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Abstract:

This document is the last deliverable of the WP26 "Topical Project on Alternatives for multi-layer networking with cross-layer optimization". This report gives an overview of the WP26 activities during the duration of the topical project (i.e. WP26). During this period, five joint activities were running and active and their main outcomes are reported in this deliverable. The scientific outcome of these Joint Activities has produced 19 joint publications out of which 13 were in major international and refereed conferences and 6 in international journals. There were also 3 more conference papers, which were published by individual partners. Moreover, 6 mobility activities were implemented with scientists meeting physically together and working collaboratively over the set activity targets. Finally, the Joint Activities has been supported by 6 independent meetings and numerous call conferences.

Keyword list:

Cross-layer optimization, optical network planning and design, Physical impairment aware routing and wavelengths assignment, Multi-layer algorithm using Bayesian theory, Traffic grooming, Traffic engineering in integrated control plane models

Disclaimer

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Table of Contents

1. Executive Summary

This deliverable presents the final report on the activities that have been performed within the duration of the work package “Topical Project on Alternatives for multi-layer networking with cross-layer optimization”.

In total there were 5 Joint Activities comprising 15 partners of the BONE project consortium. The scientific outcome of these Joint Activities has produced 19 joint publications out of which 13 were in major international and refereed conferences and 6 in international journals. Moreover, 6 mobility activities were implemented with scientists meeting physically together and working collaboratively over the set activity targets. Finally, the Joint Activities has been supported by 6 independent meetings and numerous call conferences.

Two out of the 5 Joint Activities had a more general scope and covered the following research areas: a) the development, study and comparison of RWA (routing and wavelength assignment) algorithms for semi-transparent networks and the associated optimized regenerator placement (RP), b) the development of algorithms for multi-layer optimization with ICBR constraints. Both of those Joint Activities had a wide number of participating institutes (6 and 9 partners respectively) and covered in detail a great mass of critical aspects producing also novel optimization algorithms in their related subjects. This is evident also by the large number of the resulted joint publications. The rest 3 of the Joint Activities covered more specialized topics related with a) the implementation of the Bayesian decision theory in multi-layer optimization, b) the study of traffic grooming in relationship with ICBR algorithms and c) the inclusion of traffic engineering in integrated and interconnected Control Plane Models in the presence of physical impairments

The aforementioned Joint Activities has created the basis for the first detailed studies and novel algorithmic developments in the field of multi-layer optimization and efficient routing and wavelength assignment algorithms. As a result these efforts has delivered a platform upon which the participants can develop further innovative algorithms according to well defined requirements and being also in many cases comparable to each other. This allows strong future collaborations among the leading research groups in these topics.

2. Introduction

This Topical Project (TP) (BONE WP26) combines the research activities from a large number of partners with the scope to study "Alternatives for multi-layer networking with cross-layer optimization". The nature of this work package requires combined and collaborative work on various research fields interoperable to each other in order to efficiently study the multi-layer networking issues and provide optimized solutions applicable across the network layers. The long term focus of the work package is to define the possible future solutions for converged IP/ Ethernet over optical layer and create a common platform for the protocol and algorithm designs that will result in optimised solutions. Future developments in this area could have a common approach and therefore studies can be performed according to well defined target. This will allow optimum converged solutions to be proposed and developed in a more commonly adopted fashion. Therefore, multi-layer as well as multi-domain issues can be handled both faster and in a more efficient way within the European networks.

2.1.1 TP Objectives

This TP targets the following focus points:

1) Multi-layer approaches (architectures, protocols and network characteristics) for future Internet Protocol (or Ethernet) convergence over optical network solutions.
2) Cross-layer optimization approaches that take into consideration the physical layer, transport/data link layer and network layer characteristics.

The specific objectives for each domain are as follows:

Objectives of multi-layer approaches:

- Identification of various solutions for converged IP over optical networks and the networking issues related to each solution.
- Identification of the networking parameters that must be taken into consideration when examining the performance of multi-layer networks.
- Examination of modelling challenges related to the multi-layer networking simulations.
- Development of performance evaluation tools for various multi-layer network solutions.

Objectives of cross-layer optimization:

- Identification of the lower layer parameters (e.g. physical impairments, resources availability etc) that can be offered and monitoring methods to collect and disseminate this information to the network.
- Identification of higher layer parameters (e.g. QoS requirements, traffic demands etc.) and ways that these can be included in the development of fast reconfiguration algorithms
- Development of cross-layer optimization schemes and routing/decision protocols.
- Performance evaluation and feasibility studies.

2.1.2 Deliverable goals

The main goal of this deliverable is to report the results and outcome of the performed activities within the framework of this TP.

3. Participants

Table 1 provides (in alphabetic order of partner's short name) a list of the participants in this work package who had provided their input and work within the joint activities of this WP.

Table 1: Participating partners in joint activities of WP26

Partner Number	Short Name
P19	AIT
P42	BILKENT
P24	BME
P08	COM
P09	CTTC
P01	IBBT
P37	IT
P29	POLIMI
P30	POLITO
P21	RACTI
P31	SSSUP
P10	TID
P02	TUW
P11	UAM
P47	UEssex
P13	UPC
P14	UPCT
P07	UST-IKR

4. Joint Activities

This section describes the joint activities that run within the work package duration. The following table shows key information about these joint activities:

No.	JA Title	Contact Person	Participants	Mobility Action	Deadline
1	Multi-layer algorithm using Bayesian decision theory	Víctor López (UAM) victor.lopez@uam.es Juan Fernandez Palacios (TID) jpfp@tid.es	UAM, TID		M24
2	RWA (routing and wavelength assignment) and regenerator placement (RP) in semi-transparent networks.	Eva Marin , Davide Careglio(UPC) {Careglio,eva}@ac.upc.edu	UPC, AIT, TUW, POLIMI, IT, UPCT	Yes	M24
3	Algorithms for multi-layer optimization with ICBR constraints.	Pablo Pavon Pablo.pavon@upct.es	UPCT, TID, AIT, RACTI, BME, UPC,CCTC,UAM, BILKENT,	Yes	M24
4	ICBR algorithm taking into account traffic grooming	Szilárd Zsigmond zsigmond@tmit.bme.hu	BME, AIT, IT	Yes	M24
5	Traffic Engineering in Integrated and Interconnected Control Plane Models in the Presence of Physical Impairments	Namik Sengezer namik@ee.bilkent.edu.tr	BILKENT, BME		M24

Table 2: Summary list of the planned joint activities

As it is mentioned in the above table, five joint activities with at least three mobility actions are planned for this work package. The duration of most of the joint activities covers the two years of the project.

4.1 Multi-layer algorithm using Bayesian decision theory

4.1.1 Motivation and objectives

Current backbone networks are based on the IP paradigm, where the IP routers are interconnected through point to point high capacity links. Most of the IP traffic in core routers is pass-through, and may not be processed at the IP layer. Consequently, network operators are migrating their backbone networks to IP over WDM architectures. