC) techniques in GMPLS-based networks as a way to achieve efficient resource management and provide QoS guarantees. A novel adaptive AC scheme for all-optical packet-based GMPLS networks is proposed, where an ingress node is in charge of establishing new LSPs between edge nodes while trying to maximize the throughput and meet specific QoS requirements. Two priority classes are defined within an adaptive, pre-emptive AC mechanism that extends a well-known policy called *Fractional Guard Channel* (FGC). Simulation results show the effectiveness and adaptability of the proposed approach.

2.3 Integration Results

2.3.1 Joint Research Papers

The various JAs achieved several interesting scientific results. As at the third periodic report of project year 3, the total number of joint papers sum up to 57. The complete list is attached.

Some statistical data per project year are presented in the following table:

	Year 1	Year 2	Year 3 (M9)	Total
# of Papers	12	32	13	57
# of Co-authors	66	183	73	322
Co-authors per paper (average)	5.5	5.7	5.6	5.65
# Institutions	21	25	18	28

Table 1. Statistics of joint papers per project year

The number of authorships per partner institution are plotted in Figure 1, subdivided per project year, and in Figure 2 in total. It is worth noting the highest numbers for year 2 with respect to year 1. This increase is a proof of the increased amount of integrated works developed as a results of the joint activities. In year 3 the number of joint works is less both because the figures related to the last reporting period of the year are missing and because some joint activities terminated at the end of year 2. It is reasonable to imagine that some more joint publications will be reported in the fourth reporting period and some other will follow after the end of the project, due to the delays in the journal review/publication time frame.

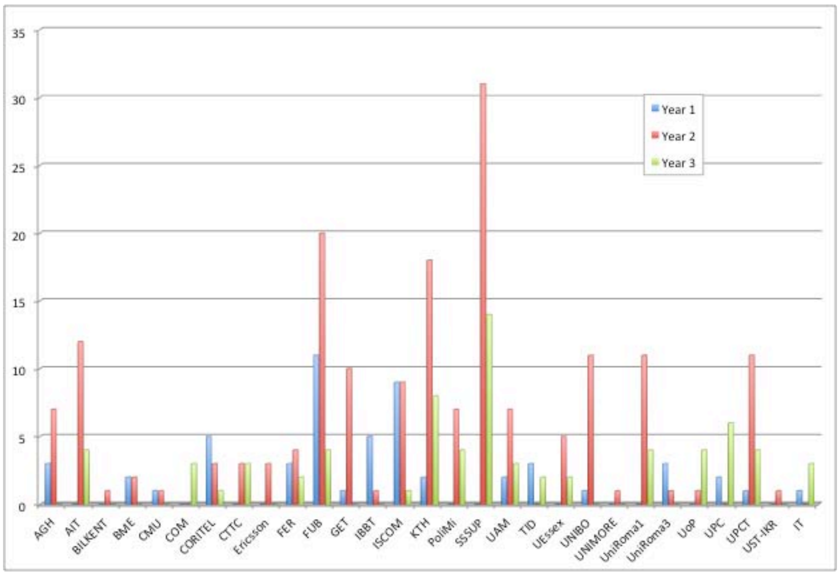

Figure 1. Number of joint paper authorships per partner institution and per project year.

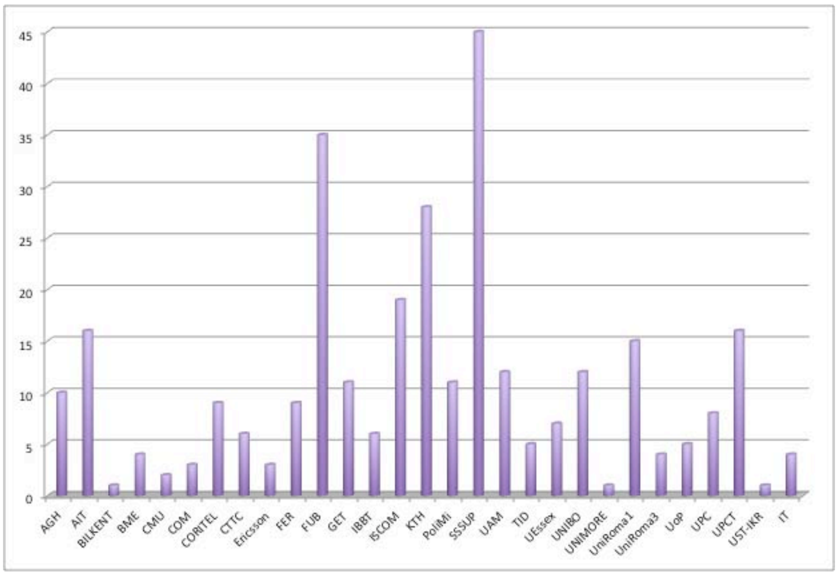

Figure 2. Total number of joint paper authorships per partner institution

The joint papers were published in journals (19) and international conferences on optical networking (38) as plotted in Figure 3. Among the conferences are outlined participations to ECOC and OFc as the two major conferences on optical technologies, indeed closely related to topics of interest of WP11.

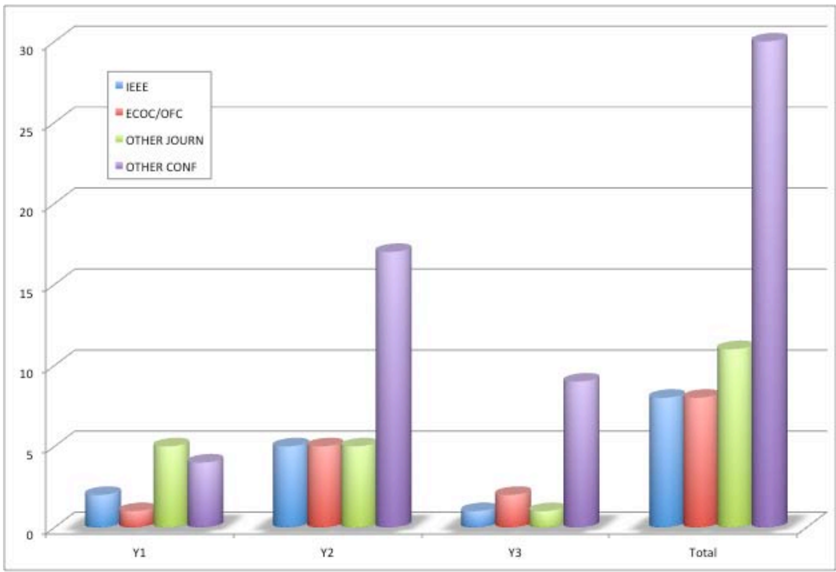

Figure 3. Joint publications placement per project year.

List of joint publications updated at the end of the third periodic reporting period of project year 3.

1 L. Wosinska (KTH), A. Jirattigalachote (KTH), P. MONTI (KTH), A. Tzanakaki (AIT), K. Katrinis (AIT), Energy Efficient Approach for Survivable WDM Optical Networks, IEEE International Conference on Transparent Optical Networks (ICTON), Munich, July 2010. (WP11 WP12 WP22)

2 N. Sambo (SSSUP), Y. Pointurier (AIT), P. Castoldi (SSSUP), I. Tomkos (AIT), Lightpath establishment in distributed GMPLS-controlled dynamic transparent optical networks using Quality of Transmission estimation, ICTON, Munich, July 2010. (WP11)

3 R. Aparicio-Pardo (UPCT), P. Pavon-Marino (UPCT), N. Skorin-Kapov (FER), B. Garcia-Manrubia (UPCT), J. Garcia-Haro (UPCT), Algorithms for virtual topology reconfiguration under multi-hour traffic using Lagrangian relaxation and tabu search approaches, Proceedings of 12th International Conference on Transparent Optical Networks (Icton 2010), June 2010. (WP11)

4 V. Eramo (UniRoma1), A. Cianfrani (UniRoma1), M. Listanti (UniRoma1), A. Germoni (CORITEL), P. Cipollone (UniRoma1), F. Matera (FUB), Performance Evaluation of OTDM/WDM Networks in Dynamic Traffic Scenario, ICTON 2010, June 2010. (WP11 WP14 WP24)

5 A. Manolova (COM), S. Ruepp (COM), R. Munoz (CTTC), R. Casellas (CTTC), R. Martinez (CTTC), I. Cerutti (SSSUP), N. Sambo (SSSUP), A. Giorgetti (SSSUP), N. Andriolli (SSSUP), P. Castoldi (SSSUP), Shared Path Protection in GMPLS Networks with Limited Wavelength Conversion Capability, Proc. of 11th International Conference on High Performance Switching and Routing , June 2010. (WP11)

6 T. Orphanoudakis (UoP), A. Drakos (UoP), C. Politi (UoP), A. Stavdas (UoP), G. Zervas (UEssex), D. Simeonidou (UEssex), A Hybrid Reservation Mode for Optical Fast Circuit Switching, 15th European Conference on Networks and Optical Communications (NOC), Faro, Portugal, June 2010. (WP11)

7 M. Lucci (FUB), A. Valenti (FUB), F. Matera (FUB), D. Del Buono (ISCOM), Investigation on fast MPLS Restoration Technique for a GbE Wide Area Transport Network: a Disaster Recovery Case, IEEE ICTON 2010 Conference, Munich, June 2010. (WP11)

8 N. Skorin-Kapov (FER), J. Chen (KTH), L. Wosinska (KTH), A New Approach to Optical Networks Security: Attack Aware Routing and Wavelength Assignment, IEEE/ACM Transactions on Networking, Vol. 18, No. 3, pp. 750-760, June 2010. (WP11)

9 L. Buzzi (PoliMI), M. Conforto Bardellini (PoliMI), D. Siracusa (PoliMI), G. Maier (PoliMI), F. Paolucci (SSSUP), F. Cugini (SSSUP), L. Valcarenghi (SSSUP), P. Castoldi (SSSUP), Hierarchical Border Gateway Protocol (HBGP) for PCE-based Multi-domain Traffic Engineering, International Conference on Communications (ICC) 2010, May 2010. (WP11)

10 M. Klinkowski (UPC), J. Pedro (IT), D. Careglio (UPC), M. Pióro (Institute of Telecommunications, Warsaw University of Technology), J. Pires (IT), P. Monteiro (IT), J. Solé-Pareta (UPC), An overview of routing methods in optical burst switching networks, Optical Switching and Networking, Vol. 7, No. 2, pp. 41-53, April 2010. (WP11)

11 L. Velasco (UPC), A. Jirattigalachote (KTH), P. Monti (KTH), L. Wosinska (KTH), S. Spadaro (UPC), G. Junyent (UPC), Probabilistic-based Approach for Fast Impairments-aware RWA in All-Optical Networks, Proceedings of OFC, San Diego, CA, USA, March 2010. (WP12 WP11)

12 A. Giorgetti (SSSUP), N. Andriolli (SSSUP), S. Ruepp (COM), P. Castoldi (SSSUP), PCE-based vs. Distributed Set Up of Bidirectional Lightpaths in GMPLS-controlled Optical Networks, Optical Fiber Communication (OFC/NFOEC 2010) Conference, San Diego, March 2010. (WP11)

13 V. Lopez (UAM), B. Huiszoon (UAM), O. González de Dios (TID), J. Fernández Palacios (TID), J. Aracil (UAM), Path Computation Element in Telecom Networks: Recent Developments and Standardization Activities, Optical Networking Design and Modeling (ONDM), February 2010. (WP11)

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16 L. Wosinska (KTH), A. Jirattigalachote (KTH), P. Monti (KTH), K. Katrinis (AIT), A. Tzanakaki (AIT), Lightpath Routing Considering Differentiated Physical Layer Constraints in Transparent WDM Network, IEEE/OSA/SPIE Asia Communications and Photonics Conference ACP2009, Shanghai, November 2009. (WP11 WP22)

17 J. Domzal (AGH), R. Wójcik (AGH), K. Wajda (AGH), A. Jajszczyk (AGH), V. Lopez (UAM), J. A. Hernandez (UAM), J. Aracil (UAM), C. Cardenas (GET), M. Gagnaire (GET), A Multi-layer Recovery Strategy in FAN over WDM Architectures, Design of Reliable Communication Networks, Washington D. C. (USA), October 2009. (WP11)

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19 B. Uscumlic (GET), A. Gravey (GET), P. Gravey (GET), I. Cerutti (SSSUP), Traffic Grooming in WDM Optical Packet Rings, ITC'09, September 2009. (WP11)

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2.3.2 Book Publication

An important achievement in terms of joint publications was the book “*Enabling Optical Internet with Advanced Network Technologies*”, J. Aracil and F. Callegati editors, published by Springer, UK, July 2009. This was the joint effort of 32 researchers belonging to 15 institutions partner of the BONE consortium. This work was started during the e-Photon/One+ project and finalised during BONE (the book acknowledges both project). The book was organized into an introduction and 5 chapters, which were edited by a chapter editor with the help of several contributors.

The 230 pages book offers an overview of advanced optical networking, focusing on the expertise of the research groups involved. It counts 286 references and a number of figures and examples.

The list of chapters, with chapter editors and contributors is as follows.

- Introduction - Franco Callegati ed. (UNIBO), Javier Aracil (UAM), Vıctor Lopez (UAM)
- Introduction to IP over WDM - Davide Careglio ed. (UPC), Javier Aracil (UAM), Juan Fernandez Palacios (TID), Andrzej Jajszczyk (AGH), David Larrabeiti (UC3M), Vıctor Lopez (UAM), Xavier Masip (UPC), Sergio Sanchez (UPC), Salvatore Spadaro (UPC)
- Optical Packet Switching – Carla Raffaelli ed. (UNIBO), Slavisa Aleksic (TUW), Franco Callegati (UNIBO), Walter Cerroni (UNIBO), Guido Maier (POLIMI), Achille Pattavina (POLIMI), Michele Savi (UNIBO)
- Optical Burst Switching – Jose Alberto Hernandez ed. (UAM), Vıctor Lopez ed. (UAM), Jose Luis Garcıa Dorado (UAM), Reza Nejabati (UESSEX), Harald Overby (NTNU), Ahmad Rostami (TUB), Kyriakos Vlachos (UPATRAS), Georgios Zervas (UESSEX)
- Advanced Optical Burst Switched Network Concepts – Reza Nejabati ed. (UESSEX), Javier Aracil (UAM), Piero Castoldi (SSSUP), Marc De Leenheer (UGent), Dimitra Simeonidou (UESSEX), Luca Valcarenghi (SSSUP), Georgios Zervas (UESSEX), Jian Wu (BUPT-China)
- Optical Switch Fabrics and Their Application, Kyriakos Vlachos ed. (UPATRAS), Lambros Raptis (Attica Telecom), Antonio Teixeira (UA), Giorgio Maria Tosi Beleffi (ISCOM), Kostas Yiannopoulos (UPATRAS)

2.3.3 Mobility

Mobility of researchers is another important measure of integration. A total of 26 mobility actions took place during the three years of the BONE project. The duration of such mobility actions varies largely from just a few days up to several months. The average duration was 38 days.

Table 2 presents a summary of the number of mobility actions as well as of their total duration. It is easy to see that the number of mobility actions increased year by year reaching its largest value during project tear 3. Such increase demonstrates that the ongoing collaboration between partners was successful and required an additional effort on integration (by mobility actions) in the third year. Most mobility actions were in support of the joint activities and it is reasonable to expect that the high number of mobilities during project year 3 will result in a number of joint publications and works after the end of the project.

	Number of mobilities	*Total duration (days)*	*Average duration (days)*
Year 1	*4*	*246,00*	*61,50*
Year 2	*7*	*162,00*	*23,14*
Year 3	*15*	*571,00*	*38,07*
Total	*26*	*979,00*	*37,65*

Table 2. Statistics of joint papers per project year

The full list of mobility actions is as follows.

- *"Network planning algorithms considering fault tolerance, security threats and periodic traffic patterns" JiaJia Chen, PhD student at KTH, hosted by FER from 18/04/2008 to 05/05/2008*
- *"Benchmarking of network architectures for guaranteed service provisioning" Michele Savi, PhD student at UNIBO, hosted by UEssex from 27/05/2008 to 07/12/2008*
- *"Network planning algorithms considering fault tolerance, security threats and periodic traffic patterns" Nina Skorin-Kapov, Assistant Professor at FER, hosted by KTH from 29/08/2008 to 14/09/2008*
- *"Network planning algorithms considering fault tolerance, security threats and periodic traffic patterns" Nina Skorin-Kapov, Assistant Professor at FER, hosted by UPCT from 22/11/2008 to 07/12/2008*
- *"Algorithm approach for the design of a WDM ring with optical traffic grooming" Isabella Cerutti, Assistant Professor at SSSUP, hosted by GET from 25/01/2009 to 01/02/2009*
- *"An analytical reliability analysis of DRDA architecture" Jerzy Domzal, assistant at AGH, hosted by UAM from 21/02/2009 to 07/03/2009*
- *"Evaluation of Congestion Control Mechanisms for Flow-Aware Networking (FAN) networks under Grid environment" Robert Wojcik, Ph D student at AGH, hosted by UAM from 21/02/2009 to 07/03/2009*
- *"Network planning algorithms and optimization considering periodic traffic patterns" Nina Skorin-Kapov, Assistant Professor at FER, hosted by UPCT from 14/04/2009 to 05/06/2009*
- *"SLA-aware Provisioning in Optical Transport Network" Massimo Tornatore, Assistant researcher at PoliMI, hosted by KTH from 07/05/2009 to 09/05/2009*
- *"Planning of Scheduled Virtual Topologies Under Periodic Traffic in Transparent Optical Networks" Ramon Aparicio-Pardo, PhD Student at UPCT, hosted by FER from 21/09/2009 to 23/11/2009*
- *"Comparative evaluation optical switching technologies (related to JA2, WP11)" Pablo Pavon-Marino, Associate Professor at UPCT, hosted by PoliTO from 23/11/2009 to 26/11/2009*
- *Dynamic Optical Multicast for Ultra High Definition Media Malek Ghandour, PhD Student at UEssex, hosted by ORC from 08/02/2010 to 11/02/2010*
- *Server file-exchange in OBS networks Victor Lopez, Assistant Professor at UAM, hosted by UEssex from 08/02/2010 to 08/08/2010*
- *Power consumption evaluation in optical switching fabric Carla Raffaelli, Associate Professor at UNIBO, hosted by UniRoma1 from 18/02/2010 to 18/02/2010*
- *Attack-aware lightpath routing under physical impairments constraint Amornrat Jirattigalachote, PhD student at KTH, hosted by FER from 08/03/2010 to 27/03/2010*
- *Impact of physical layer impairments on Carrier Ethernet control plane schemes Domenico Siracusa, PhD student at PoliMI, hosted by UPC from 24/03/2010 to 06/09/2010*
- *Optimization and planning in optical networks - multihour and attack-aware planning Nina Skorin-Kapov, Assistant Professor at FER, hosted by UPCT from 25/04/2010 to 23/05/2010*

- *Attack-aware planning in optical networks Marija Furdek, PhD student at FER, hosted by KTH from 26/04/2010 to 13/05/2010*
- *Attack-aware traffic provisioning in optical networks Konstantinos Georgakilas, Researcher at AIT, hosted by KTH from 01/05/2010 to 08/05/2010*
- *Optical network Design with Mixed Line Rate Massimo Tornatore, Assistant Professor at PoliMI, hosted by KTH from 02/07/2010 to 09/07/2010*
- *SPP in translucent WDM netwoks with physical impairments. Anna Manolova, Post Doc at COM, hosted by SSSUP from 28/09/2010 to 13/10/2010*
- *Comparative planning in optical networks Pablo Pavon-Marino, Associate Professor at UPCT, hosted by PoliTO from 04/10/2010 to 10/12/2010*
- *Optimization and planning in optical networks - multihour and attack-aware planning Nina Skorin-Kapov, Assistant Professor at FER, hosted by UPCT from 07/10/2010 to 23/10/2010*
- *Methods of realizing of admission control policies in Flow-Aware Networks Jerzy Domzal, Ph.D. Assistant Professor at AGH, hosted by UAM from 20/10/2010 to 26/10/2010*
- *Admission control policies in Flow-Aware Networks Robert Wojcik, Ph D student at AGH, hosted by UAM from 20/10/2010 to 26/10/2010*
- *Network monitoring and attack-aware planning approaches Marija Furdek, PhD student at FER, hosted by AIT from 01/11/2010 to 19/11/2010*

2.3.4 Meetings

WP11 organized plenary meetings, jointly with WP12 WP21 WP22 WP24 WP26 in June of Year 1 and year 2. These meetings were important to steer the joint activities and harmonize the topics addressed in WP11 with those addressed in related WPs.

The plenary meeting in Year 2 was in Bologna, lasted 2 days (June 8 and 9) and was organized as a workshop, with one session per WP, including a general presentation of the WP current results and some technical presentation of the selected JAs. About 60 researchers attended the meeting, as reported in the related minutes.

Several other meetings in real life or virtual were held within the various JAs to discusses the workplan and the advance of results.

2.3.5 Teaching and dissemination

WP11 participated actively in the teaching and dissemination activities within BONE.

Regarding teaching activities WP11 members actively contributed to the Summer and Master schools organized by the project, for instance the WP11 project leader gave a lecture at the 2009 Summer School and at the 2010 Master School.

Regarding dissemination the activities funded within WP11 were disseminated by means of the several joint aforementioned publication. Moreover presentations summarizing the work in WP11 were prepared yearly to be shown at ECOC and, for the booth at ECOC 2010, was also printed with the contribution of all partners a poster devoted to WP11 (Figure 4). The project coordinator also presented a paper summarizing the VCE findings at ICTON 2010 [CC2010].

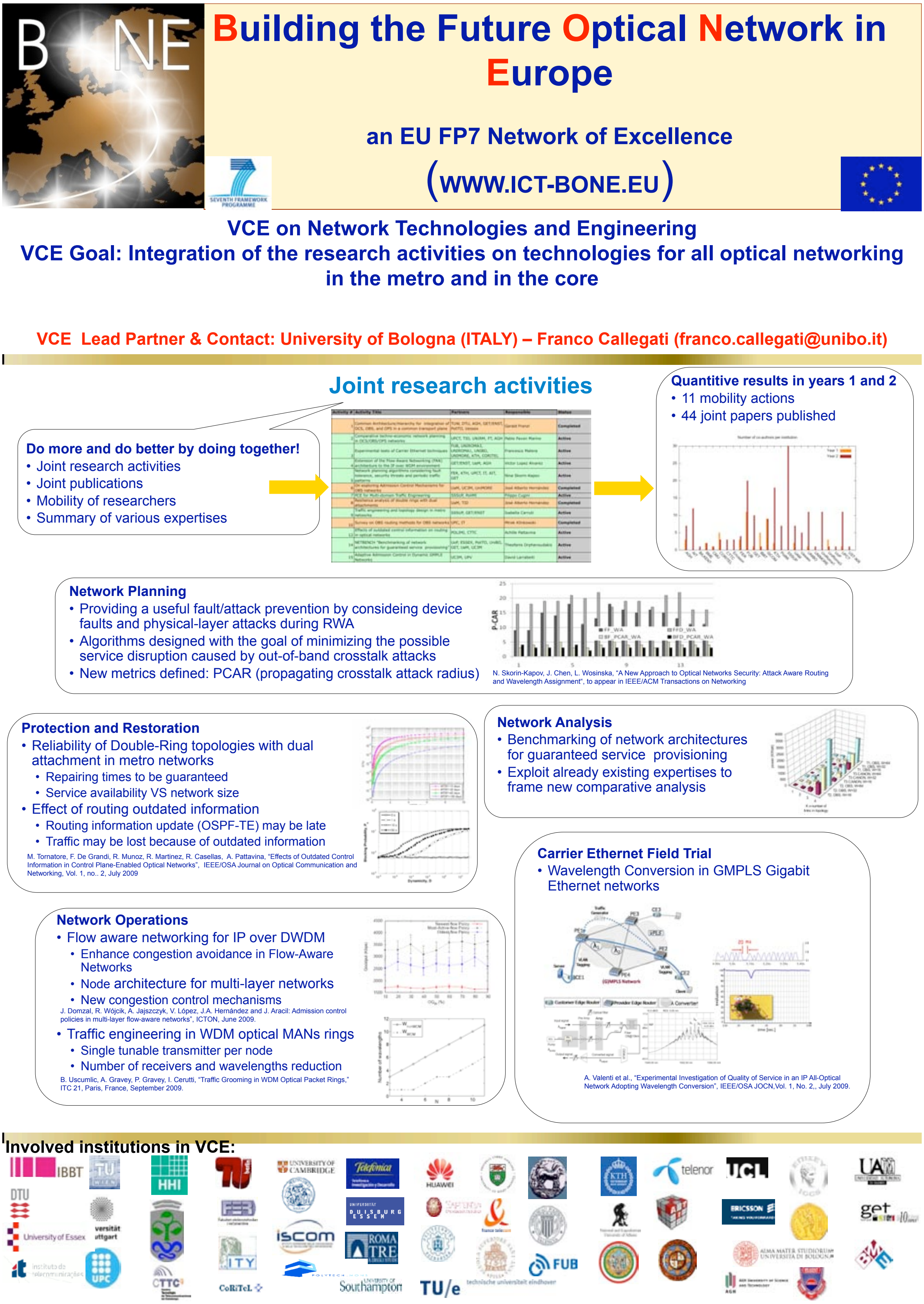


Figure 4. Poster prepared for the booth at ECOC 2010

3. Third year results for running JAs

3.1 Comparative techno-economic network planning in OCS/OBS/OPS networks

The aim of this JA is carrying out network planning studies in realistic scenarios, for optical technologies to be integrated in the short/medium or long term. This JA has evolved into two lines:

- Techno-economic comparison of OPS/OBS/OCS networks, with special focus on investigating the merits of the OBS paradigm compared to existing OCS networks.
- Techno-economic evaluation of modulation alternatives for the deployment of a photonic mesh using the OCS paradigm.

For the former objective, UPCT and POLITO have collaborated in a careful comparative evaluation of the OBS and OCS paradigms for the backbone network. A set of benchmark experiments have been designed to check the validity of two frequent assertions commonly found as inherent merits of the OBS paradigm: its ability to (i) exploit the network bandwidth more efficiently than Optical Circuit Switching (OCS) alternatives, and (ii) to efficiently solve contentions without optical buffers. Results obtained dispute the validity of these claims. A paper reporting the studies conducted has been submitted to the IEEE Transactions on Communications journal [PN2010] ("On the myths of Optical Burst Switching"). At this moment, the paper is in its second round of reviews.

For the later objective, the TID group has compared from a techno-economic point of view two types of transponders: DP-QPSK and DQPSK. The study in [AMGF2008] concludes that, in green-field deployments, the required investments for each option would strongly depend on the network size, so that while DQPSK would require lower investments in medium size scenarios, DP-QPSK would be a more cost effective option in the biggest networks. On the other hand, DP-QPSK channels can be transported over existing 50 GHz optical grids, therefore it would be a better option than DQPSK when 100Gbps channels are introduced over existing 10/40 Gbps photonic networks.

3.1.1 Objectives

The research objectives of this JA are:

- Techno-economic comparison of OPS/OBS/OCS networks, with special focus on investigating the merits of the OBS paradigm compared to existing OCS networks.
- Techno-economic evaluation of modulation alternatives for the deployment of a photonic mesh using the OCS paradigm.

3.1.2 Summary of achieved Results

A techno-economic comparison between OCS/OBS/OPS technologies

This line of the JA focused on the collaboration of UPCT and POLITO for the performance-cost comparison between OBS and OCS approaches. A paper reporting the studies conducted has been submitted to the IEEE Transactions on Communications journal [PN2010] ("On the myths of Optical Burst Switching"). At this moment, the paper is in its second round of reviews. Two mobility actions of a researcher from UPCT to POLITO facilities have been completed within the framework of this JA.

The investigations in this JA objective intend to put together a testing scenario, where the major parameters that can be engineered in an OBS and OCS network are considered, searching for the combination which optimizes the network throughput, guaranteeing a reasonable loss performance target. And then try to motivate the skepticism of the collaborating investigators towards two frequent assertions about the OBS paradigm: its ability to (i) exploit the network bandwidth more efficiently than Optical Circuit Switching (OCS) alternatives, and (ii) to efficiently solve contentions without optical buffers.

Some details about the testing scenario follow. For the OBS network, a total of 4374 simulation points were evaluated, covering every combination of the following 7 independent parameters:

- (PT) Physical topology: Three reference network topologies were tested together with their traffic matrices, as described in the literature: Internet2, NSFNET and EON.
- (W) Number of wavelengths per interconection fiber: W={20,40,80}. For OBS one of these wavelengths is used by the control channel, thereby reducing the number of data channels to W-1.

- (*TI*) Traffic intensity: Nine traffic intensities were tested. The lowest traffic intensity corresponds to that for which the traffic (without the overhead) in the most congested interconnection link is equal to 10% of the link capacity. Traffic routing is assumed to be given by optimally minimizing the congestion in the links.
- (*RP*) Reservation protocol: Three reservation protocols proposed in the literature are evaluated: JET (Just Enough Time), ODD (Only Destination Delay) and HPI (Hop-by-hop Priority Increasing).
- (*CV*) Coefficient of variation of the payload duration distribution: *CV*={0, 0.75, 1.5}. The value *CV*=0 produces fixed size bursts; it is useful for performance assessment, but not natural for the OBS paradigm.
- (T_{proc}) Header processing time: T_{proc} = {1 µs, 10 µs}. They intend to model a slow and a fast electronic unit.
- (*OSFRT*) Optical switching fabric reconfiguration time: *OSFRT*={5 ns, 1 µs, 1 ms}. They approximately represent the switching time capabilities of the fabrics based on three potential enabling technologies: Semiconductor Optical Amplifiers (SOAs), microring resonators (MRRs) and Micro-Electro-Mechanical Systems (MEMS) respectively.

OBS nodes are not equipped with optical buffering. The results for OBS have been obtained by means of simulation in the OMNET++ platform, using the simulation tool developed by UPCT group during year 1 of the project. The simulations were executed in the Ben-Arabi Supercomputing facility, located in Murcia (Spain), using more than 25,000 hours of processor time. For the OCS network, a heuristic algorithm was used to plan the network for the 81 cases given by all the combinations of the parameters: physical topology, number of wavelengths per link and traffic intensity. In this way, we are in a position to fairly compare how both paradigms carry the same traffic in the same network topology. A multilayer planning heuristic was used, considering a maximum lightpath utilization of 60%.

As a sketch of the results obtained in the JA, we include in this report the results for the maximum network throughput, as a measure of the maximum revenue that can be obtained from a network infrastructure. For OBS networks, we define the maximum network throughput as the maximum traffic intensity (*TI*) parameter, for which all the LSPs in the network showed an *end-to-end* traffic loss probability lower than 10^{-4}. In the OCS case, the network throughput is defined as the *TI* for which a feasible multilayer planning was found which fully carried the corresponding traffic demand.

The table below collects, for each physical topology and wavelengths per fiber setup, (i) the worse and best network throughput for OBS configurations varying the parameters *RP*, *CV*, T_{proc} and *OSFRT*, and (ii) the network throughput for OCS. As a main observation, results obtained for the OBS setups showed that in the vast majority of the cases, the network throughput was the same for the different *RP*, *CV*, T_{proc} and *OSFRT* values, being 10% the maximum variation of *TI* between the worse and the best OBS setup. In other words, the end-to-end traffic loss performance was approximately the same in all the tested technological scenarios, reservation protocols and traffic variability situations. This indicates that different header anticipation strategies and different switching speeds have little impact on the maximum network throughput.

Obtained results are similar for the three topologies. Unlike the OCS case, the maximum network throughput results in OBS networks are clearly dependent on the number of wavelengths in the links. This is a well-known effect, since OBS relies on the wavelength dimension to solve contentions. Conversely, the OCS paradigm is able to carry the traffic associated with *TI*=50%, for the three numbers of wavelengths. Note that since OBS networks require a large amount of wavelengths to be a competing candidate, a pay-as-you-grow migration strategy which grants a fraction of the wavelength grid to an OBS network, sharing the links with OCS equipment, is non-profitable, since the OBS part of the network would have to be grossly underutilized to be within the traffic loss target.

It is interesting to see that for 20 and 40 wavelengths per fiber, OCS is capable of managing the optical bandwidth *more efficiently* than OBS (that is, it is able to deliver more traffic with the same link capacities). Only with 80 wavelengths per interconnection link, and for the NSFNET topology, the OBS paradigm improved the results of the OCS scheme, and thus was able to carry more traffic on the same infrastructure (but with channel utilization in OCS not larger than 60%). Other results not shown in this report, but available in [PN2010], also show that OBS networks commonly require more O/E and E/O transponders for carrying the same traffic as OCS networks.

W	Topology	max TI OBS (min/max)	max TI OCS
20	Internet2	20% / 30%	50%
	NSFNET	20% / 30%	50%
	EON	20% / 30%	50%
40	Internet2	30% / 40%	50%
	NSFNET	30% / 40%	50%
	EON	30% / 40%	50%
80	Internet2	50% / 50%	50%
	NSFNET	50% / 60%	50%
	EON	50% / 50%	50%

Figure 5. OBS vs OCS network throughput comparison

The results obtained in this JA contradict a frequently repeated campaign for a bufferless operation of the OBS nodes. In fact, the evaluation studies conducted, endorses the claim that OBS paradigm *cannot* be bufferless, in order to be a competing option. In plain words, results show that a bufferless OBS alternative cannot compete with current commercial OCS networks on either side of the cost-revenue comparison: (i) the cost of a sub-wavelength switching network like OBS is higher than the cost of an OCS network, (ii) the revenue obtained from operating a bufferless OBS network, assumed to be proportional to the carried traffic, is very often smaller to that from a conventional OCS network.

Since outperforming OCS in the cost side of the comparison is not foreseeable for OBS, or any sub-wavelength switching technology (like OPS), the OCS paradigm can only be beaten in the performance side of the question. To increase its network throughput, the OBS paradigm must improve its contention resolution performance. Adding optical buffers to OBS nodes (hence contention resolution in the time domain), with the aim of improving its contention resolution capabilities, seems the obvious choice, and has already been considered in the OBS literature in numerous works. However, it brings another frequently mentioned OBS merit into discussion. OBS was originally presented as a valid approach to implement an optical sub-wavelength granularity switching making use of slow optical switching nodes. Then, OBS networks could be based on MEMS-based nodes, a mature and more cost-effective solution if compared to SOA-based fast optical switching devices. Long bursts (e.g., of an average length in the order of 10 ms) are needed in this case, in order to limit the overhead caused by the interburst gap. However, if we eliminate a bufferless operation from the equation, new issues come into play. Assuming that the optical buffering is based on Fiber Delay Lines (FDL), their length should be close to a multiple of the average burst duration to become effective. A burst duration in the ms range, means hundreds of km fiber for building one single FDL. As an example, an FDL of 10 ms needs 2000 km of fiber, and about 25 optical amplification spans. It is hard to conceive a technological situation which can make this approach profitable.

As a conclusion, the investigations in this JA critically revise two statements commonly associated with the OBS paradigm: its ability to deliver the optical bandwidth more efficiently than the OCS approach, thanks to its sub-wavelength switching granularity, and its ability to solve contention without optical buffers. By comparing cost/performance tradeoffs in them, we observed that OBS does not exhibit these frequently claimed advantages. The results suggest that, to be superior to the currently widely used OCS, OBS must be empowered with features that make it very similar to OPS (like optical buffering or optical alignment). Then, we think that these investigations seriously question the suitability of OBS as a feasible intermediate technology between current OCS and the long-term goal of OPS. In other words, we foresee that, if highly dynamic (i.e., packet-by-packet) optical switching finds technical maturity and commercial deployment, it will take a form much closer to what is today called OPS than to OBS.

Techno-economic evaluation of modulation alternatives for the deployment of a photonic OCS mesh using

TID group addressed a techno-economic comparison between DQPSK and DP-QPSK technical approaches for deploying a photonic meshed backbone at 100 Gbps. Given the different theoretical characteristics of both modulation technologies, the study includes a cost model to select the most suitable technology depending on the backbone size.

Several solutions have been proposed to achieve 100G transmission. The first and simplest way is the inverse multiplexing that allows 100G traffic to be split into multiple lower data rate carriers such as 10G. However, it has been proven that this solution makes network management more difficult and shows important problems at the receiver due to parallel transport synchronization complexity. On the other hand, 100G serial transmission must cope with challenging penalties arisen from the very restrictive optical impairments in such a high bitrate.

The best solution to deal with these restrictions is evolving towards more sophisticated modulation schemes with more than one bit per symbol so that the symbol rate becomes lower, relaxing optical impairments. DQPSK and DP-QPSK seem to be the most supported strategies by vendors.

Thanks to DP-QPSK lower symbol rate, optical reach is greater than DQPSK one; thus, all-optical links may be pretty longer in an optical mesh topology. This study analyses the cost feasibility for an all-optical mesh by comparing transparent optical links developed over either DP-QPSK or DQPSK. Furthermore, for achieving the same link length, DQPSK solution with electronic regeneration may be cost-effective because of the lower cost of DQPSK transponders in relation with DP-QPSK ones. As a result, a practical comparison between the two strategies is given regarding the length and the number of cascaded ROADMs that are traversed in a traffic path.

Next table summarizes the results obtained.

	Mean Link Reach < 3000 Km	Mean Link Reach > 3000 Km
Greenfield photonic mesh at 100 Gbps	DQPSK	DP-QPSK
Migration from an existing 10/40 Gbps photonic mesh	DP-QPSK	DP-QPSK

The study in [AMGF2008] concludes that, in green-field deployments, the required investments for each option would strongly depend on the network size, so that while DQPSK would require lower investments in medium size scenarios, DP-QPSK would be a more cost effective option in the biggest networks. On the other hand, DP-QPSK channels can be transported over existing 50 GHz optical grids, therefore it would be a better option than DQPSK when 100Gbps channels are introduced over existing 10/40 Gbps photonic networks.

3.2 Experimental tests of Carrier Ethernet techniques

3.2.1 Objectives and summary of work done in previous years

Aim of such Joint Activity is the experimental demonstration of techniques for core and metro networks regarding all the routing processes that are migrating from “layer 3” to “layer 1”, with particular interests for protection, restoration, traffic engineering, congestion resolution and resources allocation. In this migration towards layer 1, “Carrier Ethernet” approach will play a key role, and therefore it will be dominant in such JA. The activities performed in the first year were mainly focused to the management of Quality of Service (QoS) in networks based on Ethernet transmission with introduction of novel optical devices as All Optical Wavelength Conversion (AOWC). These activities were based on experimental investigations carried out by means of the multi-access multiservice IP test bed implemented in the framework of the E-Photon/One project. In particular, in the first year our investigations regarded some developments of Virtual Private LAN Service (VPLS), assumed as a technique close to layer 2 processing, both to control traffic in access networks based on ADSL2+ and to enable the introduction of the AOWC in optical networks

In 2009 we continued the investigation on techniques for core and metro networks regarding all the routing processes that are migrating from “layer 3” to “layer 2”, with the goal to reach a complete transport based on Ethernet (Carrier Ethernet). Therefore, specific studies have regarded all the techniques that, in different ways, are approaching to Carrier Ethernet: VPLS, MPLS-TP, IEEE 802.1ad (Q in Q), IEEE 802.1ah (MAC in MAC) and PBB-TE, taking into account topics of protection, restoration, traffic engineering, congestion resolution and resource allocation, especially for architectures based on GMPLS control plane. The outcome of such a study is reported in [COIRO].

A3.2.1.1 Towards Carrier Ethernet networks

Ethernet has reached a great success since 1980 as the best technology for LANs; it has become the technology of choice in both home and enterprise local area networks due to its low-cost, flexibility and plug-and-play characteristics. Ethernet transmission rate has increased from 10 Mbit/s, when Ethernet began, to 10 Gbit/s upon the approval of the IEEE 802.3ae standard in 2002, and the work of IEEE 802.3 Higher Speed Study Group (HSSG) will reach 100 Gbit/s in 2010. Moreover, 95% of all data traffic either originates or terminates as Ethernet. All these factors have led many telecom carriers to consider Ethernet as a potential convergence solution for Next Generation Networks. Nevertheless, in order to be adopted in carrier networks, Ethernet must respect requirements that carriers demand in terms of wide area scalability, resiliency, fast fault restoration, Operations, Administration, and Maintenance (OAM) capabilities, and end-to-end Quality of Service (QoS) support.

The term Carrier Ethernet (CE) refers to many technologies that enable the use of Ethernet in Provider networks, but it can be ambiguous. When discussing Ethernet, it is important to specify the context; from a carrier perspective, Carrier Ethernet can refer to:

- Ethernet services;
- Ethernet transport.

Ethernet services refer to packet-based services that ensure the delivery of Ethernet data frames between two or more User Network Interfaces (UNIs), representing points of demarcation between the customer equipment and the network service provider, in respect of a Service Level Agreement (SLA).

Metro Ethernet Forum (MEF) has provided definitions of Carrier Ethernet services, in terms of a set of attributes and parameters, in a number of recommendations for a fastest penetration of Carrier Ethernet services in the market. Ethernet services, however, do not imply an Ethernet transport, but they can be provided using a different transport technology. Most implementations of Ethernet services, in fact, use Ethernet over SONET/SDH or Ethernet over MultiProtocol Label Switching (MPLS).

Ethernet transport, instead, refers to Ethernet as a transport technology, for the transport of different kind of services; the term Carrier-Grade Ethernet (CGE) is referred to a set of technologies that are designed for giving Ethernet the transport feature it is missing. Even if the use of Ethernet has been until now confined to local area and access networks, Provider Backbone Bridging-Traffic Engineering (PBB-TE) has made Ethernet a suitable choice as carrier-grade technology for wide area transport networks.

A detailed investigation on Ethernet transport has been reported in [COIRO], where we have described Ethernet data plane evolution steps, and we have evaluated the technology drawbacks of each step and how such limitations are overcome. We also have identified the main functionalities that the Ethernet control plane shall support in order to guarantee carrier grade reliability and simplified traffic engineering. Finally, we have presented a transport network scenario in which an Ethernet layer is inserted: here it has been described the role that Ethernet can play in next generation transport network, and the advantages deriving from the adoption of this technology, in terms of network resources optimization and convergence toward a packet-based transport network.

The main reason of a transport based on Ethernet can be understood by looking at 1.1.15.1, that shows on the left side the current network layers and on the right side the network evolution based on Ethernet.

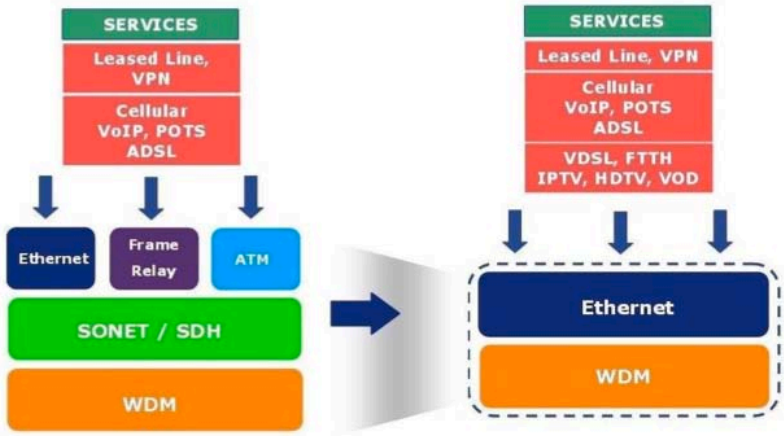


Figure 6. Network evolution

Today services are conveyed by using different techniques as ATM, Frame Relay and obviously Ethernet, to be carried in SONET/SDH channels in a WDM transmission. This step by step process appears quite onerous and, therefore, it appears much simple an evolution that cuts a layer to convey all the services on Ethernet channels in a WDM environment. This evolution is strongly supported by the rising of new generation services that is leading to profound changes in telecommunication networks. In particular, transport networks are undergoing a transition from legacy Time Division Multiplexing (TDM) networks to packet networks for delivering services. In this scenario, carriers are examining two technologies and their evolutions: Ethernet and Provider Backbone Bridging–Traffic Engineering (PBB-TE), and a transport-oriented version of MPLS, MPLS Transport Profile (MPLS-TP).

The PBB-TE is an Ethernet evolution where connectionless nature is disabled, and Spanning Tree Protocols (STP), Media Access Control (MAC) address learning and flooding features are turned off in order to obtain a deterministic behaviour and a connection-oriented approach.

In order to be considered as transport technology, MPLS needs some changes: as a consequence, a new MPLS version, MPLS-TP, has been defined by Internet Engineering Task Force (IETF). MPLS-TP works in the same MPLS framework where just transport-oriented characteristics are implemented.

Both PBB-TE and MPLS-TP are expected to be Layer 2 transport technologies with low costs and with performances, in terms of Quality of Service (QoS) and Operation, Administration and Maintenance (OAM) functionalities, comparable to Synchronous Digital Hierarchy (SDH). However, it has to be pointed out that these technologies are not yet standardised, and carriers are debating about choice of these future transport techniques.

Further themes, with normative proposal, for upgrading Ethernet towards a transport technology are listed below:

- **Synchronous Ethernet:** The ITU-T's G.8262 recommendation tackles the synchronization of packet networks to ensure successful transmission of time-sensitive services.
- **Ethernet protection switching and ring topologies:** The G.8031 and G.8032 standards specify several fault-tolerant architectures for an Ethernet service. The ability to provide 50-msec failover between primary and secondary paths and support a variety of both ring and point-to-point topologies protects an Ethernet-based transport layer against fiber cuts or system failures.
- **SLA assurance:** Standards such as 802.1ag and Y.1731 define ways for network operators to perform in-service performance monitoring on their Ethernet services. In addition, stress-testing tools utilizing the RFC 2544 test suite show a carrier whether its service delivery chain (which encompasses every end-to-end element, including across third-party infrastructure) is primed to meet SLA parameters before the Ethernet service is handed off to the customer.
- ***Circuit emulation**: The MEF's Circuit Emulation over Ethernet (CESoE) borrows on techniques developed to transport TDM services across ATM. CESoE provides the means to transparently carry T1/E1 and other established private-line offerings across Ethernet and is key in Ethernet's evolution from being a service to a transport infrastructure capable of carrying other services.*

A3.2.1.2 The current Ethernet scenario: the Virtual Private LAN Service (VPLS)

In the context of the evolution towards a Carrier Grade Ethernet, Virtual Private LAN Service (VPLS) represents a transition to Layer 2 transport. Indeed, it is a combination of Ethernet and MPLS and it inherits their characteristics. VPLS has Ethernet simplicity and cheapness and it exploits MPLS features as, for an instance, mechanisms that allow implementing QoS control, as shown in [FLAS2008] [VPRM2009] [MVPTB2009] [RVPP2009] [VBPM2009].

Currently, in the WAN context, VPLS permits to achieve the best network performance in terms of traffic management and QoS. VPLS offers a sort of Layer 2 Virtual Private Network where the customers are connected by Ethernet Line/LANs. It has to be pointed out that VPLS does not perform proper multicasting since it uses a broadcast traffic forwarding. VPLS is a Layer 2 Virtual Private Network (VPN) where the customers are connected by Ethernet Line/LANs; with respect to the conventional Layer 2 VPNs, where the customers are connected in a point to point way, in VPLS customers can be connected by a multipoint Ethernet LAN. The main feature is that users sharing VPLS seem to be in the same LAN, independently by their own geographic position.

However, it has to be pointed out that VPLS is not a full layer 2 technology since it requires a layer 3 processing, even though it results much interesting to implement a geographical network fully based on Ethernet transmission. Wide potentialities of VPLS can be achieved together with VLAN tagging technique performed at the edge of the network.

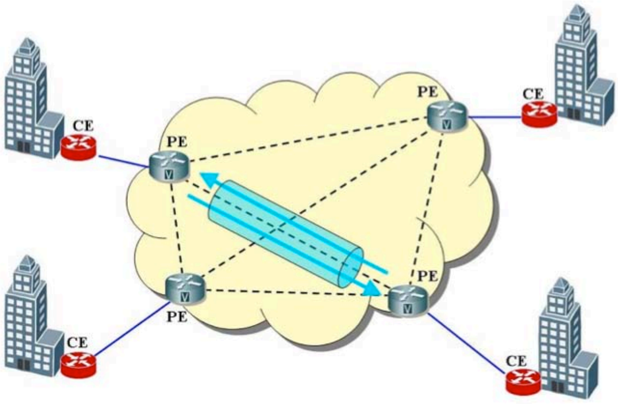


Figure 7. VPLS network

The network elements involved in VPLS are Customer Edge (CE) and Provider Edge (PE) nodes (Figure 7) the CE is completely VPLS unaware and it is connected, by means of an Ethernet connection (typically a VLAN), to the PE. The Provider Edge is the main VPLS element: it adds (inner) VPLS label and (outer) MPLS label to customer frames and it forwards them to the remote PE.

In the framework of the BONE project some experimental activities were carried out on a VPLS test bed showing the reliability of such an infrastructure for a transport network based on GbE. Details on some experiments can be found later in the deliverable. The test bed is reported in Figure 8.

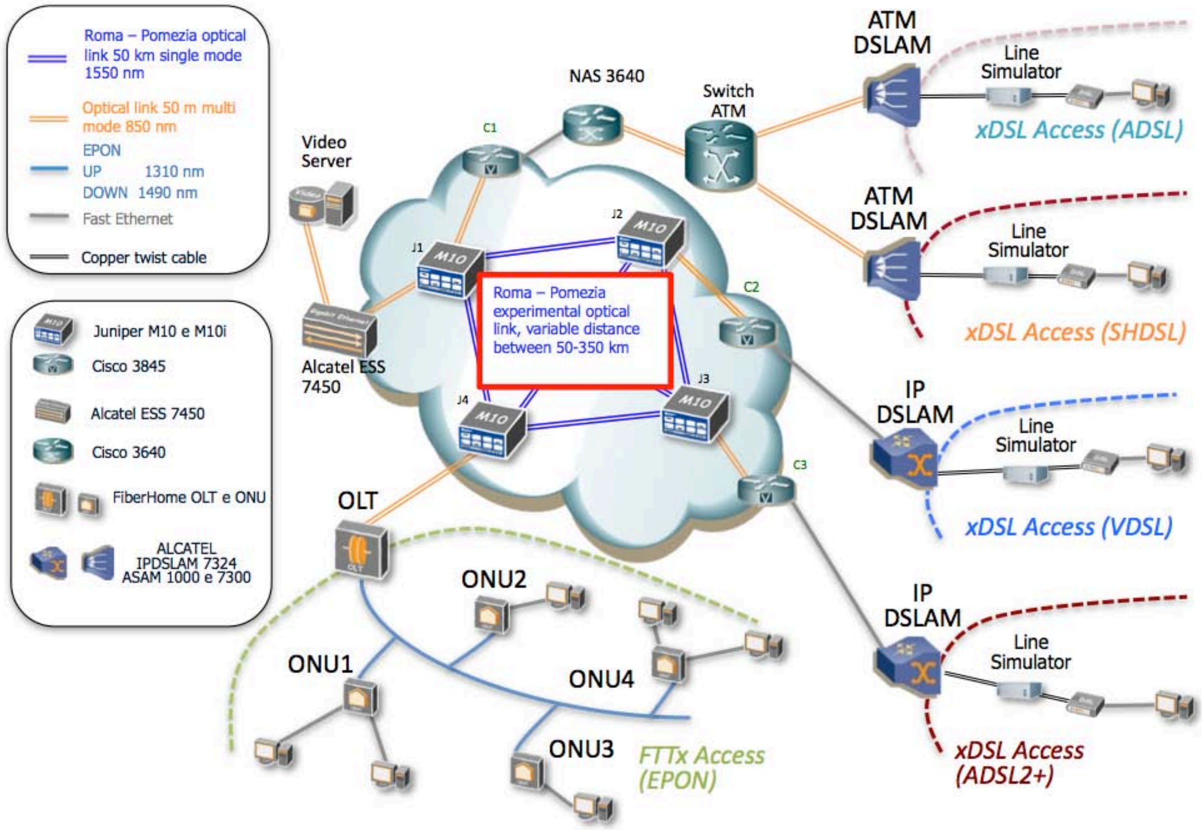


Figure 8. Experimetnal Test Bed

In PEs we set MPLS to carry VPLS traffic in a MPLS network, and Open Shortest Path First (OSPF) as Interior Gateway Protocol (IGP) for MPLS LSPs establishment. Furthermore, according to IETF RFC 4761, we set Border Gateway Protocol (BGP) as protocol for signaling (i.e. label exchange) and auto-discovery mechanisms (for PE identification) in VPLS.

The experiments performed on such a test bed confirmed that VPLS already has many characteristics to implement WAN only based on Ethernet transmission. In particular here we list the main achievements:

- WDM GbE transmissions can be used on long distance and we tested that by using optical amplifiers the distances among the routers can reach 350 km [VBPM2009];
- VPLS can be used to manage the traffic in the core network in order to control the QoS for an instance in access segments with a limited bandwidth (as for an instance in xDSL device, but also in PON network that have to share the bandwidth among several users). In particular as reported in [MVPTB2009] [RVPP2009], VPLS can be used to manage reliable unbundling in PON, guaranteeing bandwidth and QoS to the users.
- VPLS is compatible with novel optical technologies as for an instance the all optical wavelength conversion [FLAS2008] [VPRM2009]. In particular we tested the network performance of a WAN GbE with the presence of AOWC based on the Four Wave mixing in DS fiber and we verified that AOWC does not introduce any signal degradation and it can be achieved in a very fast time, compatible with the out of service required by wide bandwidth real time services as HD TV streaming.

Being a combination of Ethernet and MPLS, it is possible to use MPLS restoration and protection techniques in VPLS; in particular, we implemented Fast Reroute and Standby Secondary Path in VPLS. We demonstrated that VPLS allows to have restoration times under 50 ms, with performances equal to SDH/SONET in terms of restoration and reliability capabilities; in particular, VPLS FRR has better performances than VPLS SSP.

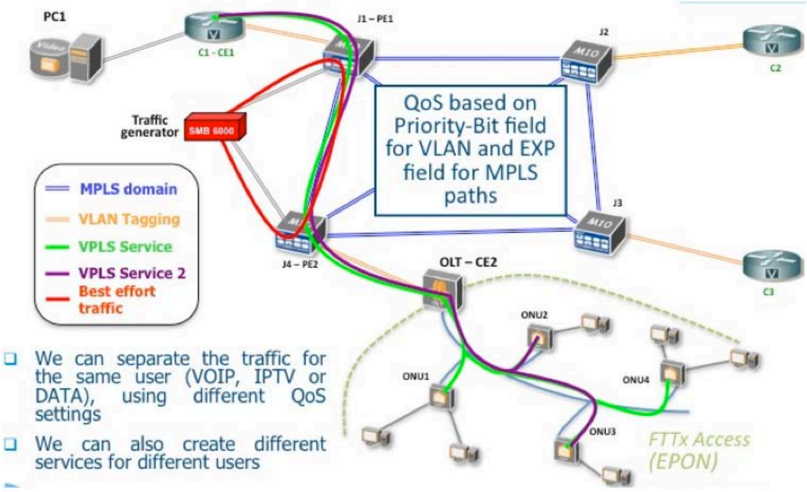


Figure 9. Experimental Setup

As shown in Figure 9 Cisco routers (C1-CE1) and the ONUs behave as CE nodes, and they are connected (by VLAN) to Juniper routers (J1-PE1, J2-PE2), configured as PE nodes.

According to these considerations, the test bed is configured to operate with CoSs based on VPLS and extended to the CE sites by means of VLAN Tagging technique. Therefore, a tunnel based on VPLS&VLAN Tagging between a Server (PC1) (connected to CE1) and a user PC (e. g., the PC connected to ONU2) can be established according to specific service requirements. In this test bed, eight different CoSs can be defined, according to the values of three bits, in agreement with IEEE 802.1p (within IEEE 802.1Q) and DiffServ over MPLS standards. In particular, the VLAN TAG CoS field (3 bits) is employed to guarantee QoS among CEs and PEs; since PE adds an outer MPLS label, the QoS among PEs is guaranteed by using the MPLS LABEL EXP field (3 bits). It has to be pointed out that recently RFC 5462 changed EXP field in Traffic Class Field.

The eight CoSs were defined in such a way that CE and PE treat the corresponding packets with different priority. In particular, in the Gold Class (User Priority Bits: 101) the packets have the highest priority and they are always immediately forwarded, even in condition of congestion; therefore, such a CoS permits to guarantee the necessary performance (throughput, jitter, data loss) independently of the network congestion. Less priority was assigned to a Silver Class (User Priority Bits: 011) and so on, up to the Best Effort (BE) Class (000) that has no priority.

A3.2.1.3 Restoration in VPLS

The birth of bandwidth-greedy services needs some change in telecommunication networks where packet networks seem to be the future way. PBB-TE and MPLS-TP are interesting future solutions but they are not standardised, and some issues have to be addressed, as for example OAM features. In this scenario, VPLS represents a transition solution to deliver next generation packet services.

In order to fully satisfy service requirements, VPLS has to be able to guarantee QoS and to implement OAM functions. In other works, we proposed methods for QoS control in VPLS [VBPM2009], and we made some investigations on restoration procedures based on Wavelength Conversion that we called Alternative Wavelength Path (AWP) [VPRM2009].

Since VPLS realizes Ethernet connections by means of MPLS LSPs, we proposed two restoration procedures in VPLS exploiting MPLS capabilities. In the first one, we implemented Fast Reroute technique in VPLS (that wecalled VPLS FRR), in the second one we proposed a restoration procedure based on Standby Secondary Path technique in VPLS (called VPLS SSP). The implementation of the two techniques are shown in Figure 10 a) (on the left side) and b) (on the right side).

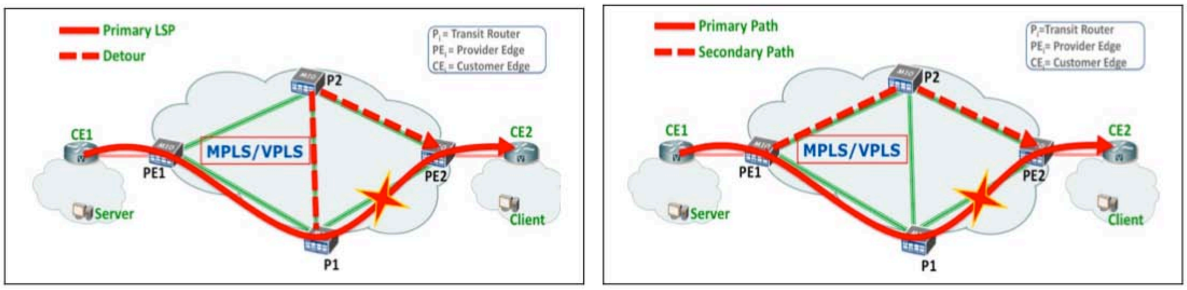


Figure 10. Restoration Techniques in VPLS

There are two Customer Edges (CE1 and CE2) interconnected by means of a VPLS instance that is composed of two Provider Edges (PE1 and PE2) and a transit router (P1). In the first case, we set also a protection mechanism based on Fast Reroute. This technique allows to automatically reroute traffic on a LSP if a link or a node fails. The ingress router (i.e. PE1) signals all the downstream routers that Fast Reroute is enabled, and then each router tries to set a detour path to immediate downstream router. In this way, it is possible to achieve fast rerouting by pre-establishing a set of detours along the LSP. In VPLS, PEs are connected by means of LSPs, and thus it is possible to use Fast Reroute for traffic protection. In particular, as shown in (a), we set Fast Reroute in VPLS: when link between P1 and PE2 fails, traffic is routed toward PE2 on a pre- established detour path crossing P2.

In the second case, we set a protection based on Standby Secondary Path. With this technique it is possible to set a primary path and a secondary path for an LSP providing an end to end protection. When the primary path fails, the ingress router reroutes traffic on the pre-established secondary path: in this way, it does not need to compute a new route and to signal new path for the LSP. As shown in 1.1.15.3(b), we set Standby Secondary Path protection in VPLS: when P1-PE2 link fails, PE1 reroutes traffic on the secondary path crossing P2.

Several tests were carried out both for VPLS FFR and VPLS SSP. In particular, we measured restoration time, throughput degradation and perceived quality. For such an aim, we used a traffic analyzer, Anritsu MD1230B, and a sniffing software, Wireshark.

For the restoration time measurement, we sent 1 Gbit/s test traffic from CE1 to CE2; the failure event occurs (by means of an optical switch controlled by a software running on a Linux PC) every 2 minutes for 1000 times, it lasts for 50 ms, and we can assume that each failure event is independent from each other. In Figure 11 (a, left side) and (b, right side) results are shown; in particular, we can observe an Average Restoration Time about 26.3 ms and 36.7 ms for VPLS FRR and VPLS SSP respectively.

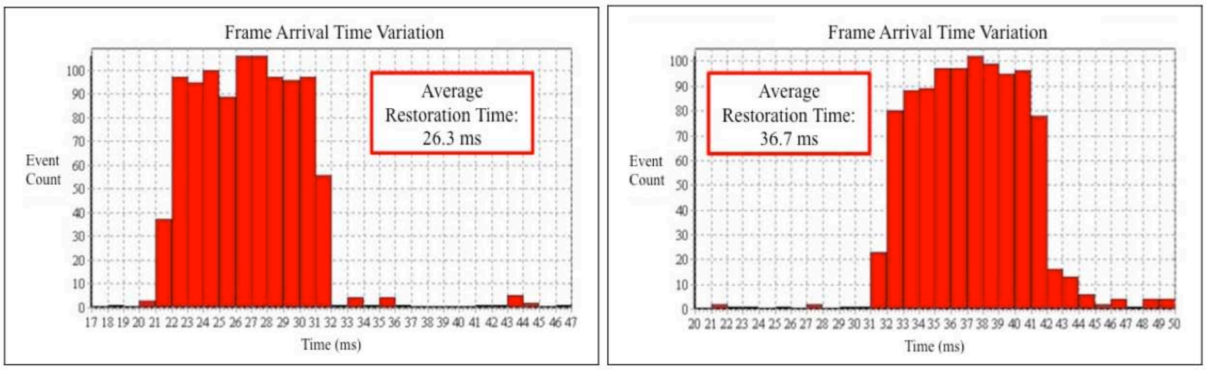


Figure 11. Restoration Time

These measurements represent a quantitative system reliability estimation, which finally points out that for 99.9% of link failure events restoration time is sub-50 ms, making VPLS restoration times and reliability equal to SDH/SONET performances. In addiction, these tests outline that VPLS FRR and VPLS SSP techniques are faster than 30 ms and 40 ms respectively, for nearly 90% of link failure events.

To perform network and subjective measurements, an MPEG2 High Definition (HD) video streaming (about 20 Mbit/s) was sent, over the VPLS instance, between a Server (connected to CE1) and a Client (connected to CE2), as shown in Figure 12, where we report a sample for the throughput when failure occurs; we can observe a service interruption that confirms results reported above for VPLS FFR (left) and VPLS SSP (right).

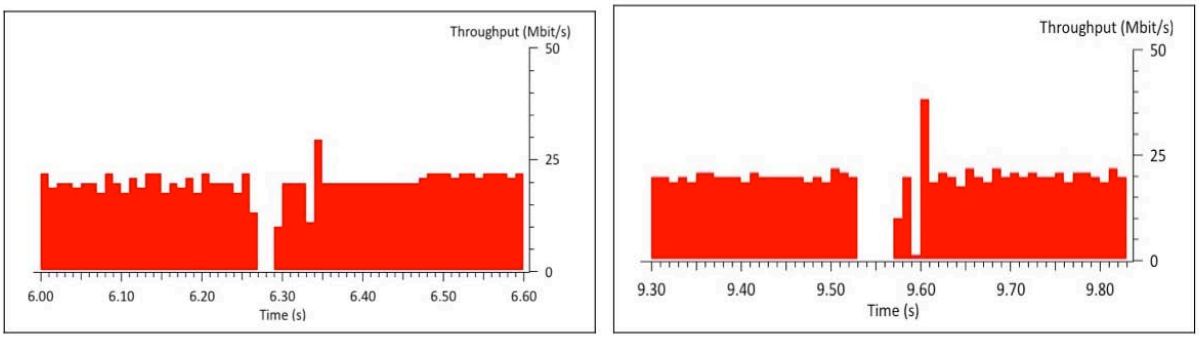


Figure 12. Throughput of MPEG2 HD Video Streaming

In Figure 13 (a, left) and (b, right), screenshots of Client’s video quality are shown.

Figure 13. Perceived quality of MPEG2 HD Video Streaming

We can underline that VPLS SSP has a stronger degradation than VPLS FRR. Both Restoration Techniques ensure a continuous service also for delay sensitive applications as HD video streaming, but it is possible to point out that VPLS FRR faster restoration times could be appreciate in a subjective evaluation of a Streaming Service.

In this work, VPLS has been implemented in a real wide area optical test-bed and some restoration techniques have been proposed. Being a combination of Ethernet and MPLS, it is possible to use MPLS restoration and protection techniques in VPLS; in particular, we implemented Fast Reroute and Standby Secondary Path in VPLS. We demonstrated that VPLS allows to have restoration times under 50 ms, with performances equal to SDH/SONET in terms of restoration and reliability capabilities; in particular, VPLS FRR has better performances than VPLS SSP.

Therefore, VPLS can be assumed as a Layer 2 technology with low costs for allowing transition toward packet transport techniques as PBB-TE and MPLS-TP.

We can conclude that VPLS can be assumed as a Layer 2 technology with low costs for allowing transition toward packet transport techniques as PBB-TE and MPLS-TP.

We also have shown that satisfying Ethernet solutions have already available using for an instance VPLS architectures.

A3.2.1.4 TCP Performance in Hybrid Multigranular OBS Networks

In this JA the research group of University of Modena and Reggio Emilia (UNIMORE) has investigating the performance of hybrid optical networks. In particular, TCP performance have been evaluated when high speed Ethernet over Passive Optical Networks (EPON) [KP2002] are interconnected by means of a core optical network based on the Optical Burst Switching paradigm [QY1999]. Passive Optical Network (PON) is a promising technology to solve the last mile problem. EPON has been regulated by IEEE [8023AH] [8023EFM] and it has been one of the subjects of first year activities [VBPM2009].

The inter-working unit, or edge node, between these two networks has to be properly studied and designed and its main function is the burst assembly: it must collect incoming EPON frames, extract IP datagrams and assembly them into optical bursts according to proper assembly algorithms. In particular, a time-based assembly algorithm has been employed and analyzed for operating with a EPON which is characterized, on the other hand, by some other parameters such as the cycle time, for managing the upstream transmissions.

This hybrid network has mainly been studied through simulations by means of the ns2 simulation tool [NS2].

Figure 14 and more numerical investigations have revealed that: (i) the cycle time in EPON has negligible impact on TCP performance, (ii) the TCP congestion window is very critical and it leads to remarkable performance differences, (iii) for different values of the congestion window a given assembly time value exists which maximizes performance, (iv) by increasing the assembly time a better intra-fairness index can be obtained, for a better bandwidth sharing [CASRAF2009] [CAS2009].

Then UNIMORE has investigated TCP performance when several high speed EPONs are interconnected through a core optical network based on OBS.

The role of a key parameter, such as the EPON cycle time used in the multiple access scheme, has been studied. TCP performance of the multi-EPON/OBS network have been evaluated through simulations with ns2. Results show that the relationship between the EPON cycle time and the burst assembly time has a fundamental role and requires proper tuning to optimize the TCP throughput.

Figure 15 shows for two EPONs the evolution in time of the total average TCP throughput for each them, defined as the sum of the average throughput of all the TCP sources within a given EPON. An observation time window of 200 s is simulated and four different values of Tass are considered, assuming Tc1 = Tc2 = 2ms and AW = 512 segments. For each case, the two curves representing EPON 1 and 2 are displayed with the same line style and color. After the initial transient, the curves stabilize around the average value of the EPON throughput. For a given burst assembly time Tass, the two

EPONs show practically the same behavior, as proved by the two curves being almost identical. Furthermore, the intrafairness index measured in all cases for both EPONs is close to 0.90. This demonstrates that the multi-EPON/OBS architecture offers efficient and quite fair resource sharing capabilities.

The figure also shows that by increasing Tass all flows increase their throughput: this is due to the beneficial effect on TCP caused by the larger bursts generated when Tass is larger. In fact, when a larger burst is available, it is more likely that an entire TCP transmission window is carried by a single burst, resulting then in a higher number of acknowledgments (ACKs) being sent back in a shorter time, which accelerates the increase of the TCP throughput.

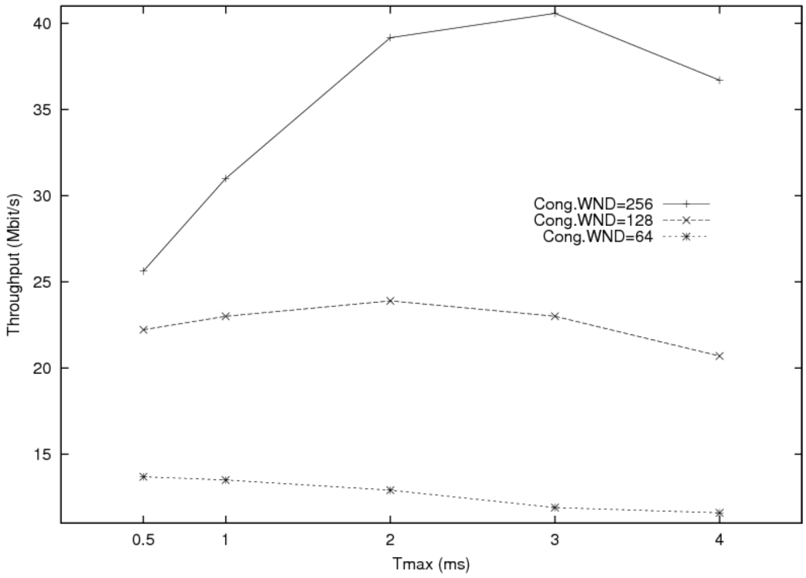


Figure 14. Average throughput for 10 TCP clients (ONUs) vs. T_{max} with Burst Loss Prob.=10^{-3} and different values of the TCP congestion window.

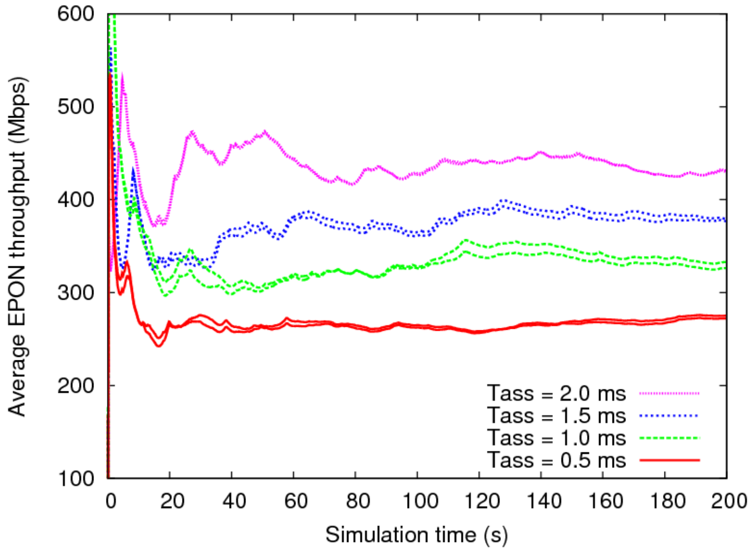


Figure 15. Total average TCP throughput for each of the two EPONs vs. simulation time for different values of the burst assembly timeout, with Tc1 = Tc2 = 2ms and AW = 512.

3.2.2 Advances in Y3

A3.2.2.1 Test Bed upgrade and future developments

During this year we had the opportunity to upgrade our test bed of two Alcatel 7750 routers that came with the possibility to run Provider Backbone Bridging with Traffic Engineering extension. So this is our actual test bed:

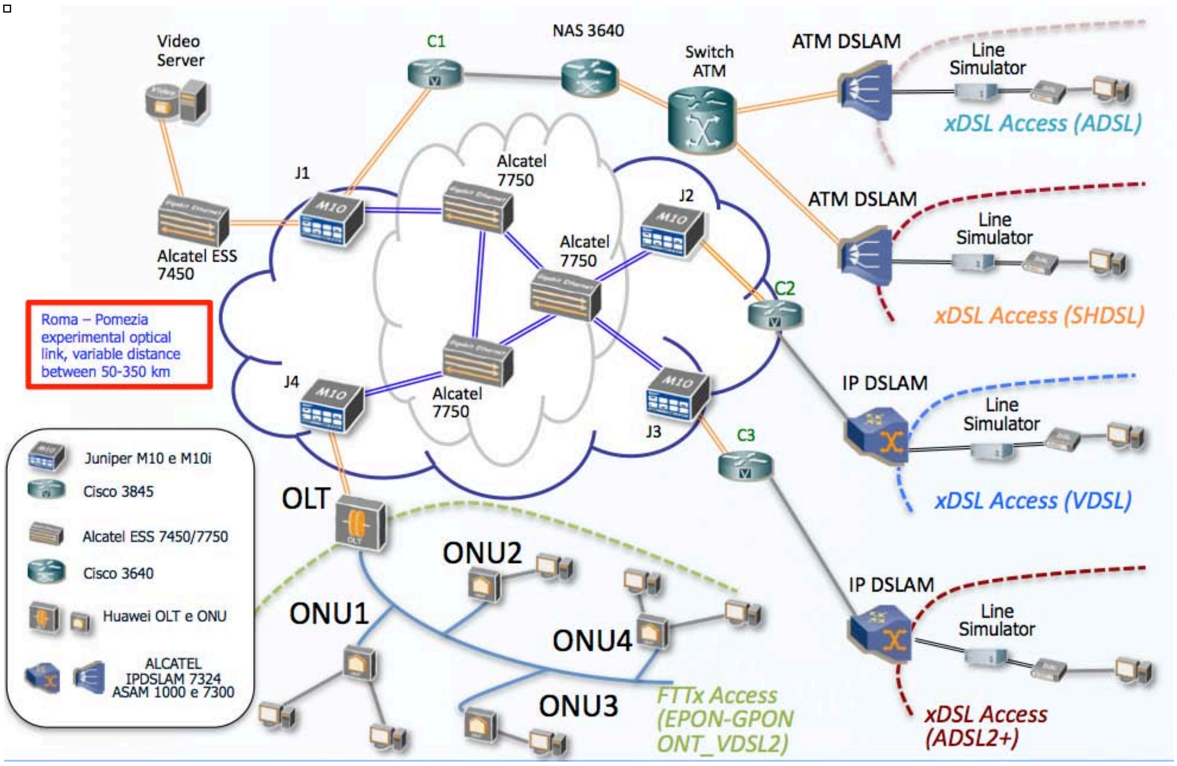


Figure 16. Upgraded Test Bed

We are actually studying the integration of the PBB architecture with the VPLS for Traffic Engineering extension in a way to use the tree Alcatel, two 7750 and one 7450, as core routers for carrier Ethernet. We can interface them by VPLS with the four Juniper M10 used as edge routers.

3.3 Extension of the Flow-Aware Networking (FAN) architecture to the IP over WDM environment

This JA studied Flow-Aware Networking in the IP over WDM networks. First, we defined Multilayer Flow-Aware Networking (MFAN) to work in IP over optical networks. Secondly, we assessed its performance in congestion scenarios. UAM and GET defined MFAN, while AGH introduced congestion control mechanisms for FAN. The added value of this collaboration is that we have merged the contributions of three different partners in a single collaborative work.

The research in Quality of Services (QoS) technologies started many years ago, but now the networking engineers start to understand the keys to QoS provisioning. The traditional traffic engineering is based on demand predictions, while the modern concepts revolve around measurement-based approaches or state based (automatic) approaches.

Flow-Aware Networking (FAN) appears as a new approach to offer QoS. FAN observes and makes decisions at flow level instead of packets level. Flow-based traffic engineering uses more tractable mathematical models than packet-based traffic engineering (self-similar models). Flow-based traffic engineering focuses on the probabilistic relation between demand-performance-capacity (represents almost human behaviour and is near to telephone systems).

Operator networks are migrating to an IP over WDM scenario where IP layer is directly connected to the optical layer. Moreover, the optical layer is becoming more and more intelligent and it is able to establish and tear down lightpaths automatically. This new technology creates not only new problems but also solutions, such as the utilization of the optical layer to solve congestion problems at IP layer. We call this solution Multilayer Flow-Aware Networking (MFAN).

There are various approaches to control congestion in the FAN architecture. Firstly, there are flushing mechanisms which work based on partial or total cleaning of the protected flow list in the FAN routers. Secondly, there is Multilayer FAN that introduces the possibility of cooperation of an IP level FAN with lower layers. While both proposals are valid and possess certain advantages, in this JA, we have evaluated them in details and compared them in terms of performance and cost. We have defined a new congestion control mechanism taking into account techniques that are used by both approaches.

3.3.1 Objectives

This joint activity was focused on the enhancement of the congestion avoidance in Flow-Aware Networks. The objectives of this work are as follows:

- define the node architecture for multi-layer networks as well as the policies to deal with the incoming flows to the system,
- compare congestion control mechanisms,
- define new congestion control mechanisms with the advantages of previous proposals.

3.3.2 Summary of achieved Results

We can split our results into three topics: MFAN evaluation, multi-layer recovery mechanism and congestion control mechanisms.

A3.3.2.1 Multi-layer Flow Aware Networking evaluation

An MFAN node is composed with a FAN queue at the IP level and a module that is able to ask for extra resources in the optical layer when congestion is detected at the IP level. When FAN queue can not deal with the incoming flows, extra resources are provided in the optical layer. The proposed solution is shown in the next Figure.

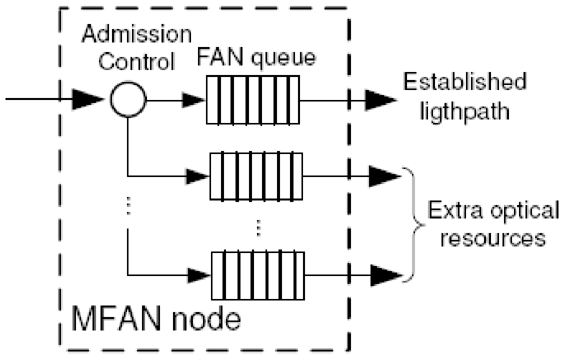


Figure 17. Multi-layer Flow-Aware Networking (MFAN) node architecture

At the beginning of this joint activity, we evaluated the performance of Multilayer Flow-Aware Networking (MFAN) in a UDP dominated scenario, where multimedia applications were the main traffic source. In previous work we assumed that the congestion was due to TCP traffic, however the UDP traffic can congest the system as well. It is necessary to know the performance of the policies when this situation occurs (see next figure).

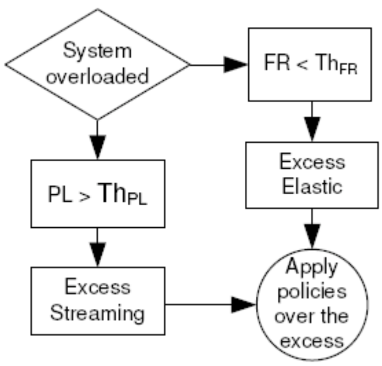
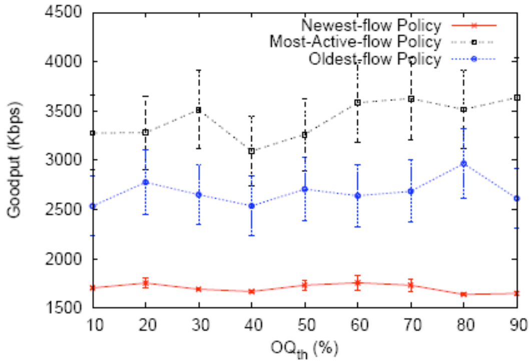
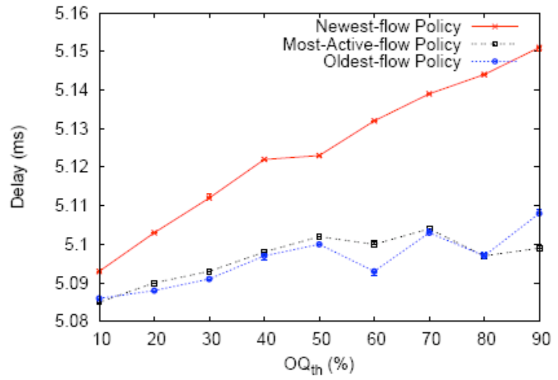


Figure 1. Optimal decision for the flows.

The performance of MFAN in a UDP dominated scenario is different than in the TCP scenario. Due to the nature of the UDP flows, Most-Active Flow policy is able to extract suitable flows from the IP layer allowing a better performance in the optical queue. This can be seen in the following figures. Delay is similar to the Oldest Flow policy, however the achieved goodput is higher.



TCP flows goodput in the optical queue



Mean delay of the UDP packets in the optical queue

Figure 18. Performance in a UDP dominated scenario in a dumb-bell topology.

To check this behaviour, the amount of TCP traffic varied from 80% to 20%. This experiment proved that the performance of the Oldest Flow policy is better when the amount of TCP traffic is more than 50%, while Most-Active Flow policy is more suitable when UDP traffic is congesting the IP layer.

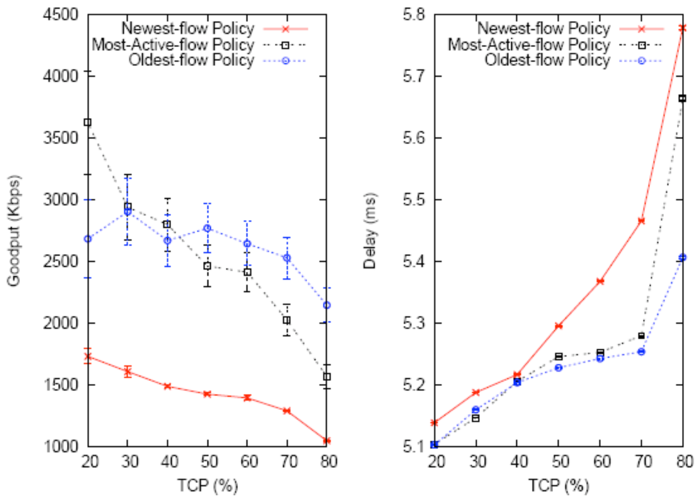


Figure 19. Policies performance evaluation when the percentage of TCP varies.

This experiment shows that a solution based on a “Hybrid policy”, which combines the benefits of Oldest and Most-Active Flow policies, is the solution for all kind of traffic profiles.

A3.3.2.2 Multi-layer recovery mechanism.

The second contribution of this JA is the definition of a recovery mechanism for FAN based on IP over WDM architectures. The motivation to study the recovery mechanism for FAN based on IP over WDM architectures, comes from the fact that FAN does not ensure the reliable transmission. There are no protection and restoration mechanisms in FAN which means that in case of a link or a node failure the traffic has to be redirected. The disadvantages of such a situation are summarized in the following table:

TABLE II
THE ADVANTAGES AND DISADVANTAGES OF FAN ARCHITECTURES, BASIC, FAN/WDM AND FAN/WDM WITH EHOT

Link failure	Advantages	Disadvantages
Basic FAN	simple (only rerouting)	relatively slow rerouting: - in congestion rerouted flows are not accepted; - in congestionless the number of accepted flows after rerouting may be too large
MFAN without EHOT	chance for fast recovery in optical layer	rerouting in IP layer and recovery in optical layer at the same time
MFAN with EHOT	chance for recovery without rerouting in the IP layer (fast and short outage in transmission and without changes in flows assignment)	complexity of the algorithm

We evaluated the performance of FAN over WDM environment and we proposed to implement the MFAN architecture to improve the chances of making the link restoration process quicker than 50 ms. We proposed an MFAN solution with the EHOT algorithm that improves the performance of a single-layer FAN and FAN over WDM. An extended version of these results can be found in [DWW2009].

A3.3.2.3 Assessment of congestion control mechanisms.

The third study in this JA was focused on admission control policies for Flow-Aware Networking. The Enhanced Flushing Mechanism (EFM) was defined previously by AGH. The EFM algorithm identifies all elastic flows to be removed from the PFL, when there is congestion. This congestion control mechanism has one important drawback. The number of accepted flows in the PFL right after a flushing procedure can be too high (see next table). Consequently, we integrated the EFM mechanism with the flow classification of MFAN (Oldest and Most Active Flows). We showed that if this flow information is included into the mechanism the number of flows in reduced, but there are some flows that are not accepted again. Finally, we proposed to use the EFMP (EFM with Priority) to ensure quick acceptance of the removed flows while ensuring all advantages of the mechanism described previously. The results of this work were published in [DWJ2009].

Table 3. Performance and assessment of EFM and EFMP

Architecture or mechanism	*waiting time* [s]	No. of admitted flows	Advantages	Drawbacks
EFM (5s)	*1.43±0.91*	*160.43±10.91*	• quick acceptance of streaming flows • low cost	• instability of fair rate • high number of accepted flows
EFM (1s, oldest flow)	*3.55±0.53*	*23.55±0.62*	• quick acceptance of streaming flows • low cost • fair rate assurance • low number of accepted flows	• removed flow may not be accepted again
EFM (1s, most active flow)	*3.68±0.45*	*23.13±0.45*		
EFMP (1s, oldest flow)	*4.73±1.06*	*23.48±0.56*	• quick acceptance of streaming flows • low cost • fair rate assurance • low number of accepted flows • quick acceptance of removed flows	• none

The second step in this admission control mechanisms evaluation was to compare the results of EFMP with MFAN. In light of these results we can conclude that MFAN obtains a better performance since it is using two connections while EFMP is working in a single link. Therefore, depending on the scenario we can implement both solutions based on the configuration of the network and the performance required for the flows. We will submit this work to a journal shortly.

Table 4. Performance and assessment of MFAN in terms of admission control

Architecture or mechanism	***waiting time* [s]**	**No. of admitted flows**	**Advantages**	**Drawbacks**
MFAN (oldest flow, FIFO)	*1,58±0,36*	17,98±*1,35*	• short acceptance times of all flows • low number of accepted flows	• cost • lack of fair rate assurance
MFAN (most active flow, FIFO)	*1,52±0,28*	*19,15±1,51*		
MFAN (oldest flow, FAN)	*9,62±3,34*	*24,16±0,58*	• fair rate assurance • low number of accepted flows	• high cost • long acceptance times of new flows
MFAN (most active flow, FAN)	*7,76±2,67*	*24,70±1,34*		

3.4 Network planning algorithms considering fault tolerance, security threats and periodic traffic patterns (JA5)

This Joint Activity (JA5) was mainly focused on developing a novel security planning framework for transparent optical networks. Security and reliability issues are crucial in such networks due to the extremely large fiber throughput involved and the vulnerabilities associated with transparency. The difficulty in detecting and locating physical-layer attacks or malicious behaviour is enhanced since monitoring must be performed in the optical domain. Successful prevention techniques, as well as fast and efficient reaction and restoration mechanisms in the presence of faults and/or deliberate attacks, can prevent from loosing large amounts of critical data which can cause severe service disruption. While most existing prevention measures are hardware-oriented, our goal was to achieve significant prevention measures without the need for specialized equipment, i.e. at minimal extra cost, through careful network planning. The work was aimed towards developing network planning algorithms to solve problems such as Virtual Topology Design (VTD) and Routing and Wavelength Assignment (RWA) which not only efficiently utilize network resources, but also consider potential faults and physical-layer security threats. In this sense, we aimed to incorporate protection mechanisms in our network planning algorithms. Furthermore, we investigated the advantages of incorporating multi-hour traffic patterns known *a priori* in network planning in order assess the cost effectiveness of reconfigurable equipment. The partners participating in JA5 joined their individual expertise to successfully achieve the activity objectives. Partners FER, UPCT and GET were focused on developing the planning algorithms, applying their experience in optimization, while partners KTH, AIT and IT provided the expertise on physical-layer components and security threats.

3.4.1 Objectives

In WDM (wavelength division multiplexing) optical networks, all-optical channels, called lightpaths, are established between pairs of nodes forming a virtual topology over the physical interconnection of optical fibers. Lightpaths can span multiple physical links without undergoing opto-electronic conversion at intermediate switches. Network planning in such transparent WDM optical networks is based on solving the problems of Virtual Topology Design (VTD), Routing and Wavelength Assignment (RWA), and Traffic grooming. Virtual topology design determines the set of lightpaths to be established based on a given static, scheduled or dynamic traffic pattern. The process of finding a physical route and assigning a wavelength to each of the users' lightpath demands, is called routing and wavelength assignment. It is subject to two main constraints. The wavelength clash constraint prohibits assigning the same wavelength to lightpaths traversing a common directed physical link. The wavelength continuity constraint dictates assigning the same wavelength along a lightpath's entire physical path. Finally, the process of routing packet switched traffic over the established virtual topology is referred to as traffic grooming.

Since optical networks employ extremely high data rates, any malfunction puts large amounts of data at risk of getting lost or corrupted. Deliberate physical-layer attacks aimed to deteriorate the QoS and/or deny service, analyze traffic or eavesdrop, can cause severe damage to proper network functioning. Furthermore, due to network transparency, malicious signals can propagate through the network. All of this makes fault and attack management a key element of network security. In the framework of this joint activity, we proposed a novel approach to optical networks security aiming to achieve significant prevention measures without the need for specialized equipment through careful network planning. The idea is to consider the potential consequences of various physical-layer attacks, faults and security threats (e.g., power jamming, fiber cuts, eavesdropping) and arrange the set of lightpaths in such a way as to minimize the possible service disruption which can be caused in case of such scenarios. By limiting the number of lightpaths that can be affected by an attack, not only is network service disruption minimized, but failure detection and localization algorithms can be more efficient.

The general objective of this joint activity was to design a cost-effective security planning framework for transparent optical networks. The first main objective associated with this was to investigate various physical-layer attack and fault scenarios and design new planning algorithms, specifically algorithms to route and assign wavelengths to lightpaths, in a way which can create a more robust network with respect to various attacks. The second main objective was aimed at investigating and developing a supervisory channel model to help achieve faster and more robust system-wide communication in the context of failure management. The third main objective conducted within the framework of this JA was focused on multi-hour virtual topology design and planning. This implies searching for the temporal evolution of virtual topologies, and its corresponding traffic grooming, which efficiently adapt to known traffic variations. Besides developing efficient algorithms for multi-hour VTD, an additional aim of this investigation was to assess the advantages of using reconfigurable equipment and its cost-effectiveness.

3.4.2 Summary of achieved Results

In the first phase of the activity, we investigated various physical-layer attack and fault scenarios and designed new planning algorithms, specifically algorithms to route and assign wavelengths to lightpaths, in a way which can create a more robust network with respect to out-of-band crosstalk attacks. We proposed a new objective criterion for the Routing and Wavelength Assignment problem defined as the maximum number of lightpaths any one lightpath is adjacent to, i.e., with which it shares at least one common physical link, including itself. The new objective, called the Lightpath Attack Radius (LAR), is aimed to arrange a given set of lightpaths in such a way as to minimize potential disruption, i.e. minimize the maximum number of lightpaths which can be disrupted by out-of-band crosstalk attack scenarios. Consequently, if fewer lightpaths are attacked, not only is network service disruption minimized, but detection and localization algorithms can be faster since they search for the source among fewer potential lightpaths.

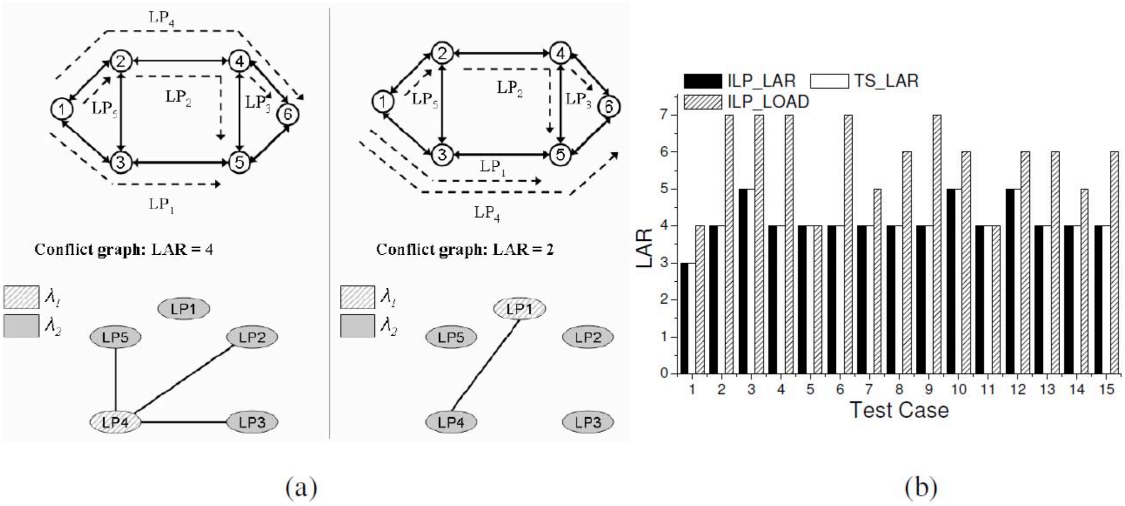


Figure 20. (a) An example of two RWA schemes with the same number of wavelengths and the same congestion but with different values for the LAR. (b) The LAR obtained by the proposed ILP_LAR formulation, the proposed heuristic TS_LAR, and the ILP_LOAD formulation for a 6-node network.

Each routing solution obtained by solving the routing sub-problem of RWA corresponds to one so-called conflict graph, where nodes represent lightpaths and two nodes are connected if they are routed over a common link in the physical topology. The LAR is the maximum degree in such a graph, incremented by one, as shown in Figure

20(a) on a small example. Furthermore, solving the wavelength assignment sub-problem is equivalent to solving the graph coloring problem on the conflict graph. Since it is known that the maximum degree of a graph incremented by one is an upper bound on the number of colors needed to successfully color a graph, it follows that the LAR is also an upper bound on the number of wavelengths required. Consequently, if our objective is to minimize the LAR, we simultaneously minimize the worst case on the number of wavelengths needed for wavelength assignment. We developed a tabu search algorithm (TS_LAR) in [SCW2008] and formulated the routing sub-problem of the RWA problem with the objective to minimize the *LAR* as an exact Integer Linear Program (ILP), denoted as ILP_LAR, in [S2009], extended in [SCW2010]. Test results for a 6-node network and 15 sets of lightpath requests are shown in Figure 20.b. For comparison purposes, we used a formulation which minimizes congestion, denoted as ILP_LOAD. We can see that the ILP_LAR formulation achieves significantly better results for the LAR. Analogous results for larger networks can be found in [SCW2010].

Regarding attack-aware planning, we also investigated the consequences of intra-channel crosstalk attacks and developed wavelength assignment schemes to minimize its propagation in [SF2009] and [FSG2010]. Namely, in optical switches, channels on the same wavelength can interfere with each other causing in-band or intra-channel crosstalk. A deliberate intra-channel crosstalk attack is achieved by injecting a high-powered signal (e.g. 20 dB higher than the other channels) on a legitimate lightpath causing such significant leakage that attacked signals can acquire attacking capabilities themselves. Consequently, such an attack can propagate though the network, affecting links and nodes not even traversed by the original attacking signal as illustrated in Figure 21(a).

In [SF2009], we introduced a new objective to minimize for Wavelength Assignment, called the Propagating Crosstalk Attack Radius, or P-CAR. As a secondary objective, we minimize the number of wavelengths used. We define the P-CAR of lightpath LP_i as the total number of lightpaths that a jamming signal propagating on LP_i can affect via intra-channel crosstalk occurring in switches between lightpaths on the same wavelength. The maximum P-CAR over all lightpaths in a RWA scheme determines the P-CAR value of that scheme. We consider the worst case scenario in which we assume indefinite attack propagation. In reality, the attacking potential of a signal decreases along its path due to several factors, such as the traveled distance and the number of switches traversed. However, since we are offering a strictly preventive WA technique, our model aims to minimize the worst-case crosstalk attack propagation with minimum loss of power.

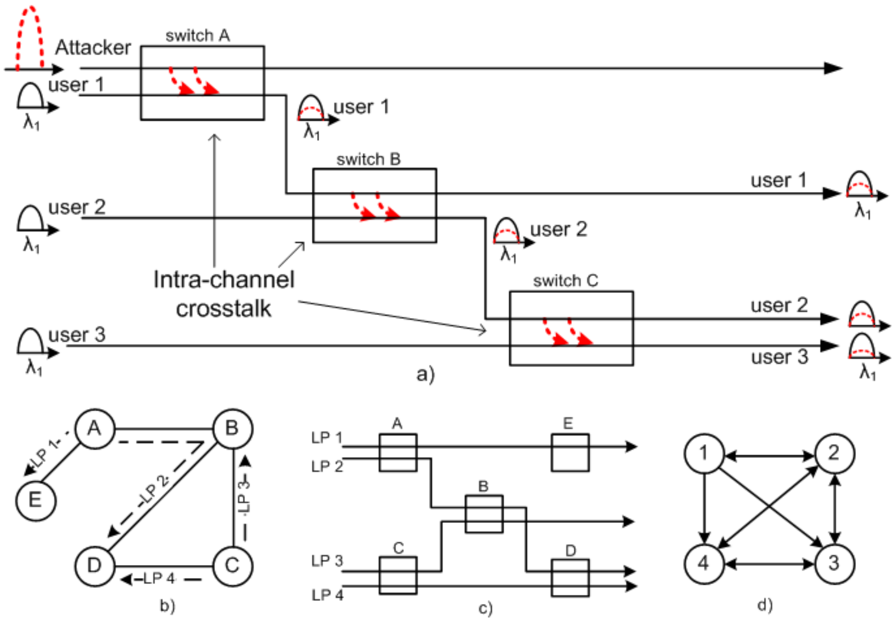


Figure 21. (a) Intra-channel crosstalk attack propagation. (b) An RWA scheme with 4 lightpaths on the same wavelength. (c) Common switches (i.e. potential points of intra-channel crosstalk attacks) and the corresponding attack graph for the given lightpaths (d).

In Figure 21(b), a simple RWA scheme is given, with 4 lightpath requests routed on their shortest paths. They do not share any common directed physical links and can thus be assigned the same wavelength. Figure 21(c) shows their common switches, i.e. potential points of attack. An attack originating from, e.g., LP 1 can affect LP 2 via their common switch A, which then, in turn, after the point where it has been attacked itself, gains attacking potential and attacks LP 3 in switch B and LP 4 in switch D. Therefore, the P-CAR of LP 1 is 4. We model attacking relations among lightpaths with a simple structure we call the attack graph, shown in Figure 21(d) where nodes represent lightpaths routed on the same wavelength, connected to others if an attack can spread from one to the other, directly or indirectly, through intermediate lightpaths. The P-CAR of a lightpath equals the out-degree of its corresponding node in the attack graph, incremented by 1. In [FSG2010] we designed heuristics based on bin-packing and graph coloring aimed to solve WA by minimizing the PCAR.

In the last phase of the first main objective, we started investigating a new attack-aware planning problem. Namely, the propagation of high-power jamming attacks causing gain competition in optical amplifiers and inter-channel crosstalk in fiber links can be efficiently prevented by installation of power equalizers in the network nodes. However, due to the high cost of such equipment, the number of power equalizers should be minimized and their placement in the network should be done in such a way that the attack propagation for a given routing scheme, especially those that are not attack-aware, is minimized. In [JSF2010], we proposed a node architecture with power equalizers (based on wavelength-selective attenuators), and a Greedy Randomized Adaptive Search Procedure (GRASP) to solve the power equalization placement problem so that the propagation of high-power jamming attacks is reduced by using a minimum number of power equalizers.

To solve the second objective dealing with optical networks security, in [STP2008] and [STP2009] we investigated the topological structures of the established lightpaths, not just considering their individual attacking relations, but their global interconnectivity. Namely, fast and successful reaction and restoration mechanisms can prevent from loosing large amounts of data which can cause severe service disruption. These mechanisms rely on monitoring information exchanged via optical supervisory channels along each physical link. We proposed applying common structural properties of self-organizing systems (specifically, the small-world and scale-free models) to help achieve faster and more robust system-wide communication in the context of failure management. We proposed creating a hybrid supervisory plane whose structure is such that it can speed up and improve critical security information exchange and, thus, improve the network's ability to reconfigure and re-establish communication in the presence of failures. In order to achieve faster communication for more efficient failure management, we aim to reduce the average path length of the supervisory plane, while maintaining high clustering to aid failure detection mechanisms and improve resilience to false alarms. We propose creating a hybrid supervisory plane by maintaining the bidirectional point-to-point supervisory channels along each physical link, but also introducing a few long-range 'supervisory lightpaths' between distant nodes.

The third avenue of research in optical networks planning conducted within the framework of this JA, focused on multi-hour, or scheduled, virtual topology design. This implies searching for the temporal evolution of virtual topologies, and its corresponding traffic grooming, which efficiently adapt to known traffic variations. We assume known multihour, i.e. periodic, traffic patterns. In [SPG2009] and [GAP2009], we propose a set of algorithms for solving the aforementioned problem, which we denote as SVTD (Scheduled Virtual Topology Design). More formally, a SVTD instance receives a series of traffic matrices, and returns one or more virtual topology designs, together with associated flow routings. We consider two variants of the problem. In the first variant, the switching equipment is assumed to be non-reconfigurable or hard-wired. Therefore, the virtual topology is constrained to be constant along time.

In [PAG2009] we perform a more detailed analysis of just the non-reconfigurable case, but for various types of flow routing schemes. As before, we consider offline virtual topology planning in transparent optical networks given a multi-hour traffic demand, i.e. for known or estimated traffic variations. However, here we assume that the virtual topology cannot be changed along time, i.e. we determine a static set of lightpaths capable of routing all traffic as it varies over all time slots. Thus, the network can be based on non-reconfigurable optical switching equipment. Our target is finding an optimal fixed virtual topology, and the associated traffic flow routing on top of it, which is capable of fully carrying the given traffic in all time slots. The cost to minimize is measured in terms of the number of lightpaths in the network, which define the number of transceivers (transmitters and receivers) needed as in the above problem.

In the final phase of this activity, novel, efficient and scalable algorithms were developed for the Multihour VTD (MH-VTD) problem where the lightpaths are considered reconfigurable, but by penalizing the frequency of reconfiguration. We developed algorithms for virtual topology reconfiguration under multi-hour traffic using Lagrangian relaxation and tabu search approaches in [APS2010], and developed and tested a new greedy algorithm called GARF in [ASP2010], which significantly improves our previous results. We introduce a tunable parameter $r=\{0, 1, \ldots, T-1\}$, where T is the number of timeslots in the multi-hour traffic which allows us to control the increase in the overall number of required transceivers as a tradeoff with minimizing reconfiguration frequency. To achieve insight into the performance of GARF, we observe the joint evolution of the number of transceivers and the frequency of the reconfigurations in the GARF designs. Namely, there exists a trade-off between the increase in the number of transceivers and the obtained decrease in the number of reconfigurations, depending on parameter r. To illustrate this relation, we ran the GARF algorithm with parameter r ranging from 0 to T, in T/8 increments, for the Abilene-24 and Abilene-168 scenarios extracted from the publically available Abilene traffic trace (http://totem.run.montefiore.ulg.ac.be/datatools.html). Figure 22(a), (b) and (c) collect the results for various loads (denoted as ρ=0.1, ρ=1 and ρ=10 respectively), where the frequency of reconfiguration (average number of reconfigurations per time slot) is shown versus the quotient r/T. We can see that setting r to a small value for medium and high loads can create an advantageous trade-off between transceivers and reconfiguration. These results have been written in a joint paper which we have submitted to IEEE/ACM Transactions on Networking [ASP2010].

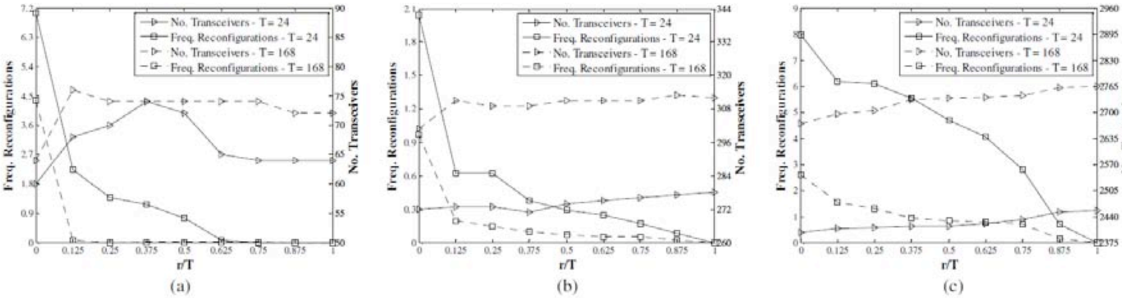


Figure 22. Frequency of Reconfigurations (No. of Reconfigurations per Time slot) and Number of Transceivers vs. Quotient r/T for different test cases: (a) Abilene traffic averaged on 1 day (T=24) and on 1 week (T=168) with ρ = 0.1, (b) Abilene traffic averaged on 1 day (T=24) and on 1 week (T=168) with ρ = 1, (c) Abilene traffic averaged on 1 day (T=24) and on 1 week (T=168) with ρ = 10.

3.5 PCE for Multi-domain Traffic Engineering

The objective of this Joint Activity is to investigate the Path Computation Element (PCE) architecture capability to provide effective Traffic Engineering (TE) solutions in multi-domain BGP-based networks.

PCE architectures have been proposed to perform constraint-based path computations both in single and multi-domain networks. However, in multi-domain networks, the effectiveness of PCE-based computation of inter-domain paths is affected by the limited visibility of TE information which is usually restricted to a single domain. To overcome this limitation, two procedures called Per-Domain and Backward Recursive PCE-based Computation (BRPC) have been proposed. In particular, the BRPC procedure has been proposed for computing, given a specific metric, optimal multi-domain paths. It resorts to the PCE communication Protocol (PCEP) to allow the PCE controlling the destination domain to initiate, in a reverse fashion, the recursive path computation towards the PCE controlling the source domain. However, in BRPC, the sequence of domains to be traversed is given. The PCEP protocol allows the Path Computation Client (PCC), e.g. the Network Management System (NMS) or the source PCE, to specify the sequence of domains to be traversed. Such sequence is included within the PCEP Include Route Object (IRO) carried in the PCEP PCReq message. The problem of defining the optimal sequence of domains to be traversed for the multi-domain path computation (i.e., to be included in the IRO object) has been addressed mainly theoretically or experimentally in management-based networks. Few solutions have been proposed for Border Gateway Protocol (BGP)-based networks. This is motivated by the limited amount of resource information typically exchanged by BGP among domains. Indeed, to preserve network scalability, BGP does not advertise bandwidth information and multiple alternative routes, thus providing the same route choices and causing link congestion. As a consequence, the acquisition of multi-domain resource information from BGP databases drives the PCE to typically consider just one sequence of domains per network prefix. The Per-Domain and BRPC procedures may then be applied along non-optimal sequence of domains, thus potentially affecting the overall network performance.

The expertise of POLIMI on the dynamic simulation models and of SSSUP on the experimental implementation have been combined together. Moreover, both partners conveyed in the joint work their knowledge about the multi-domain networks.

3.5.1 Objectives

The objective of this JA is to address the aforementioned issues by introducing the dissemination of additional routing information enabling the effective utilization of PCE-based procedures.

3.5.2 Summary of achieved Results

The JA started at the end of Y1 with the definition of the objective and the necessary requirements and responsibilities to complete the joint research study. During the Y2, we focused on the PCE architecture capability to provide effective multi-domain TE solutions. We proposed to pre-compute the sequence of domains on the basis of the information provided by a hierarchical path-vector protocol dedicated to TE information. In particular, a hierarchical instance of BGP (HBGP) is proposed to operate within a restricted set of authorized domains. This is in-line with the PCE architecture applicability, which is defined to operate within a limited set of domains with known relationships, like the peering relationships (e.g., up to 20 domains). In terms of confidentiality, it restricts the multi-domain information received by a node to the network view provided by the adjacent domains. In addition, commercial constraints could be adequately supported since transit domains have the capability to potentially treat each customer/prefix in a different way. Moreover, a path-vector view of the network resources is compatible with the view provided by the PCE architecture, which is based on path information exchanged between adjacent domains.

The integrated HBGP-PCE architecture enables the implementation of multiple schemes that differently exploit the various configuration features. They include: the announcement through HBGP of single or multiple routes per each domain or network prefix, the possible announcement of inter-domain bandwidth availability information, the use of Per-domain or BRPC path computation procedures, and the possibility to perform multiple attempts along different sequences of domains.

The performance of the proposed HBGP-PCE architecture has been evaluated through simulations. The reference multi-domain network is a PAN-EUROPEAN topology composed of six ASes: GEANT2 and five National Research and Education Networks (NRENs). Simulations evaluate connection setup time and blocking probability of intra- and inter-domain connections as a function of the offered load. Figure 23 (left) shows an extract of the simulation results. Results show that the worst blocking probability is achieved by a scheme exploiting just the information typically provided by current BGP protocol implementations. On the other hand, the best performance is achieved by a scheme which exploits additional information provided by HBGP as well as the BRPC procedure.

The proposed HBGP-PCE architecture has been implemented in a network testbed composed of commercially available Label Switched Routers (LSRs) configured in N=5 ASes. The implementation successfully includes PCE prototypes, PCEP Per-domain and BRPC path computation procedures and the introduced HBGP modules. Figure 23 (right) shows an extract of the HBGP and PCEP messages exchanged among the considered network nodes.

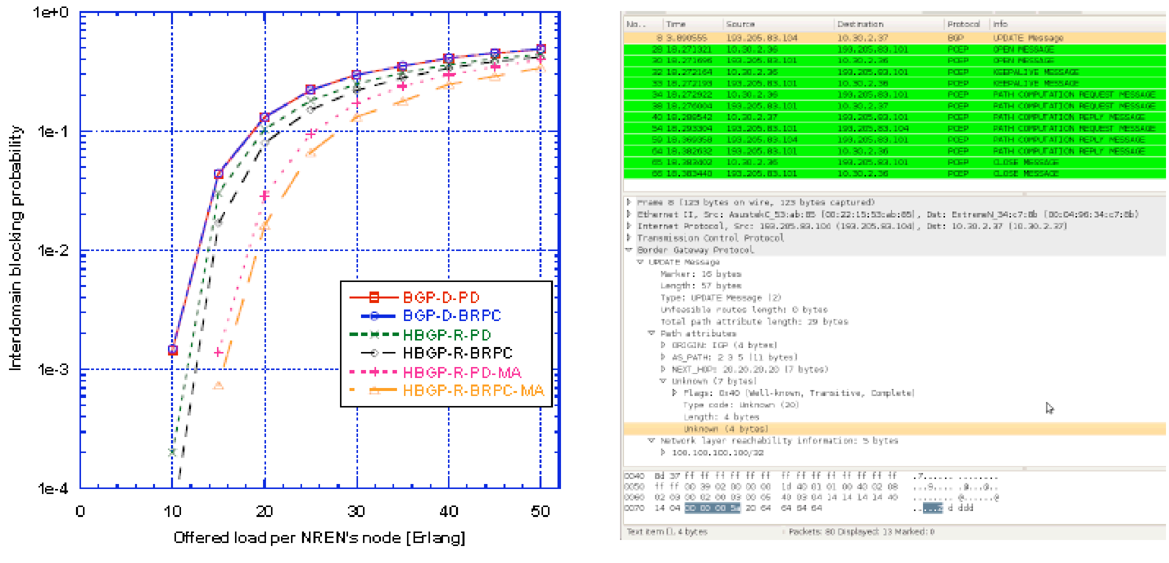


Figure 23. HBGP-PCE Schemes: Blocking probability (left); HBGP and PCEP messages among network nodes (right).

During the Y3 the writing of a journal paper on the aforementioned reported activity has been initiated.

3.6 Traffic engineering and topology design in metro networks

This Joint Activity (JA6) targets the issue of traffic engineering and topology design of metropolitan area network (MAN). In the JA6, the expertise of TELECOM Bretagne on optical packet switching and quality of service has been joined with the expertise of Scuola Superiore Sant'Anna (SSSUP) on optical network dimensioning.

During the first year, the JA focused on the definition of the MAN architecture. In particular, an optical MAN based on optical packet switching and WDM technology was identified as the most suitable candidate to offer high capacity and flexibility. A unidirectional ring topology was considered (the second direction could possibly be used for ring protection but this issue was not considered in this JA). Transmissions are time-slotted and synchronized. On each wavelength, each time slot can support a single fixed-size optical data packet. Each node presents a single fully-tunable transmitter and can transmit at most one packet on any wavelength during a time slot. Each node can be equipped with one or multiple fixed single-wavelength receivers. A schematic representation of the considered node architecture is presented in Figure 24. The node is able to receive the packets on wavelengths λ_2 and λ_4. In the considered time-slot, the node receives a packet on λ_2 and then transmits a new packet destined to node 3 on the same wavelength. The packet destined to node 3 on wavelength λ_1 and the packet destined to node 2 on wavelength λ_4 bypass transparently the node. In the example, it is assumed that node 3 has receivers tuned on λ_1 and λ_2 and that node 2 has a receiver tuned on λ_4.

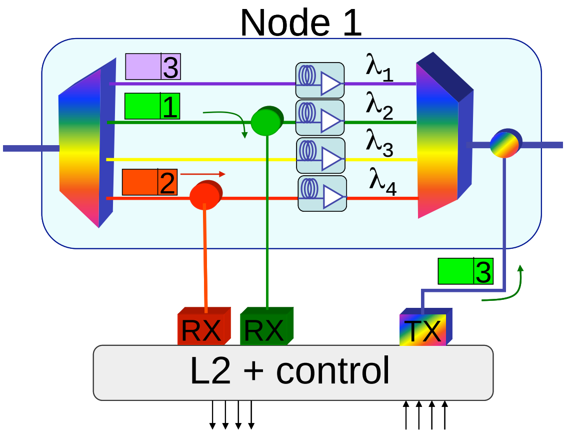


Figure 24. Architecture of the optical packet switching node

As indicated by the example, the main advantage of the proposed node architecture is that it permits to blend packet switching technique with optical transparency, leading to a flexible MAN architecture that is able to accommodate large amounts of traffic. The main difference between the proposed optical packet switching ring and those studied (or implemented) in the previous projects (such as in projects HORNET, RINGO, DAVID, DBORN, and FLAMINGO) is the possibility to install multiple receivers at each node and thus to aggregate different flows of optical packets (i.e., with different destinations) onto the same wavelength.

3.6.1 Objectives

The main objectives of JA6 were:

1. cost-efficient dimensioning of the proposed optical packet switched ring;
2. high-performance scheduling algorithms for the proposed optical packet switched ring;
3. combination of the previous two objective for a cost-efficient and stable dimensioning of the ring.

The dimensioning problem consists in determining the number of receivers required at each node, their wavelength tuning and the overall number of wavelengths required in the ring. On the one hand, when each node is equipped with only one receiver (such as in projects HORNET, RINGO, DAVID, DBORN, and FLAMINGO), all the packets with the same destination are transmitted on the same wavelength. Traffic is aggregated on each wavelength on a per-destination basis. The number of receivers to be installed in the ring is the minimum, to detriment of the number of wavelengths that should be equal to the number of nodes. Thus, some wavelength capacity may be wasted. On the other hand, if the wavelength capacity is fully exploited by aggregating the traffic to different destinations on the same wavelength, multiple receivers operating on the same wavelength may be required. The number of wavelengths can be minimized, but the number of receivers required at each node can be up to the number of wavelengths. Therefore, a trade-off between a design at minimum number of receivers and a design at minimum number of wavelengths exists. The optimal selection among these two designs and the other intermediate designs that trades wavelengths per receivers is driven by the cost of the various components. The first objective of JA6 is thus the modelling of the dimensioning problem and the derivation of algorithms for the optimal dimensioning problem.

A good dimensioning must also ensure the stability of the system, i.e., the packets must experience a bounded delay. Since each node is equipped with a single (tunable) transmitter, at most one packet can be transmitted on each time-slot. Therefore, it is necessary to identify the scheduling policies, i.e. the methods for selecting the packet to transmit at each node and each time-slot, when several packets are queued in the node buffers. The stability of the system depends not only on the traffic conditions, such as packet arrival rate, but also on the scheduling policy. Thus, the second objective of JA6 has been the derivation of the stability conditions and the definition of the scheduling policies able to meet the stability criteria.

The final objective is to combine together the achievements of the previous two objectives with the aim to dimension the optical packet ring in a cost-efficient and stable way. In the dimensioning problem, the traffic is represented by the flow of optical packets, i.e., flow-based. Stability issues arise due to packet-nature of the traffic and have been traditionally neglected in the dimensioning problems available in literature. Therefore, the final ambitious target is to derive a novel design that embeds the stability conditions (derived in the second objective) into to the dimensioning problem.

3.6.2 Summary of achieved Results

The JA6 led to two conferences publications [UGG2009] and [UGC2009], one PhD thesis [USC2010], and two journal papers under preparation. The most relevant results are summarized here.

The first interesting result of the JA is that in the proposed optical packet switching ring the number of wavelengths required to support a given traffic matrix is minimum, thanks to the blending of optical transparency and optical packet switching in WDM [UGG2009]. In other words, the well-known wavelength continuity constraint does not impact the dimensioning on the number of wavelengths. Thus the number of wavelengths required by the proposed optical packet switching ring is the same as in a ring in which electronic traffic grooming is performed at each node (or alternatively wavelength converters are freely available). This result is summarized by the following lemma.

Lemma: Given a set of flows of optical packets whose maximum load on a unidirectional WDM ring is L, then the ring can support the wavelength-continuous flows with $\lceil L/B \rceil$ wavelengths, where B is the channel rate of each wavelength, if the flows can be split on the different wavelengths.

Proof of the lemma can be found in [UGG2009].

When the dimensioning problem aims at minimizing the overall cost due to wavelengths as well as to receivers, the problem becomes NP-complete. In [UGC2010], the optimal problem has been modelled as an integer linear programming (ILP) formulation and an heuristic algorithm, named Minimize the Receiver Cost First (MRCF), has been proposed. The objective is the minimization of the overall cost due to receivers and wavelengths. A rough estimate of the cost of a receiver, C_r, and the cost of a wavelength along the ring, C_w, is $C_r \approx 300$, $C_w \approx 30 \cdot D$, where D is the ring length, in km. For a metro ring with a circumference of 100 km, the cost ratio is $(C_r / C_w) \approx 0.1$.

Figure 25 compares the results of the MRCF algorithm with a lower bound (LB), an upper bound (UB), and the optimal results found by solving the ILP formulation, on a ring with N=6 nodes when the cost ratio C_r / C_w =0.1. Traffic matrix is uniform and complete (i.e., flows are required between each node pair with same traffic rate). The x-axis of the figure is the traffic rate generated at any node, normalized to the wavelength capacity. The figure shows that the proposed MRCF algorithm is able to achieve the optimal solutions for low traffic rates. For higher traffic rate, MRCF solution cost is within 33.3% of the optimal solution. The UB represents a design in which a receiver is installed at each node and a wavelength is dedicated to each node (i.e., flows cannot be aggregated on the same wavelength). The UB design is thus the same of the previous projects on optical packet switching rings (e.g., HORNET, RINGO, DAVID, DBORN, and FLAMINGO). The main achievement of the study is that the design cost of the considered ring is significantly reduced with respect to previously studied solutions (up to 3 times lower when receiver cost and wavelength cost contribute to the overall ring cost).

The above presented dimensioning assumed that traffic flows can be split on different wavelengths. However, splitting of traffic demands has a negative impact on the complexity of packet scheduling algorithms. In [UGC2009], a “Design Oblivious” (DO) scheduler that randomly selects an available slot with uniform probability is compared with a “Design Enforcing” (DE) scheduler that enforces, through a Leaky Bucket like mechanism, the proportion of slots used for each traffic flow on each wavelength, according with the dimensioning solution. The study in [UGC2009] clearly indicates that there is a trade-off between network design cost and scheduler complexity. Indeed, flow splitting is a cost-effective solution but impose a ”Design Enforcing” scheduling policy which leads to a unrealistic configuration burden. Forbidding flow splitting avoids this burden, but increases dimensioning cost.

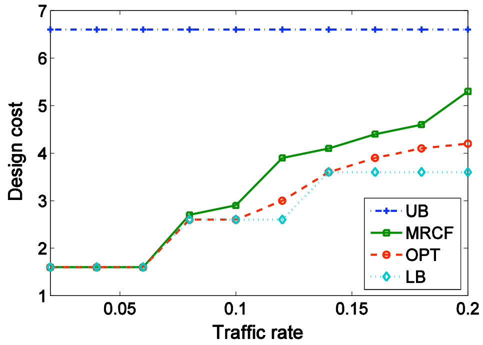


Figure 25. Dimensioning cost vs. traffic rate when C_r / C_w =0.1 and C_w = 1

Not only the scheduling policies impact the dimensioning cost but they also affect the stability of the optical packet switching ring. The stability issue arises due to the packet switching nature of the ring and the random generation of packets at the nodes. Since only one packet can be sent per slot, the scheduling policy specifies the method used to select the packet to transmit (and thus the wavelength to use) at each time slot, when several packets may be awaiting in the queues. One important finding is that the stability conditions for the optical packet switching ring can be derived from the conditions presented in [TAE1993] for a general system and can be described as follows.

Necessary Conditions for Stability. Consider w wavelengths $\{\lambda_i$, i = 1, ..,$w\}$. For each wavelength, a FIFO queue stores the packets to be transmitted to nodes able to receive on the corresponding wavelength. Assume that at most a single packet can be scheduled per time slot. Let μ_i be the probability that wavelength λ_i is available for transmission in a given slot, and let λ_i be the arrival rate for queue i. The existence of a scheduling policy for which all queues are stable implies the following set of conditions:

$$\sum_{i \in Q} \lambda_i < 1 - \prod_{i \in Q} (1 - \mu_i) \qquad for\ all \quad Q \subset \{1, 2, ..., w\} \tag{1}$$

where Q represents any sub-set to wavelengths. The scheduling policies meeting the stability conditions are given in [TAE1993]:

Scheduling Policies. If Longest Queue First (LQF) or Largest Virtual Waiting Time First (LVWTF) is the scheduling policy, the set of stability conditions implies the stability of the model.

The main results achieved in the stability study is that the necessary conditions derived in [TAE1993] are equivalent to the stability conditions derived in [STO2004], leading to necessary and sufficient conditions as follows:

Necessary and Sufficient Conditions for Stability. The conditions given in Eq. (1) are necessary and sufficient conditions for the stability of the optical packet switching ring.

Proof of the above results can be found in [USC2010]. Further studies would be necessary to derive a condition ensuring that the packet delay is lower than a given bound.

The minimum cost dimensioning presented above may not meet the necessary and sufficient conditions for stability. For instance, consider the traffic matrix (normalized to the wavelength capacity) shown in Figure 26 (left). The minimum cost dimensioning is found with two wavelengths: wavelength λ_1 supporting the packet flows A|B, A|C, D|E, E|A, and wavelength λ_2 supporting the packet flows A|B, A|C, C|D, D|E, E|A. The wavelength occupancy is given in Figure 26 (right). Consider node A. Node A is supposed to add a packets at a normalized rate of 0.4 on λ_1 and of 0.4 on λ_2 , when both wavelengths are already occupied at 0.5. While feasible from the dimensioning point of view (0.4 < 0.5), the solution is not meeting the stability conditions given in Eq. (1), i.e., 0.4 + 0.4 > 1- (1-0.5)(1-0.5). To meet the stability conditions, additional wavelengths and/or receivers need to be installed.

	A	B	C	D	E
A	0	0.2	0.2	0.2	0.2
B	0	0	0	0	0
C	0	0	0	0	0
D	0	0	0.5	0	0
E	0	0	0	0.5	0

	A-B	B-C	C-D	D-E	E-A
λ_1	0.9	0.4	0	0.5	0.5
λ_2	0.9	0.9	0.9	0.5	0.5

Figure 26. Dimensioning example: traffic matrix (left) and wavelength occupancy (right)

The final result of the JA6 is the cost-efficient and stable design, realized by embedding the necessary and sufficient stability conditions (Eq. (1)) into the ILP formulation derived for the optimal dimensioning [USC2010]. The optimal result is named packet-aware design (PAD) and is compared with a packet-unaware design (PUD) in Figure 27. The figure shows the design cost and the number of wavelengths and receivers versus the traffic load (normalized to the wavelength capacity) generated by any node, on a ring with N=5 nodes when the cost ratio C_r/C_w = 1. Traffic matrix is uniform and complete (i.e., flows are required between each node pair with same traffic rate shows that for the considered scenario, the PAD and the PUD have the same cost for any load, indicating that the stability conditions are not affecting the optimal dimensioning (Figure 27). While this is not true in general (see previous example), further study are required to assess whether PAD is equivalent to PUD in most of practical cases. Finally, the figure clearly shows the flexibility of the proposed ring architecture: an increase of load can be supported by installing an additional wavelength without requiring additional receivers (e.g., when load increases from 0.1) or by installing additional receiver(s) without requiring additional wavelengths (e.g., when load increases to 0.12 or higher).

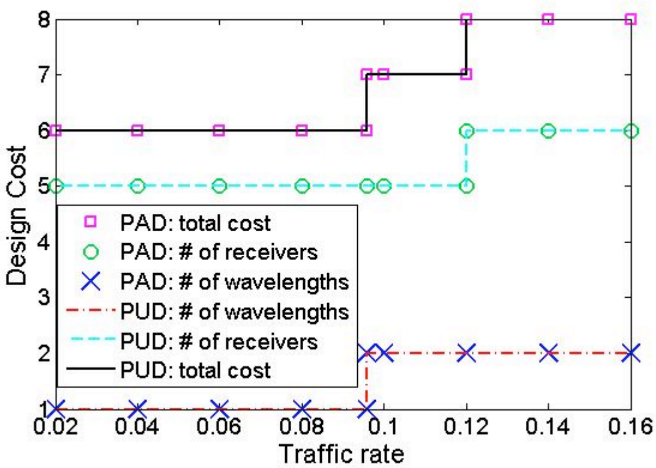


Figure 27. Packet-aware design (PAD) vs. packet-unaware design (PUD) for increasing traffic rate generated at the node, when C_r / C_w =1 and C_w = 1

The dimensioning study carried out in JA6 attracted the interest of Alcatel-Lucent for a possible study on the energy-efficiency of the proposed optical packet switching ring. As a result, the JA members submitted a joint paper in collaboration with Alcatel-Lucent personnel to OFC conference 2011 [PUC2011].

3.7 Effects of outdated control information on routing in optical networks

3.7.1 Objectives

In the first year of this joint activity, the research group of Politecnico di Milano (POLIMI) investigated the effects of outdated control information in control-plane-enabled optical networks. The dissemination of control information (usually provided by routing protocols such as OSPF-TE) is essential in this kind of control-plane enabled networks: in particular, this information has to be continuously updated to allow routing algorithms to efficiently carry on the path computation [1].

The control information depends on various factors, mainly on which protection technique is applied and if wavelength conversion is enabled. E.g., while the standard distributed information (e.g., link state advertisement in OSPF-TE) is the link-state and the free capacity available on each link, in a not-wavelength-convertible case, the single channel status has also to be distributed if the wavelength continuity constraint needs to be satisfied.

Our investigation introduced innovative elements with respect to the previous body of research, since this was the first work covering the peculiar effect on protection (especially, backup sharing in shared protection) and comparing the cases with and without wavelength conversion. We explored a wide range of values of control delays, analyzing the deriving performance loss over three different dimensions: (i) the value of control delay, (ii) the routing strategy adopted (namely, unprotected, dedicated path protected and shared path protected) and (iii) the conversion capabilities (the wavelength convertible case will be referred as Virtual Wavelength Path ,VWP, as opposite to the not wavelength convertible case referred to as Wavelength Path, WP)

Path computation elements (PCEs) in nodes are not always updated and routing may be carried on according to an outdated image of the network. When introducing relevant control delays, new contributions to blocking can be identified:

- RC - Resource Conflict: the PCE routes s connection along a path that is no more available, because in the meanwhile those resources have been taken and the connection is blocked even if there are chances that alternative free paths were available.
- FS - False Saturation Conflict: PCE is unable to route a connection because no routes seem to be available between source and destination nodes. The connection is blocked even if, in the meanwhile, some resources have been released .
- SR- Sub-optimal Routing: The PCE routes a connection along a suboptimal route.

As we will describe in the results section, the first part of this joint activity was methodologically based on software-based simulations, since this such computationally-lightweight approach allowed us to cover a very large set of scenarios and network parameter [TDM2009].

The second objective of this joint activity is to experimentally evaluate the impact of the traffic dynamics when the control information on resource sharing is either flooded by OSPF-TE or collected by RSVP-TE. In this work we consider three information dissemination strategies by the OSPF-TE routing protocol, comparing them when collecting shareable resource information by means of the standard or extended RSVP-TE signalling protocol. The GMPLS routing (e.g., OSPF-TE) disseminates network resource availability and topology information so that each node maintains a detailed network view, stored in the traffic engineering database (TED). Resource information is aggregated on a per link basis (e.g. TE link *unreserved bandwidth*). Additionally, to ensure the disjointness between working and backup paths, the *shared risk link group* (SRLG) concept is used: the SRLG indicates a group of links that share a common risk of failure. If one considers a single SRLG per TE link, two paths being SRLG-diverse are also link disjoint. The three considered dissemination approaches differ on the granularity of the disseminated TE link information:

- *Aggregated unreserved bandwidth* (UBw): in this first approach (GMPLS standard), only information about unreserved link bandwidth is flooded.
- *Aggregated shared bandwidth* (SBw): in this second approach, besides the above information, shareable bandwidth on a given TE link is also flooded. In this case, it is also needed to disseminate the list of the TE links (SRLGs) being protected by such shareable bandwidth. In [MMC2007], the authors proposed to extend the GMPLS OSPF-TE protocol for this purpose.
- *Wavelength-channel granularity* (WCh): the third routing strategy disseminates resource availability at the wavelength channel granularity, using a bitmap encoding, as proposed by the authors in [MMC2009]. Similar to the second approach, the GMPLS routing protocol is further enhanced to disseminate the list of TE links being protected by each shared backup wavelength [MMC2007].

This study relies on three SPP-oriented *path computation and routing algorithms* defined in [MCM2009] that make use of the information disseminated by the three proposed strategies. The computed spatial routes (i.e., a list of nodes and links) are passed to the signalling mechanism as *Explicit Route Objects* (ERO) and the subsequent signalling phase consists of a label request within a RSVP Path message from the source to the destination node, and a generalized label assignment (reservation) sent in a RSVP Resv message which travels backwards to the source node. In WSON networks with wavelength continuity constraint, the wavelength assignment is always done at the destination node. Two information collection and wavelength assignment strategies are considered:

- *Wavelength Availability (WA):* GMPLS uses the *Label Set* (LS) of the RSVP-TE protocol. The Label Set (GMPLS Standard) collects the available and contiguous wavelengths identifiers from the source to the destination node during signalling. At the destination node, a wavelength is selected from the resulting label set according to a wavelength assignment policy (First-Fit, Random, etc.). If the Label Set becomes empty, the entire connection is blocked, releasing previously allocated resources.

- *Shareable Resource information (SRI):* in [MRM2008], the authors extended the GMPLS Label Set to the so-called *Shared Label Set* (SLS), aiming at collecting not only the wavelength availability but also its sharing information, following a hop-by-hop procedure from the source to the destination node through the Path Message during the establishment of the backup lightpath. It relies on appending a per wavelength counter at the source node that collects information about the number of hops along the route where each wavelength is found in a shared reserved state, and collecting, for each wavelength, information about its status and the number of protected sessions, links, and working paths. This strategy relies on the Maximum-Sharing Maximum-Protecting (MS−MP) wavelength assignment algorithm defined in [MRM2008].

If the source node is able to provide the associated wavelength (i.e., in the WCh dissemination strategy), two wavelength assignment strategies can be considered:

- *Loose Source Wavelength Suggestion* (LWS): it relies on the use of the Suggested Label, which is an optimization allowing an upstream node to suggest (and start reserving) a label to a downstream node in the Path message. If the suggested label received by a downstream node is unavailable, it is ignored and removed from the Path message, and the LSP request continues with its normal procedure. It is worth noting that it is used in combination with the WA information collection strategy. Thus, when the Path message reaches the destination node, a wavelength is selected from the received Suggested Label or from the resulting label set according to a WA policy (First-Fit, Random, etc.).
- *Strict Source Wavelength Suggestion* (SWS): it is possible to enforce the wavelength channel within the Explicit Route Object (ERO) by means of Explicit Label Control or a Label Set containing only that channel. If the specified wavelength is unavailable, the connection request is blocked. Otherwise, the destination node assigns the wavelength provided by the source node.

3.7.2 Summary of achieved Results

Simulation results

Applying the very general control-delay representation described, we were able to provide wide-range simulative study to quantify the effect of signalling on routing performance, mainly by using the blocking probability (P_b) metric: since blocking stems from different causes, the influence of the various P_b components have been also investigated.

We simulate a dynamic network environment with the assumptions that the connection–arrival process is Poissonian and the connection–holding time follows a negative exponential distribution. Requests are uniformly distributed among all node pairs; average connection–holding time is normalized to unity; the cost of any link is unity; and our example network topology with 16 wavelengths per fiber is a carrier's U.S. nationwide backbone network topology

In Figure 28, P_b curves are plotted for 200 and 240 arrivals per second (correspondent to a network load of 0.446 and 0.55, respectively) in the UN case. P_b curves, independently of the routing strategy adopted, can be described by three well distinct phases:

- I phase - Not influential delay: in this first phase P_b is stationary and it is not influenced by the delay. Essentially performance are equivalent to the ideal (zero-delay) case.
- II phase - Linear increase of P_b: delays in network-state reception start affecting the quality of source-routing, causing a significant and linear increase on P_b
- III phase - P_b saturation: P_b is no more affected by a further increase of the network-state-information delay, since the network image in the source-routing node is totally uncorrelated to the actual network state. The situation is equivalent to route connections with no information about network state.

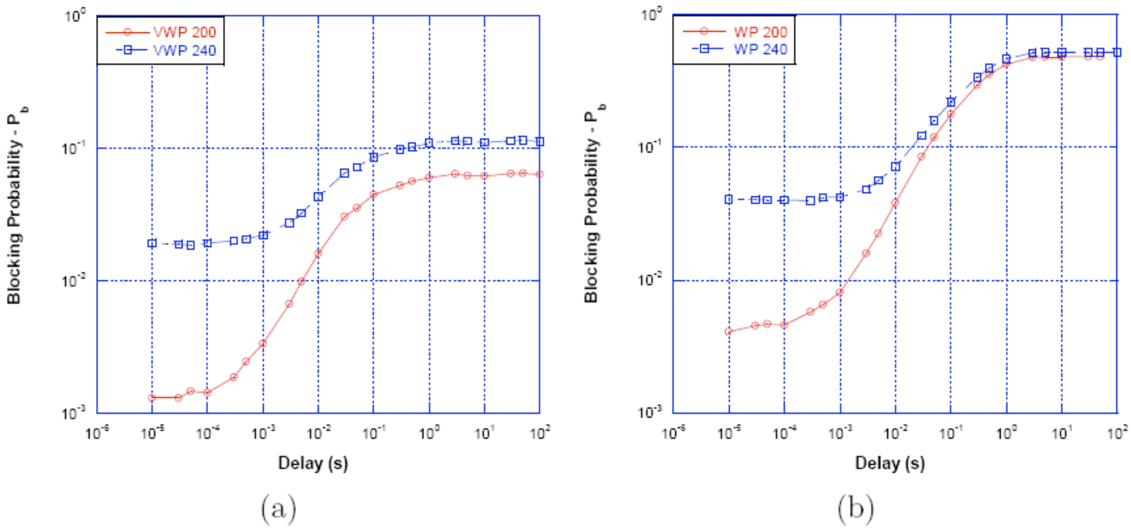


Figure 28. Total Pb for unprotected routing in (a) VWP and (b) WP case.

In the WP cases, P_b values are higher than in VWP case: while in the first phase this is a well-known effect of wavelength continuity constraint, in the saturation phase we should also consider that an higher P_b is achieved because the routing algorithms for VWP cases are more tolerant to outdated information in the VWP case than the WP case.

The contributions of the various components have trends that are strictly interdependent; in particular:

- for very small delays, FS and PS curves grow linearly, while the CB component is almost constant (actually it slightly decreases of a value equal to the sum of PS and FS that are very small in this phase) and largely constitutes the overall probability.
- when the PC contribution equals the CB contribution (at about D = 10^{-3}), the CB curve start rapidly decreasing, while the PC curve keeps growing linearly until it stabilizes for value of D comparable with the average holding time (i.e., about 1).
- also the FS contribution keeps growing until it reaches comparable values with CB. Then it decreases consistently to stability on very small probabilities below 10^{-5}.

The overall P_b is dominated initially by CB, then for higher delay values PC is the dominant term; FS plays a significant role only on a limited range of delays values after PS has intersected CB.

The main contribution of this simulative activity has been achieved during this first year, but some further investigation has been conducted also in the second year. In particular additional simulations have been carried on to investigate effects of outdated information vary for different traffic dynamicity

In fact, for a fixed value of traffic load in a network, the outdated information may induce different effects according to the characteristics of the traffic. It is intuitive that the same control delay has a weaker effect on traffic composed by long and rare connections than on traffic composed by short and numerous connections. We found out that the effect of control delay is exacerbated by higher dynamicity [TDM2009].

Testbed results

As for the experimental evaluation, we consider the following performance indicators, experimentally measured in the ADRENALINE testbed [MPM2005]: the blocking probability, the resource overbuild, the required bandwidth for either RSVPTE and OSPF-TE control protocols and the average connection setup delay. Additionally, a new key performance indicator is introduced in this work to evaluate the outdated information: the *routing convergence time* for an update, defined as the time period required for an LSA update to be received and processed by all the nodes within the network i.e., the time span starting from the time the LSA is generated or refreshed until the LSA is integrated by the routing controllers into their respective databases. Such processing results in a common view of the network topology in terms of TE attributes of Links and Nodes. Final results of this investigation have been published in [MCM2010].

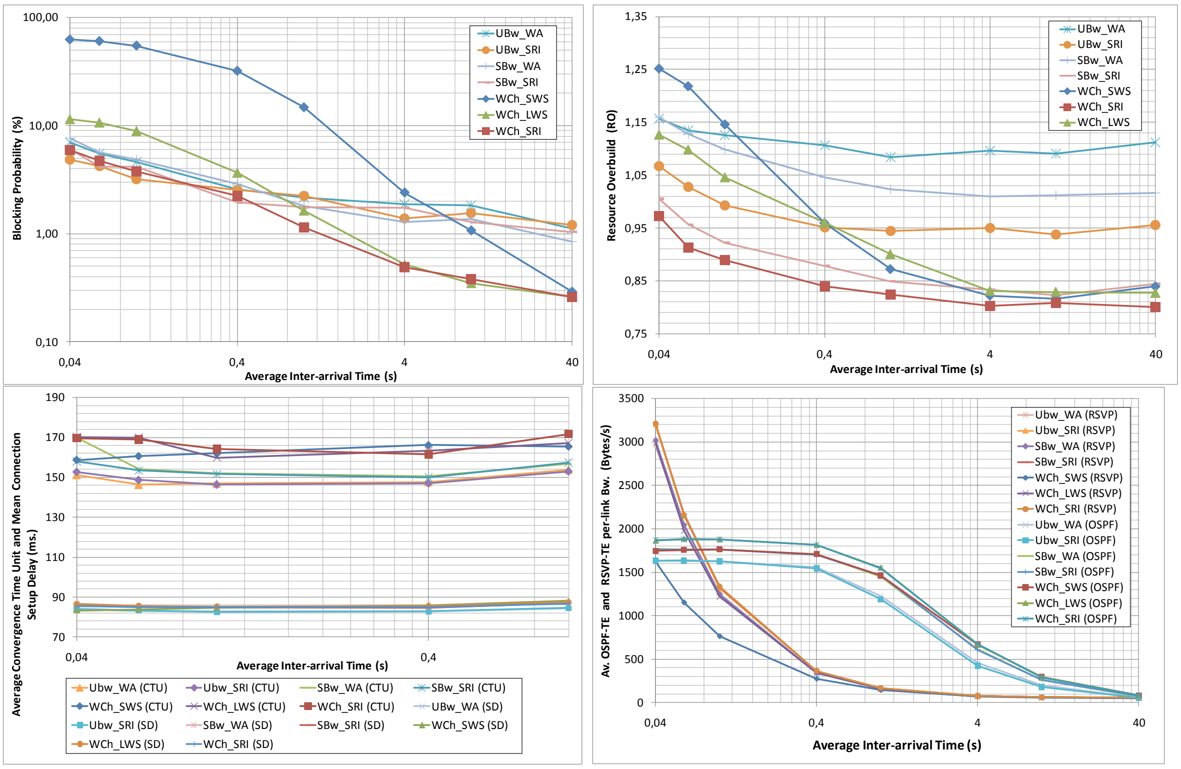


Figure 29. Blocking Probability

From the experimental evaluation (Figure 38), it can be observed that RSVP-TE resource information collection strategies are less sensitive to the concurrence of multiple connection requests, since it collects the wavelength availability and sharing information hop-by-hop, much faster than OSPF-TE resource information dissemination strategies. Therefore, the best SPP recovery strategy for the considered traffic dynamics, in terms of blocking probability and resource overbuild is to compute, at the source node, an spatial path using as input information the availability and shareability of the network resources on a per-wavelength channel basis gathered in the node's TED repository by the extended OSPF-TE routing protocol (i.e., WCh dissemination strategy), and to perform the wavelength assignment at the destination node taking advantage of the collection of the shareable resource information attained by the extended RSVP-TE signalling protocol (i.e., SRI collection strategy). In general, SRI collection strategy is less sensitive to the concurrence of multiple connection requests and the outdated information, since it collects the wavelength availability and sharing information hop-by-hop, much faster than the WCh, that is, in turn, the most sensitive dissemination strategy to the multi-concurrence. However, it is worth noting that both SRI and WCh introduces a penalty in terms of the consumed RSVP-TE and OSPF-TE bandwidth, requiring an overall extra bandwidth between 10% and 30%. Thus, we state a clear tradeoff between network performance and the generated control bandwidth.

3.8 NETBENCH "Benchmarking of network architectures for guaranteed service provisioning"

The main concept of this Joint Activity was for different partners to collaborate and to provide a complete (to the extent possible) study and performance evaluation of different optical networking technologies of interest. In the optical networking and switching field these technologies include a range of optical networking schemes from OBS and OPS to circuit/wavelength switching, offering a certain degree of dynamic resource allocation and/or guaranteed end-to-end performance. The collaboration of the partners focused on the following tasks:

- Collection and documentation of requirements and assumptions to be used in the evaluation phase
- Definition of performance evaluation scenarios
- Modeling and performance evaluation
- Analysis, evaluation and presentation of the results

3.8.1 Objectives

The selected methodology defined a set of requirements and assumptions to be used in the evaluation phase for the definition of performance evaluation scenarios. According to the selected parameters for benchmarking, several end-to-end networking scenarios can be modelled and simulated. The objective is to collect a set of results and expose several advantages or weakness of specific dynamic network reconfiguration, resource allocation and traffic forwarding mechanisms under specific operation conditions.

In order to proceed in the performance evaluation study, first a number of benchmarking parameters had to be set.

The first and one of the most significant parameter affecting the performance is the set of requirements imposed by the network topology. Details about the reference network topology were described in terms of: topology (connectivity), path distances and capacity. Depending on the case to be demonstrated, either existing backbone network topologies (NSF network, European network), for which details are available in the literature, or "ideal" reference topologies serving specific cases to be demonstrated, were used. Additionally, since this JA aimed at the evaluation of different networking schemes, novel network architectures as CANON, an approach where the nodes of a wide area network (typically 20-30 nodes) are organized in clusters mainly based on vicinity, traffic, legacy infrastructure and administrative criteria, were also assumed.

The functionality of the nodes was also specified. Most optical switching techniques require an adaptation unit employed at the network edge and potentially transparently switch traffic at the inner core network. In the CANON approach the nodes are separated as core and edge nodes depending on being an intra-cluster node (a node inside the cluster) or an inter-cluster node (Master Node, a node to connect with other clusters). With the CANON architecture, electrical buffers exist only in the periphery thus once a packet enters the optical domain it will travel until the destination without any further queuing while two granularity levels are used: the transceivers of the cluster node are operating on a slot-by-slot basis while data are exchanged between clusters in much longer fixed-size frames. Thus the switching node architecture and the wavelength conversion capability were included in the list of parameters for evaluation

Since the benchmarking methodology extends to an overall network solution, the control plane architecture could not be ignored. The usage of OBS alternatives (TAW, JIT, JET) or GMPLS based protocols, create a major effect on the performance evaluation of the system.

Finally the performance metrics had to be pointed out. They can be divided in two major sections

- CAPEX: the switching node and the overall network cost. The cost can be extended in number of components used, cost for implementing the network system, or even in power consumption and switching or node dimensions.
- OPEX: traffic performance. Performance evaluation of the system that can be showed by metrics of delay, packet loss probability, jitter, utilization, etc .

3.8.2 Summary of achieved Results

During the first phase, the basic assumptions towards capturing and analyzing requirements were concluded. The objective was to clarify (especially among the collaborating partners) the basic operational parameters that have been considered in each study and the potential assumptions that have been made. In the second phase relevant network and node architectures where investigated and a comparative evaluation has been performed through a set of simulations in order to draw useful conclusions regarding performance.

Work on the following years proceeded along the same lines going into more technical details and producing first results. The benchmarking methodology including results obtained by using network simulators was mainly followed by UoP, UniBo and UoEssex. Evaluation of selected scenarios progressed in two directions investigating the impact of network topology, optical transport and control plane architecture on performance as well as focusing on the optical node architectures and investigating the performance of node architectures with multi-service traffic.

A3.8.2.1 Evaluation of end-to-end performance

The first direction aimed to evaluate end-to-end performance in wide area network topologies, including core optical networks and integrated access-core optical networks.

Evaluation of large-scale network topologies was performed through modelling and simulation of hybrid topologies and mixed end-to-end resource reservation schemes including:

- Evaluation of the impact of network dimension on performance

- Evaluation of traffic grooming techniques for transparent access-core network integration and impact of optical access-core technologies on transport layer protocols

The objective of the above study was twofold; first to evaluate efficient aggregation and switching with appropriated reservation schemes in ultra-high speed optical transport networks and second to investigate the efficient integration of optical access and core networks.

Benchmarking of networking paradigms for large scale optical networks

The first study covers the benchmarking evaluation of different networking schemes under unified assumptions. In [ODL2009] we evaluated the alternative CANON hierarchical network architecture in the NSF network, where the 14 nodes of the NSF network were considered as MNs collecting regional traffic from clusters of 5 nodes. The performance of the proposed scheme was compared to that of just-enough- time (JET) OBS and OBS-INI schemes. As observed in the results CANON and OBS-INI introducing 2-way reservations exhibited higher average delay than plain OBS-JET, remaining though within acceptable limits for any type of service, while at the same time they achieved significantly lower losses than when using OBS-JET. It is worth noting that CANON loss probability outperformed the other two solutions due to the exclusive use of two-way reservations in CANON, where losses occur only due to buffer overflows.

in [DOP2010] we demonstrated that using an existing infrastructure as the Pan-European network, the fully dynamic CANON can efficiently combine statistical multiplexing gains and improved blocking performance, compared to meshed S-OBS (Slotted OBS), due to a reduction of the contention points, improved network design and resource allocation. S-OBS suffers excessive burst loss since plain wavelength conversion cannot offer substantial contention resolution at high loads. We showed that by efficiently clustering the optical nodes, loss performance has been improved. By applying the CANON scheme, a reduction in the number of contention points can be achieved, justifying the improved loss performance. In addition, we have shown that CANON is a considerably more cost-effective solution due to the lower overall component count, lower overall power consumption and better utilization of the installed capacity. As shown, S-OBS needs more wavelengths just to avoid collisions compared to CANON, which keeps burst loss quite low while packing bursts into much fewer wavelengths, increasing utilization. Indicative results are shown below. To investigate further the relation between the deployed network resources, the achieved performance and network utilization we compared CANON against other solutions in terms of resources needed to achieve the above loss performance. Since the loss probability factor - albeit its major impact on the system performance - is not the only indicative performance metric, we introduced the utilization factor as a metric for comparison. The utilization factor was expressed as the ratio of the sum of the successfully served traffic for all network nodes over the installed network resources. Finally of interest was to investigate the power consumption especially when scaling the size of the network, and we showed the gain of using a novel architecture as CANON to reduce the power consumption of the network.

Finally in [ODP2010] we introduced a hybrid reservation mode for optical fast circuit switching (OFCS) which can implement sub-wavelength and time-limited bandwidth reservations. We used the Pan-European network of [DOP2010] in order to evaluate the OFCS against the fully dynamic reservation scheme of S-OBS under different network dimensioning. We showed that the OFCS scheme can achieve an improved packet loss probability and an increased utilization of the network resources against the S-OBS solution. On the hand, the two way reservation mode that OFCS utilize, introduces an overall delay penalty, a delay that is constrained under an acceptable limit for a core network, but which remains an unavoidable trade-off compared to of S-OBS.

Evaluation of optical Access and Core networking technologies and potential integration

- Performance evaluation of a WDM-PON based integrated access-core optical infrastructure:

To successfully realize the transformation of broadband networks and the Internet to a multi-service platform the structural limitations of current networking architectures must be raised so that information transport infrastructure gracefully evolves to address transparent core-access integration, optical flow/packet transport

and end-to-end service delivery capability, overcoming the limitations of segmentation between access, metro and core networks and domains. Towards this end we evaluated an integrated control plane for optical access and core networks, which addresses the above considerations. The proposed control plane can lead to a unified transport infrastructure integrating state-of-the-art components and technologies including Wavelength Division Multiplexing, Passive Optical Networking and Optical Packet Routers with inherent traffic grooming capabilities. The performance of the proposed architecture is assessed my means of simulation in terms of cost, resource utilization and delay. The main innovation is the extension of the control plane and unified resource allocation, so as to minimize the cost of per packet processing, which cannot be tolerated in photonic backhaul networks. The proposed architecture addresses the above by optical burst aggregation over passively split optical access networks employing hybrid WDM-TDM multiplexing into fixed-size containers called frames. This frame aggregation technique can exploit efficient synchronous switching technologies and achieve high utilization of optical core networks. We evaluated this architecture in comparison to typical approaches that have been proposed for dynamic resource allocation utilizing burst switching techniques and have shown that it can better utilize network resources at the cost of a limited increase in delay. More significant performance gains are expected when dynamic resource allocation over the core network is performed, which is currently work in progress.

- Performance evaluation of the TCP protocol over multi-granular networks: The effect of offset time in OBS has been evaluated in the presence of hybrid switching technology with different switching time

The objective of the above study has been to evaluate the performance of TCP with hybrid technologies providing fast and slow paths for supporting multi-granular connections (i.e. multi-granular switching nodes implementing mixed technologies with different properties and speeds e.g. SOA, MEMs etc.). The switch properties result in two alternatives for optical switching of data transport units (bursts): i) fast connections (paths), in which case a sequence of bursts is switched in core nodes with fast optical technologies (short setup times) and ii) slow connections (paths), where a sequence of bursts is switched in core nodes with slower optical technologies (long setup times).Since different switching set up times imply different offsets times in burst switching modes the impact on performance has been measured and was shown that fast and slow paths get best throughput for different values of the TCP window size, while for low burst losses (e.g. lower than 10-) fast paths give remarkably better throughput than slow paths, otherwise the throughput is almost the same, despite of different transmission rates and technologies employed.

- Performance evaluation of TCP protocol with different access techniques to OBS networks
    - Wi-Fi, Ethernet and EPON are considered.
    - Key parameters are investigated; burst assembly time is thoroughly studied as a key parameter to tune performance

The interworking between different access networks and an optical burst switched network is considered here. The end-to-end performance of the TCP (Transmission Control Protocol) is evaluated by jointly accounting for access network protocols and the burst assembly procedure at ingress edge nodes, both with wired and wireless access solutions, based on electrical and advanced optical technologies. The influence of the assembly timeout in different access contexts is presented, and numerical investigations are performed by means of ns-2 simulations. Results show that end-to-end throughput is mostly influenced by the delay introduced by access protocols, which arise in the analyzed different scenarios, and by assembly timeout. These results provide meaningful insights about interconnected systems to the task of overall network design and, in particular, to the setup of the interworking unit parameters.

A3.8.2.2 Performance of node architectures with multi-service traffic

In the expected multiservice scenario of future networks, the core resource usage must be subjected to rules, which in this study are referred to as QoS differentiation mechanisms and are defined in relation to the characteristics of available network elements. The main problem to face in packet-oriented optical networks the lack of an optical equivalent of the electronic random access memory (RAM) that does not permit the use of large buffers and the direct migration of the typical approaches used in electronic IP routers, such as, e.g., the use of active queue management. Thus in this study a bufferless optical packet switches with QoS differentation mechanisms for OPS networks has been evaluated.

The proposed QoS mechanism must be kept very simple to allow fast processing according to the very fast packet–burst forwarding requirements. Several QoS mechanisms have been proposed in the past for this kind of network, which provide QoS based on a per flow or a per class classification of the traffic. Furthermore, QoS parameters can be expressed in relation to either relative or absolute bounds. With absolute guarantees, QoS parameters are given as upper bound while with relative guarantees, QoS parameters of a given class are given relative to another class. Within each QoS model different algorithms can be defined depending on the specific networking context to which they are applied. For example QoS differentiation schemes for asynchronous bufferless OPS, such as the wavelength allocation algorithm (WA), the pre emptive drop policy (PDP), and intentional packet dropping (IPD).

With the aim to reduce switch cost while keeping contention resolution in the wavelength domain based on wavelength conversion, switch architectures that employ shared wavelength converters (WCs) have been considered. In this kind of architecture, packet loss is caused not only by wavelength contention on the output fibers (OFs), but also by lack of WCs. The most important example of such switches is represented by the shared-per-node (SPN), where a pool of r WCs is shared among all the input wavelength channels (IWCs). This sharing scheme represents a sort of reference, as it allows one to obtain the best savings in terms of WCs, achieving the same loss probability as other bufferless schemes. The wavelength converter sharing scheme has a relevant impact on switch architecture and WC characteristics.

The QoS models mentioned above can be applied to this kind of sharing scheme. In particular a differentiation scheme based on the allocation of the output wavelength channels (OWCs) can be extended to the allocation of the shared WCs. This means that when the OWCs and WCs are assigned to the incoming packets, the QoS mechanism can be applied to arbitrate among classes of service.

A switch architectures that employs fixed-input, tunable-output wavelength converters (FI- TOWCs) is supposed to be easier and less costly to realize, and their employment naturally leads to a new sharing scheme named "shared per wavelength" (SPW). Such switch architectures can be designed in a scalable and feasible way and can be implemented by using multistage organization of modular and scalable switching matrices.

The application of the QoS differentiation scheme to SPW switches in a slotted context with multiple classes of service has been evaluated. Starting from the switch architecture for a slotted best-effort undifferentiated context, a migration to class-based context was presented with the aim to provide a QoS mechanism over a simple and cost-effective architecture. Such a switch, equipped with this QoS differentiation mechanism, can represent a network element to support the functionalities and needs required by applications in optical networks for the future Internet. A new mathematical model for the evaluation of the packet loss performance for the different classes of service and an extended version of the control algorithm that manages packet forwarding according to the classes of service is presented have been developed. Analytical results have been validated against simulation, and the developed numerical analysis showed the effectiveness of the proposed QoS mechanism to provide basic service class isolation.

Overall, this study showed how a simple QoS scheme can be effectively applied to an OPS to make this network element suitable to face basic service differentiation requirements. Within this approach the only aspect of service differentiation that is taken into account is packet loss, because the switch architecture is bufferless. The application of the model allows the maximum average load of each class to be determined to ensure the required maximum loss rate.

3.9 Adaptive Admission Control of LSPs in GMPLS Networks

This JA carried out by UPV and UC3M deals has focused on the design of a novel adaptive admission control (AC) scheme for GMPLS networks that handles at the ingress node the set up of all-optical packet-based *label switched paths* (LSP) between the edges of the network—a.k.a. lightpath—through one or several *label switching routers* (LSRs) with lambda-switching capable (LSC) interfaces. This AC scheme tries to maximize the carried traffic while meeting a specific QoS objective for high priority LSPs.

The resources of the system may be identified with the capacity (bandwidth) available in terms of the number of lightpaths that can be accommodated there, because each LSP is created by reserving a dedicated wavelength channel on each and every link along the path for as long as the LSP lasts (the lifetime of the session)—for convenience it may assumed that wavelength channels were previously established between the LSRs and therefore are already available for use, but this might not be true for systems where the overall capacity fluctuates with time. We assume that: i) the LSPs belong to two different classes: *low-priority* (LP-) and *high-priority* (HP-) LSPs; ii) HP-LSPs enjoy a higher precedence over LP-LSPs, hence if a HP-LSP needs to be established in a lightpath without enough resources, some LP-LSPs from the lightpath may be terminated to attend the demands of HP-LSPs.

The AC scheme under development is an adaptive extension to multiple LSRs of a well-known trunk reservation policy called *fractional guard channel* (FGC). The scheme aims at enforcing a strict upper bound to the QoS objective, which is defined in terms of the termination probability (i.e. the probability that an already established LP-LSP experiences a termination when a HP-LSP set up request arrives to the system). The new scheme is intended to be adaptive in the sense that if the offered load (HP-LSP plus LP-LSP set up requests) or the number of resource units changes, or both simultaneously, the AC system will act in response trying to meet the QoS objective as long as possible. Therefore, when completed, the proposed scheme may be deployed in both systems with fixed or variable capacity.

The network consists of R LSRs connected by means of I links (fiber connections). The capacity Ci of the i^{th} link is expressed in units of resource—where the meaning of such unit depends on the specific definition of bandwidth, and could be expressed, for example, in terms of total bit rate.

We will define two types of arrival classes, identified with incoming requests to set up HP-LSPs and LP-LSPs. Note that for the sake of convenience Table 5 summarizes the symbols deployed in this subsection.

Notation	Meaning
I	Link index
I	Total number of links in the network
C_i	Capacity of link i
R	Ingress router index
S	Egress router index
R	Total number of routers in the network
$r \rightarrow s$	The path between router r and router s
H, L	Abbreviation for high and low priority LSPs
$\lambda^{\mathrm{H}\ r \rightarrow s}$, $\lambda^{\mathrm{L}\ r \rightarrow s}$	Arrival rate of HP-LSP and LP-LSP requests to be established between router r and router s
μ^{H}, μ^{L}	Resource holding time of HP-LSPs and LP-LSPs
d^{H}, d^{L}	Resource units demanded by HP-LSP and LP-LSP requests
$P^{\mathrm{H}\ r \rightarrow s}$, $P^{\mathrm{L}\ r \rightarrow s}$	Blocking probability perceived by HP- LSP and LP-LSP requests to be established between router r and router s
$T^{\mathrm{L}\ r \rightarrow s}$	Termination probability of LP-LSPs established between router r and router s
$O^{\mathrm{L}\ r \rightarrow s}$	Objective for the termination probability of established LP-LSPs
n_i^{H}, n_i^{L}	Number of HP-LSPs and LP-LSPs established that are using resources from link i
$\boldsymbol{n}_i$.	Vector of established LSPs
$c(\boldsymbol{n}_i)$	Number of busy resource units at lighthpath i

Table 5. Notation used

Requests to set up HP-LSPs arrive to a ingress router r with destination egress router s ($r \rightarrow s$). It is assumed that for a specific structure of the network (defined by the number of nodes, number of links and their capacity, and the topology) the set of links that define the route chosen by the network between nodes r and s is always the same. HP-LSP requests require (and demand) d^{H} units of resource during session lifetime. Similarly, LP-LSPs requests need d^{L} units of resource. For variable bit rate sources, d^{H} and d^{L} allude to the effective bandwidth of the session. Note that the appropriate design of upper bounds for the effective bandwidth may accomplish the desired performance objectives at the packet level (e.g. delay and loss rate) [BS1997].

As stated previously, a HP-LSP request that requires to be established in a link with depletion of resources, triggers a procedure in the LSR to check whether the termination of a number of LP-LSPs will release enough resources to attend the demands of the HP-LSP. If so, that number of (arbitrary selected) LP-LSPs are terminated; otherwise, the HP-LSP request cannot be attended and is blocked. Also note that a LP-LSPs request that needs to be established in a link without enough resources will be blocked. We will focus on the performance parameters as measured at router r with respect to a destination router s; thus we denote by $P^{\mathrm{H}\ r \rightarrow s}$ the blocking probability perceived by HP-LSPs requests, by $P^{\mathrm{L}\ r \rightarrow s}$ the blocking probability perceived by LP-LSPs requests, and by $T^{\mathrm{L}\ r \rightarrow s}$ the termination probability of an already established LP-LSP. The QoS objective is expressed as a global upper bound $O^{\mathrm{L}\ r \rightarrow s}$ for the termination probability of established LP-LSPs.

Admission control policy

Number-based AC is a common technique in systems whose capacity is limited by blocking. The definition of the FGC policy for link i is as follows. Let the vector of ongoing sessions at link i be $\boldsymbol{n}_i := (n^{\mathrm{H}}_i, n^{\mathrm{L}}_i)$ where n^{H}_i, n^{L}_i is the number of currently established HP-LSPs and LP-LSPs that are using resources from link i, respectively.

We denote by $c(\boldsymbol{n}_i) = n^{\mathrm{H}}_i\, d^{\mathrm{H}} + n^{\mathrm{L}}_i\, d^{\mathrm{L}}$ the number of busy resource units in state $\boldsymbol{n}_i$ at i. One threshold parameter t^{L}_i is associated with LP-LSPs requests at link i, $t^{\mathrm{L}} \in \mathbf{R}$.

When the set up of a LP-LSP needs some resources of a given link i in state $\boldsymbol{n}_i$, the request is blocked if there are not enough resources at the link, i.e. $c(\boldsymbol{n}_i) + d^{\mathrm{L}} > C_i$; otherwise, the policy will make the suitable admission decision according to the following cases (where $\lfloor x \rfloor$ denotes the *floor function*, i.e. the largest integer not greater than x):

$$c(\boldsymbol{n}_i) + d^L = \begin{cases} \leq \lfloor t_i^L \rfloor & \text{accepts the request} \\ = \lfloor t_i^L \rfloor + 1 & \text{accepts with probability } t_i^L \quad \lfloor t_i^L \rfloor \\ > \lfloor t_i^L \rfloor + 1 & \text{blocks the request.} \end{cases}$$

This policy is inspired by the protection strategy of static trunk reservation policies—where a certain number of *guard channels* (equivalent to the threshold parameter defined above) is allocated in advance to meet the QoS objectives of all the classes of requests while maximizing the total offered traffic in a system modelled with stationary parameters. In the present case, the threshold parameter t^{L}_i gives indication of the amount of resources that LP-LSPs have access to for a given link *i*. As a result, note that increasing (decreasing) t^{L}_{i} augments (reduces) the termination probability T^{L}_{i} experienced by LP-LSP requests that arrive to router *r* and demand resources from link *i*—the reason is that providing LP-LSPs more access to resources in turn increases the probability that established LP-LSPs could be terminated to make room for incoming HP-LSPs requests. The purpose of the proposed adaptive scheme is to take advantage of such behaviour, dynamically controlling the threshold parameters so as to meet the objective for the termination probability of LP-LSPs with substantial accuracy.

Adaptation strategy

In order to extend the static FGC policy from a stationary to a nonstationary scenario we propose a novel adaptation strategy to dynamically adjust the FGC threshold according to the termination probability perceived by LP-LSPs requests. For clarity purposes, the operation of the adaptation strategy is described assuming that although the arrival processes are nonstationary the rate of change in the parameters of the system (e.g. arrival rates) is slow enough to allow the system to reach (momentarily) a provisional steady state.

To focus on the basic operation of the adaptation strategy, a network with a single one-way only link *i* between two nodes *r* and *s* is supposed. We also assume, without significant loss of detail, that the QoS objective of LP-LSPs (the upper bound for the termination probability) can be expressed as the irreducible fraction $O^{L} = b^{L}/a^{L}$ where $b^{L}, a^{L} \in \mathbf{N}$. When the termination probability experienced is equal to the QoS objective $T^{L\, r\rightarrow s} = O^{L}$, it is expected that LP-LSPs will experience, in average, b^{L} terminations out of a^{L} accepted LP-LSP requests. For example, a QoS objective of $O^{L} = 2\%$ implies that $b^{L} = 1$ and $a^{L} = 50$.

From the previous reasoning it seems logical to think that two conditions should be satisfied simultaneously: i) an adaptation strategy should increase (decrease) the threshold parameter t^{L}_{i} to augment (reduce) the termination probability; ii) an adaptation strategy should maintain the threshold parameter if the termination probability matches the QoS objective

Two possible adjustment methods are studied:

Adjustment method 1

Whenever one of the following cases is verified, an adjustment of the AC policy threshold is done:

- If a LP-LSP request is accepted, then update threshold $t^{L}_{i} := t^{L}_{i} + \Delta^{+}$
- If a established LP-LSP experiences a termination, then update threshold $t^{L}_{i} := t^{L}_{i} - \Delta^{-}$

where $\Delta^{+} = kb^{L}$ and $\Delta^{-} = ka^{L}$, where $k \in \mathbf{R}$ is the adjustment step for the threshold parameter.

The reason for this is that under the stationary traffic assumption, if $T^{L\, r\rightarrow s} = O^{L}$ then, t^{L}_{i} is increased by Δ^{+} an average a^{L} times (i.e. for each LP-LSP request accepted) and decreased by Δ^{-} an average of b^{L} times (i.e. for each LP-LSP terminated), and therefore the mean value of $T^{L\, r\rightarrow s}$ is kept stable.

Adjustment method 2

An adjustment of the AC policy threshold is performed every time one of the conditions below is true:

- if a established LP-LSP ends without experiencing termination, then update threshold $t^{L}_{i} := t^{L}_{i} + \Delta^{+}$
- if a established LP-LSP experiences a termination, then update threshold $t^{L}_{i} := t^{L}_{i} - \Delta^{-}$

where $\Delta^{+} = kb^{L}$ and $\Delta^{-} = k\,(a^{L} - b^{L})$ where $k \in \mathbf{R}$. The reasons are similar to those of Adaptation Strategy 1.

Notice that if $d^{H} > d^{L}$ when the termination of ongoing LP-LSPs is needed, then several LP-LSPs must be terminated simultaneously, and $t^{L}_{i} := (t^{L}_{i} - x\,\Delta^{-})$ where $x = \lceil d^{H} / d^{L} \rceil$ and $\lceil x \rceil$ denotes the *ceiling function* (i.e. the smallest integer not less than *x*). Besides, note that in a nonstationary scenario this adaptation strategy will adjust the threshold constantly in order to meet the QoS objective for the given traffic conditions. Note also that during the description for the operation of this simple strategy no assumptions have been made concerning the distribution for the arrival processes or the distribution of the duration for HP-LSPs or LP-LSPs.

General adaptive scheme

To deploy the adaptive AC scheme in the ingress nodes of a network of arbitrary topology, the basic adaptation strategy developed must be extended to a scenario with multiple nodes and links. A given HP-LSP comprises the path $H = \{h_1, h_2, ..., h_j, ..., h_u\}$, containing *u* different links h_j, each one in state $\boldsymbol{n}_{h_j}$. Similarly, a certain LP-LSP is defined by the set of *v* different links $L = \{l_1, l_2, ..., l_k, ..., l_v\}$, each one in state $\boldsymbol{n}_{l_k}$. Since link *i* is an arbitrary link, for convenience, when *i* is part of a particular *H* or *L* (i.e. $i \in H$ and $i \in L$), link *i* refers to either a specific link h_j or l_k, without losing generality.

AC policy extension criteria

Since a LP-LSP request will demand resources at the subset of links that trace the route connecting the ingress node *r* and the egress node *s*, it is reasonable to think that the value of several (or all) of those thresholds should be involved in a given AC decision; consequently, in the full adaptive scheme one threshold t^{L}_i of the FGC AC policy is associated with each link *i*. It is assumed that information about the value of all the thresholds is readily available to assist the AC system implemented at each ingress node. In fact, we may define a number of different criteria to exploit the information about a given set of thresholds to produce one AC decision, effectively extending the AC policy explained. In general, the LP-LSP request is blocked if at least one link $l_k \in L$ has not enough resources to accommodate the LP-LSP; otherwise, the policy will make the suitable admission decision depending on the chosen criterion. In this paper the following criteria are considered:

Criterion 1

$$c(\boldsymbol{n}_{lk}) + d^{\mathrm{L}} \begin{cases} \le \lfloor t^L_{lk} \rfloor \ \forall \text{ links } l_k \in L \text{ accepts} \\ \text{otherwise, blocks.} \end{cases}$$

Criterion 2a

Given a link l_k, we denote by $\mathrm{C}^{\mathrm{A}}_{lk}$ if the condition for non-probabilistic admission $c(\boldsymbol{n}_{lk}) + d^{\mathrm{L}} \le \lfloor t^L_{lk} \rfloor$ is satisfied, by $\mathrm{C}^{\mathrm{P}}_{lk}$ if the condition for probabilistic admission (or, which amounts to the same thing probabilistic blocking) $c(\boldsymbol{n}_{lk}) + d^{\mathrm{L}} = \lfloor t^L_{lk} \rfloor + 1$ is satisfied; and by $\mathrm{C}^{\mathrm{B}}_{lk}$ if the condition for non-probabilistic blocking $c(\boldsymbol{n}_{lk}) + d^{\mathrm{L}} > \lfloor t^L_{lk} \rfloor + 1$ is satisfied. Then:

$$\text{if } \begin{cases} \mathrm{C}^{\mathrm{A}}_{lk} \forall \text{ links } l_k \in L \text{ accepts} \\ \exists \text{ link } l_k \in L : \mathrm{C}^{\mathrm{B}}_{lk} \text{ blocks} \\ \text{otherwise, accepts with probability } p_2. \end{cases}$$

where p_2 = min ($t^L_i - \lfloor t^L_i \rfloor$) for those l_k such that $\mathrm{C}^{\mathrm{P}}_{lk}$ is true.

Criterion 2b

Similar to Criterion 2a, but p_2 = mean ($t^L_i - \lfloor t^L_i \rfloor$) (i.e. the arithmetic mean) for those l_k such that $\mathrm{C}^{\mathrm{P}}_{lk}$ is true.

Criterion 3

For all links $l_k \in \mathrm{L}$:

$$\sum_{k=1}^{v} (c(\boldsymbol{n}_{lk}) + d^L) \begin{cases} \le \left\lfloor \sum_{k=1}^{v} (t^{\mathrm{L}}_{lk}) \right\rfloor \text{accepts} \\ = \left\lfloor \sum_{k=1}^{v} (t^{\mathrm{L}}_{lk}) \right\rfloor + 1 \text{ accepts with probability } Q \\ > \left\lfloor \sum_{k=1}^{v} (t^{\mathrm{L}}_{lk}) \right\rfloor + 1 \text{ blocks} \end{cases}$$

Where $Q = \sum_{k=1}^{v} (t^{\mathrm{L}}_{lk}) - \left\lfloor \sum_{k=1}^{v} (t^{\mathrm{L}}_{lk}) \right\rfloor$.

Adaptation strategy extension

In a simplified manner, the general adaptive scheme can be perceived as composed of one single adaptation strategy per link, being the adaptation strategy responsible for updating the associated FGC policy threshold. In an arbitrary network, several link may be involved in a given LP-LSP, and logically, the adaptation strategies associated with the links where a new LP-LSP is established or at least one LP-LSP is terminated must work together to bring their thresholds up to date simultaneously.

Thus, the straightforward extension of the adaptation strategy explained is:

- if a LP-LSP request is accepted, then update threshold $t^{\mathrm{L}}_i := t^{\mathrm{L}}_i + \Delta^+ \ \forall$ links $l_k \in L$
- if a established LP-LSP experiences a termination, then update threshold $t^{\mathrm{L}}_i := t^{\mathrm{L}}_i - \Delta^- \ \forall$ links $l_k \in L$

Performance evaluation

The performance evaluation of the adaptive scheme is compiled in this section. The NSFNET topology shown in Figure 30 (with labelled routers and links) is assumed. All routers generate homogeneous traffic, which consists of requests to establish a shortest-path HP/LP-LSP from the source router to a random router.

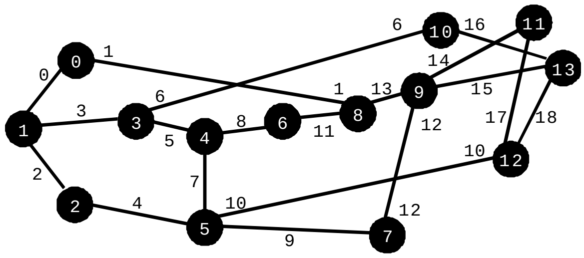


Figure 30. Network topology

Puzzlingly, selected simulation results for stationary traffic scenarios show that within reasonable offered load ranges, using any adjustment method or AC policy extension, the balance conditions enforced by the adaptive scheme result in a complete blocking of LP-LSPs instead of naturally arising a trade-off value that would produce a LP-LSP termination probability close to the QoS objective. For example, using adjustment method 1 with AC policy extension 3, when $\lambda^{H\ r\rightarrow s} = 30.0$, $\lambda^{L\ r\rightarrow s} = 10.0$, $\mu^{H} = \mu^{L} = 1.0$, and a forced termination objective of 10%, the mean number of simultaneously established HP-LSPs is 383.558, while for LP-LSPs this value is a mere 0.0136 (i.e. almost all requests are blocked).

These paradoxical results prompted further research on the influence of the network topology on the AC decisions, and specifically, how to naturally include such information in the adjustment methods and policy extensions defined. In this sense, Table 6 compiles the minimum length paths between any source router (green column) and any destination router (red row). As shown, for some source-destination connections a single path is available, while some connections may be established by means of multiple alternative shortest-paths. For those source-destinations having only a single path the situation worsens when the links required are already highly utilized (e.g. 0-13, 1-9, 6-2, which include the most loaded links: L1, L13, L10, L7, L8). Most certainly, the number of forced termination events triggered by such routes has a non-negligible influence in the global behaviour of the adaptive AC scheme that should be taken into account. In this regard, a way to find out the available resources for LP-LSPs is by studying the blocking probability that HP-LSPs requests are experiencing; thus, Figure 31 and Figure 32show the average (Figure 31) and detailed (Figure 32) blocking probability of HP-LSPs with respect to the offered load per source router; while Figure 31gives an idea of the quality of the summarized information that the adaptive scheme is using to justify its modifications of the admission conditions, the actual fact is that there is significant variance in the blocking probability experienced by HP-LPSs (Figure 32), where 4-11, 4-12, 6-12 as examples of routes crossing highly loaded link and 11-12 as an example of a route crossing practically a dedicated link. Therefore further, in-depth understanding of the interaction between the topology and the dynamic of traffic is a prerequisite to design an effective adaptive AC scheme using global information to perform local decisions.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	-	L0	L0 L2	L0 L3	L0 L3 L5 L1 L11 L8	L0 L2 L4	L1 L11	L1 L13 L12	L1	L1 L13	L0 L3 L6	L1 L13 L14	L1 L13 L14 L17 L1 L13 L15 L18 L0 L2 L4 L10	L1 L13 L15
1	L0	-	L2	L3	L3 L5	L2 L4	L0 L1 L11 L3 L5 L8	L2 L4 L9	L0 L1	L0 L1 L13	L3 L6	L2 L4 L10 L17 L0 L1 L13 L14	L2 L4 L10	L3 L6 L16
2	L2 L0	L2	-	L2 L3	L4 L7	L4	L4 L7 L8	L4 L9	L2 L0 L1	L4 L9 L12	L2 L3 L6	L4 L10 L17	L4 L10	L4 L10 L18
3	L3 L0	L3	L3 L2	-	L5	L5 L7	L5 L8	L5 L7 L9	L3 L0 L1 L5 L8 L11	L6 L16 L15	L6	L5 L7 L10 L17 L6 L16 L15 L14 L6 L16 L18 L17	L5 L7 L10 L6 L16 L18	L6 L16
4	L5 L3 L0 L8 L11 L1	L5 L3	L7 L4	L5	-	L7	L8	L7 L9	L8 L11	L7 L9 L12 L8 L11 L13	L5 L6	L7 L10 L17	L7 L10	L5 L6 L16 L7 L10 L18
5	L4 L2 L0	L4 L2	L4	L7 L5	L7	-	L7 L8	L9	L7 L8 L11 L9 L12 L13	L9 L12	L7 L5 L6 L10 L18 L16	L10 L17	L10	L10 L18
6	L11 L1	L11 L1 L0 L8 L5 L3	L8 L7 L4	L8 L5	L8	L8 L7	-	L8 L7 L9 L11 L13 L12	L11	L11 L13	L8 L5 L6	L11 L13 L14	L8 L7 L10	L11 L13 L15
7	L12 L13 L1	L9 L4 L2	L9 L4	L9 L7 L5	L9 L7	L9	L9 L7 L8 L12 L13 L11	-	L12 L13	L12	L12 L15 L16	L12 L14	L9 L10	L12 L15
8	L1	L1 L0	L1 L0 L2	L1 L0 L3 L11 L8 L5	L11 L8	L11 L8 L7 L13 L12 L9	L11	L13 L12	-	L13	L13 L15 L16	L13 L14	L13 L14 L17 L13 L15 L18	L13 L15
9	L13 L1	L13 L1 L0	L12 L9 L4	L15 L16 L6	L12 L9 L7 L13 L11 L8	L12 L9	L13 L11	L12	L13	-	L15 L16	L14	L14 L17 L15 L18	L15
10	L6 L3 L0	L6 L3	L2 L3 L6	L6	L6 L5	L6 L5 L7 L16 L18 L10	L6 L5 L8	L16 L15 L12	L16 L15 L13	L16 L15	-	L16 L15 L14 L16 L18 L17	L16 L18	L16
11	L14 L13 L1	L17 L10 L4 L2 L14 L13 L1 L0	L17 L10 L4	L17 L10 L7 L5 L14 L15 L16 L6 L17 L18 L16 L6	L17 L10 L7	L17 L10	L14 L13 L11	L14 L12	L14 L13	L14	L14 L15 L16 L17 L18 L16	-	L17	L14 L15
12	L17 L14 L13 L1 L18 L15 L13 L1 L10 L4 L2 L0	L10 L4 L2	L10 L4	L10 L7 L5 L18 L16 L6	L10 L7	L10	L10 L7 L8	L10 L9	L17 L14 L13 L18 L15 L13	L17 L14 L18 L15	L18 L16	L17	-	L18
13	L15 L13 L1	L16 L6 L3	L18 L10 L4	L16 L6	L16 L6 L5 L18 L10 L7	L18 L10	L15 L13 L11	L15 L12	L15 L13	L15	L16	L15 L14	L18	-

Table 6. Shortest-path length routes for NSFNET

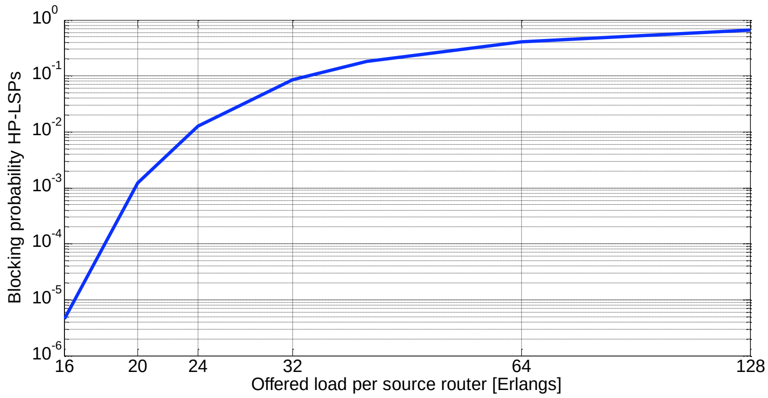


Figure 31. Average blocking probability of HP-LSPs with respect to the offered load per source router

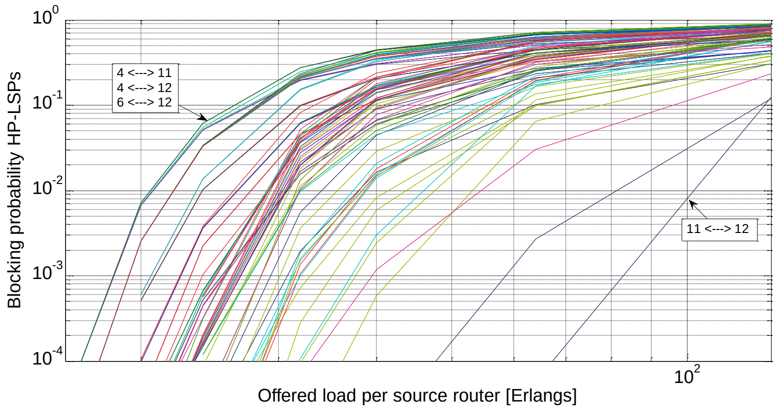


Figure 32. Detailed blocking probability of HP-LSPs per source-destination pair with respect to the offered load per source router

3.10 Server file-exchange in OBS networks

3.10.1 General objectives

UESSEX has a promising OBS test-bed, which has shown experimental results using a multi-granular node structure. The purpose of the joint activity is twofold: firstly, evaluate the performance to transmit traffic using the burstifier implemented in UESSEX, and secondly, improve the connection to the data plane to increase the throughput.

The goal is to program a FPGA card to improve the information exchange between servers using OBS test-bed. The main benefit of the research stay at UESSEX is to gain knowledge and to advance technology regarding optical burst switched architectures via the experimental validation of the proposed solutions.

3.10.2 Motivation

Network operators want to deliver multiple services to the end customers. This leads in the efficient transmission of data using network technologies. OBS is a promising technology for metro networks, where the operator can locate their servers to provide services such as video, backup or PC virtualization. These services are competing for the bandwidth in the network when they are transmitted at the same time.

This work aims to provide an edge node architecture that assures bandwidth for each service in OBS networks. Consequently, an access node is design to operate with multiple QoS applications.

3.10.3 Description of work

The collaboration is based on two steps:

1. Develop a basic Ethernet to SFP interface in a Virtex 5 architecture.
2. Create a module that reads VLAN tags of the incoming traffic and classifies it into CoS for OBS networks.

The current state of the JA is that the first step is completed and the second one is in a simulation phase. Following it is shown the architectural design to show the solution developed.

A3.10.3.1 Architectural design

We have used a Virtex 5 – SX95T2C for the design. The transmitter FPGA modules are the ones shown in the figure.

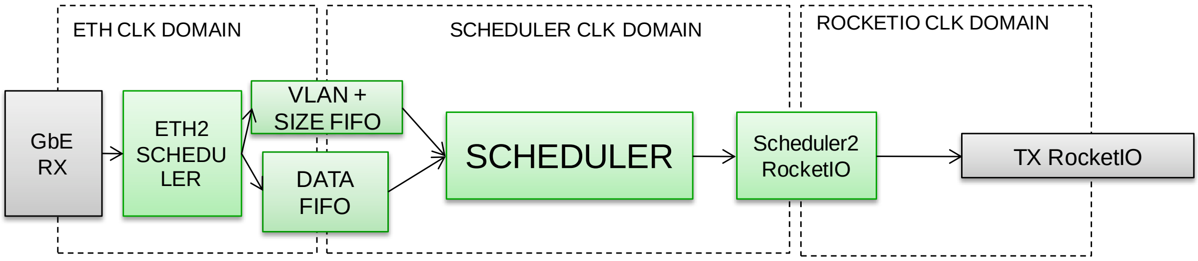


Figure 33. Transmitter FPGA modules

The modules description is listed following:

- **GbE module:** Virtex5 embedded Tri-mode Ethernet MAC Wrapper generated using the Coregen.
- **Ethernet2RocketIO:** this modules is composed by three submodules
  - **Ethernet2Scheduler:** this module reads Ethernet frames and extracts the size and VLAN information.
  - **Scheduler:** this module reads the VLAN of the incoming Ethernet packets and maps the traffic to the QoS queue in this module. Moreover, it reads the packet size which is used in the burst generation. Once there is a burst in one queue, scheduler asserts the burst information for the scheduler2rocketIO module.
  - **Scheduler2RocketIO:** this module signals the burst information so the receiver can know the burst structure thus is it delimits the burst and packets. A detailed description of the burst is done in the next section.
- **RocketIO:** this module is created using the coregen. It has been configured to operate in burst mode.

The burst receiver is composed by the GbE and SFP modules that are interconnected by a Burst2Ethernet module. This module is in charge of decodifying the burst and sending the Ethernet packets to the GbE interface.

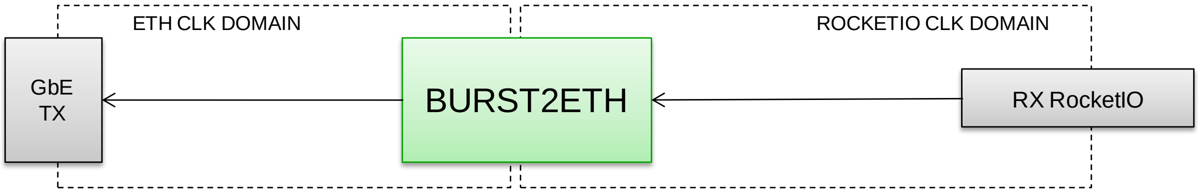


Figure 34. Receiver FPGA modules

A3.10.3.2 Burst format

RocketIO uses K-Characters to carry out signalling process. This K-Characters can be use to send inband signalling. Each Ethernet frame is stored in a FIFO and a Flag 1 (K-Character) is inserted between each frame. This flag allows in the burst receiver to process the burst. To detect the burst end a Flag 2 is included. The burst structure is defined in the next figure.

	Flag 1	Packet ETH1	Flag 1	Packet ETH2	Flag 1	Packet ETH3	Flag 2	

Figure 35. Burst format

A3.10.3.3 Burstifier behaviour

The developed burstifier can modify the burst length and timer to change the QoS parameters for the end users based on VLANs. At this moment, the burstifier sends traffic with a single VLAN. To show the proper behaviour of the burstifier we connected two boards both sending and receiving bursts as depicted in the next figure.

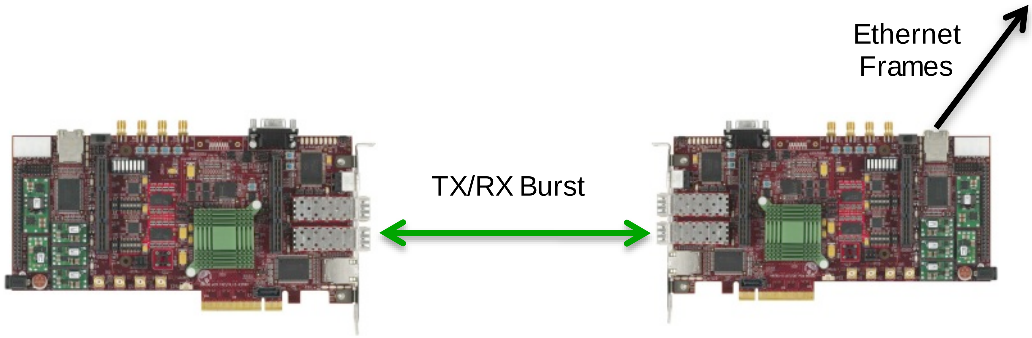


Figure 36. Burstifier behavioural experiment

Using Wireshark the traffic is captured in a remote PC to check the burst size and the delay between bursts. Thanks to this experiment we have validated the proper burst generation when varying timer and burst size. The next figure shows the number of packets per second received when the maximum burst size is 50 packets of 128 bytes. For this example we have used a fixed packet size of 128 bytes.

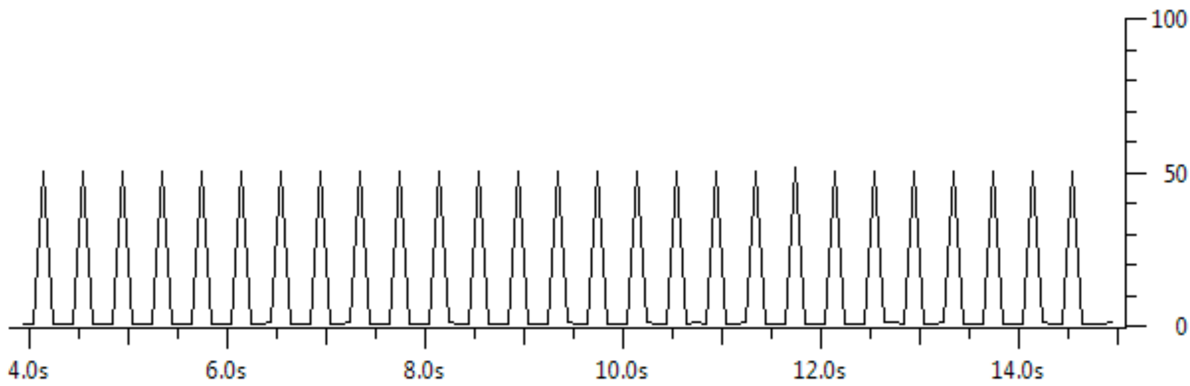


Figure 37. Packets per second when transmitting bursts with size threshold of 50 packets.

3.10.4 Future work

This joint activity started on February 2010, so we have not finished the collaboration between UAM and UESSEX. The next steps will be:

- Perform stress tests to achieve the maximum link capacity. This experiment will be limited by the GbE connections.
- Include the support to multiple VLANs.
- Carry out a validation design at UESSEX test-bed with OBS core nodes.

We expect to submit an article with the results achieved with this joint activity.

3.11 Sharing of resources in GMPLS-controlled WSONs

This Joint Activity is focused on GMPLS-based Shared Path Protection schemes for Wavelength-Routed Networks (WRN), taking into account the two major challenges of wavelength-routed networks, namely, the wavelength continuity constraint and the degradation of the optical signal quality. The degradation of the optical signal is due to the accumulation of physical impairments while the signal travels from the source towards the destination. Such impairments include fiber attenuation, losses, cross-talk, amplified spontaneous emission (ASE) noise, chromatic dispersion (CD), polarization mode dispersion (PMD) and non-linear effects. The combined effects of these impairments may render the quality of the optical signal unacceptable at the receiver, i.e., below the required level of Quality of Transmission (QoT). In order to ensure the QoT at the destination, OEO regenerators are required at intermediate nodes to re-amplify, re-shape and re-time the optical signal (i.e., 3R regeneration). On the other hand, the wavelength continuity constraint (WCC) imposes the allocation of the same wavelength on each link along the lightpath. In order to relax this constraint, wavelength converters (WC) are required at intermediate nodes. The issue is that typically a limited number of 3R regenerators and WC are installed at each or few selected nodes, due to both their high cost and power consumption.

The Shared Path Protection (SPP) scheme is widely accepted as the most capacity-efficient recovery scheme achieving an acceptable recovery time. Such benefits are accomplished through the so-called backup sharing, i.e., the sharing of resources among the existing protection (or backup) lightpaths (Label Switched Path - LSP in GMPLS context). Specifically, resources along backup LSPs are pre-reserved, but not cross-connected. Therefore, to ensure 100% survivability of the LSPs affected by a single-link failure, shared-reserved resources can be reserved by one (or more) backup LSPs provided that the corresponding working LSPs do not share any link (i.e., no sharing violation). Similarly to the wavelength resources, this joint activity extends the concept of sharing the protection resources to 3R regenerators and WCs. In this way, regenerators and WC are handled as resources that can be shared among backup paths whose working path are link-disjoint.

3.11.1 Objectives

The objective of this joint activity is to investigate the sharing of wavelengths, regenerators and wavelength converters for ensuring:

- 100% survivability against single-link failures with SPP, in GMPLS WSON networks with a limited number of WCs to overcome the constraints derived from the wavelength continuity requirements of the lightpaths.
- Both QoT and 100% survivability against single-link failures with SPP, in GMPLS WSON networks with a limited number of 3R regenerators. 3R regenerators are used for regenerating the optical signal and/or converting the wavelength channel.
- Joint optimization of the designation of the QoT points (i.e., the nodes where optical signal regeneration is required) and the WC points (i.e., the nodes in which wavelength conversion is needed) in GMPLS WSON networks (Both for provisioning and SPP) with a limited number of 3R regenerators. 3R regenerators are used for regenerating the optical signal and/or converting the wavelength channel.

In GMPLS controlled optical networks, the label (i.e wavelength) assignment is constrained by the nodes wavelength conversion capabilities, ranging from link-local assignment (opaque networks) to end-to-end assignment (transparent networks). In general, the allocation takes place in transparent segments and, in this sense, the available wavelengths are collected in the RSVP-TE Label Set object, so the destination node and the upstream intermediate nodes with conversion capabilities can perform their selection. However, it is not optimal in transparent WSON with limited WC capabilities. To improve this approach, in [ABR2006], the authors propose a mechanism for ensuring the WCC between consecutive WCs, while minimizing the use of scarce WCs (i.e., the nodes where wavelength conversion is required or WC points). The mechanism is based on a new RSVP-TE object, called Suggested Vector (SV). In [CSA2007], the authors propose a new extension to RSVP-TE named regenerator availability object (RAO) to gather the 3R regenerator availability: during the signaling mechanism, each node traversed by the RSVP-TE Path message appends the number of its available regenerators to the RAO. Finally, in [MCM2008], the authors extend the GMPLS Label Set to the so-called Shared Label Set, adding a counter that collects information about the number of hops along the route, from the source to the destination node, where a wavelength in the Label Set is found in a shared-reserved state. Optionally this extension also collects, for each wavelength, information about its status and the number of protected connections, links, and protected spatial working paths. The Shared Label Set without collecting optional information is referred to as Shared Wavelength Vector (S-WV).

This joint activity addresses the procedures for properly managing the sharing of wavelengths, regenerators and wavelength converters in the GMPLS control plane. In particular, the GMPLS extensions proposed in [ABR2006], [CSA2007], and in [MCM2008] are jointly exploited, and a novel vector carrying information about the sharable WC/3R is proposed:

- Shared Regenerator/WC Vector (S-RV) includes an element for each wavelength contained in the Label Set. Each element indicates the number of sharable regenerators/WCs that are required for establishing the LSP on the corresponding wavelengths. This is a novel vector, proposed in [MRM2010] for sharing of WCs and in [MGC2010] for sharing of 3Rs.

Moreover, the following standard objects are required in the Path message for the implementation of the proposed SPP: the Label Set, the Explicit Route Object (ERO) and the Primary Path Route Object (PPRO). Each node stores a copy of each received Path message and updates it as follows, before forwarding it. If neither idle nor sharable regenerators are locally available or regenerators are not usable for wavelength conversion purpose, the outgoing Label Set is computed by intersecting the incoming Label Set with the set of wavelengths that are idle or sharable in the outgoing link. Otherwise, if an idle or a sharable regenerator is locally available and regenerators are usable for wavelength conversion purpose, the outgoing Label Set includes all the wavelengths that are idle or sharable in the outgoing link.

For each wavelength included in the outgoing Label Set, the corresponding weight in the S-WV and S-RV objects is updated as follows:

- Shared Wavelength Vector (S-WV): if the wavelength is not contained in the received Label Set, the corresponding S-WV entry is set to 0 or 1, if the wavelength is idle or sharable in the outgoing link, respectively. If the wavelength is contained in the received Label Set, the corresponding S-WV entry is incremented by 0 (1) if the wavelength is idle (sharable) in the outgoing link, respectively.
- Shared Regenerator Vector (S-RV): if a wavelength conversion is locally required for a wavelength the corresponding S-RV entry is the minimum weight in the received S-RV incremented by 1 if there is a local sharable regenerator. If wavelength conversion is not required, the corresponding S-RV entry is left unchanged.

The destination node receiving a Path message performs the wavelength selection according to one of the following strategies:

- random (RA): random selection;
- first fit (FF): selects the lowest-indexed wavelength;
- last fit (LF): selects the highest-indexed wavelength;
- maximum wavelength sharing (WS): selects the wavelength with the highest S-WV weight. Ties are broken by using LF strategy;
- maximum 3R regenerator sharing (RS): first, the S-RV is checked if any wavelength has a weight of 0 (i.e., no conversion is required using that wavelength). If present, LF is used as a tie breaking policy among null weight wavelengths. If absent, the wavelength with the highest S-RV weight (i.e., highest regenerator sharing).

In the backward phase, each node designated for regeneration (i.e., its node-identifier is in the RO included in the received Resv message) reserves an idle or sharable regenerator according to the following strategy: When a regenerator is required for QoT and/or for wavelength conversion purposes, it is locally selected by the node. In particular, the required regenerator is randomly selected among all sharable regenerators. In absence of sharable regenerators, a regenerator is randomly selected among all idle regenerators. The SRLGs of the working LSP are appended to the list of SRLGs protected by the regenerator in the Local Database. If neither idle nor sharable regenerator is available, then the reservation is blocked.

Then, the node checks if the Label Set of the stored Path message (i.e., the Path message of the same RSVP-TE instance) contains the wavelength selected for reservation and performs the following operations:

If the wavelength is included in the stored Label Set and is available on the incoming link, this wavelength is reserved for the protection LSP.If the wavelength is not included in the stored Label Set and both the regenerators can be used for wavelength conversion purpose and an idle or sharable regenerator is available (or has been already reserved for QoT), then the regenerator is reserved and another wavelength is selected on the incoming link for the protection LSP, according to one of the strategies described above. If the wavelength is not included in the stored Label Set and either regenerator cannot be used for wavelength conversion purpose or no idle nor sharable regenerator is available, the LSP is blocked.

If the LSP is not blocked, the SRLGs of the corresponding working LSP are appended to the list of SRLGs protected by the selected wavelength, in the Local Database.

3.11.2 Summary of achieved Results

The main outcome of this joint activity is two joint papers presented at the 11th International Conference on High Performance Switching and Routing (HPSR 2010) and IEEE Global Communications Conference (IEEE GLOBECOM 2010). A mobility action took place in October 2010 (from DTU to SSSUP) and as a result a journal paper is currently under preparation.

Next, we present the main results achieved when ensuring QoT with 3R regenerators that can also be used for wavelength conversion. The performance of the proposed strategies is evaluated by means of simulations performed with the event-driven simulator OPNET [10]. The simulation scenario is a European network topology with N = 28 nodes and L = 60 bi-directional links, each carrying W = 32 wavelength channels is considered. Each link belongs to a different SRLG. Requests for protected lightpaths are dynamically generated following a Poisson process and uniformly distributed among all source-destination pairs. The inter-arrival and holding times of the lightpath requests are exponentially distributed with an average of $1/\lambda$ and $1/\mu$ seconds, respectively, where $1/\mu$ is fixed to 30 minutes. All results are plotted against the network load defined as μ/λ. The processing time of the packets is considered negligible compared to the optical propagation and transmission time. The average inter-arrival time $1/\lambda$ is higher than the set-up time, so that the probability of resource contentions in the backward direction is negligible. Computation of the working and the protection LSPs are carried out by running the Suurballe disjoint path computation algorithm. It is assumed that optical signal must undergo 3R regenerations after 3 hops for ensuring an acceptable QoT.

Wavelength selection strategies are compared in terms of blocking probability, wavelength overbuild (WO) (i.e., the ratio between the number of wavelengths reserved for protection LSPs and the number of wavelengths reserved for working LSPs), and regenerator overbuild (RO) (i.e., the ratio between the number of regenerators reserved for protection LSPs). Two different scenarios have been considered. In the first scenario regenerators are only used for regeneration purposes, while in the second scenario regenerators are also used for performing wavelength conversion:

1. Regenerators used for QoT only: Figure 38 presents the blocking probability for the different wavelength selection strategies. Due to the considered load conditions and the relatively long paths in the network, the dominating blocking is due to the lack of regenerators rather than lack of wavelength resources. For this reason, the blocking probability is almost unaffected by the wavelength assignment scheme. Figure 39 and Figure 40 show the resource overbuild for wavelengths and regenerators, respectively. The WS strategy clearly achieves the best wavelength sharing. The strategy achieves between 37% and 21% improvement compared to the worst performing strategy (RA), and 10%-7% improvement compared to the second-best performing strategies (LF and RS). As observed with the blocking, the wavelength selection strategies have no influence on the regenerator overbuild (see Figure 40).

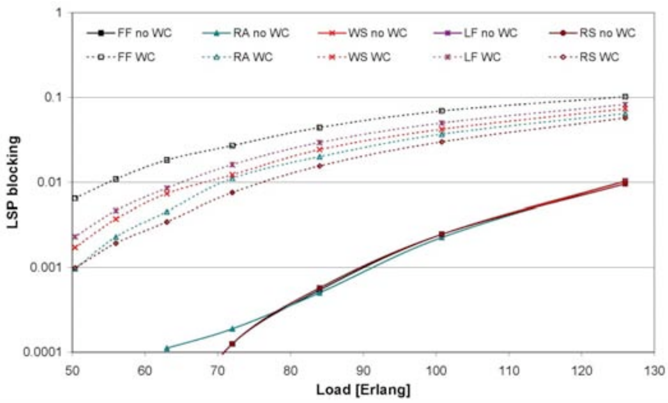


Figure 38. Blocking Probability

2. Regenerators used for QoT and wavelength conversion: Figure 38 illustrates the blocking probability when regenerators can be used for QoT as well as for wavelength conversion purposes. It can be seen that the blocking has increased compared to scenario 1 (regenerators used for QoT only). This is due to the fact that regenerators are used also for wavelength conversion and thus a lower number of regenerators is available for QoT. Since the dominating blocking is due to lack of regenerators rather than lack of wavelength resources, the overall blocking is negatively affected by the utilization of regenerators as wavelength converters. However, contrary to scenario 1, the wavelength selection strategies have a significant impact on the blocking performance. This is due to the possibility of

performing wavelength conversion. The best performing strategies are RS and then RA as they minimize the utilization of the regenerators and thus the blocking due to lack of regenerators. Figure 39 and Figure 40 show the wavelength and regenerator overbuild, respectively. When the regenerator can be exploited also as wavelength converters, the wavelength overbuild is improved by up to 17% with respect to the scenario in which regenerator usage is only for QoT (see Figure 39). Greater improvements are achieved in terms of regenerator overbuild. Both improvements indicate that the wavelength conversion can help to increase effectively and efficiently the sharing of the protection resources. Due to the wavelength conversion capabilities, the wavelength overbuild as well as the regenerator overbuild are both affected by the wavelength selection strategy. Results on resource overbuild highlight a clear trade-off between the strategies that minimize the regenerator utilization (i.e., RS and RA) and the strategies that minimize the wavelength utilization (i.e., WS, LF, and FF). The former strategies achieve an excellent regenerator overbuild at the expense of the wavelength overbuild. On the other side, the latter strategies worsen the regenerator overbuild by more than 40% but improve the wavelength overbuild. Among all the strategies, in the considered scenario, RS is the most appealing, as it achieves a minimum blocking and regenerator overbuild, while the wavelength overbuild is mildly affected.

Finally, it is worth noting that the proposed object could be relevant to GMPLS standardization.

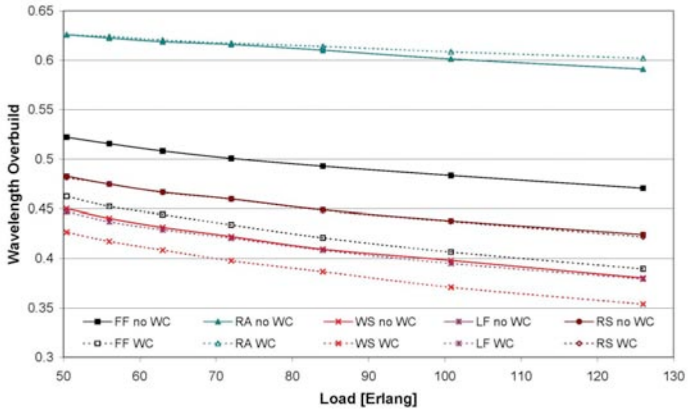


Figure 39. Blocking Wavelength Overbuild

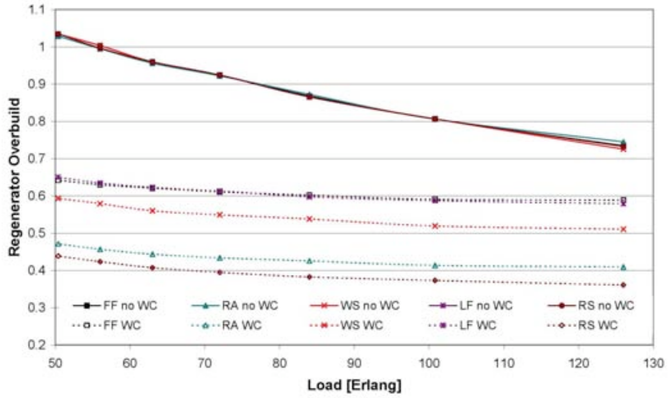


Figure 40. Regenerator Overbuild

4. List of relevant publications

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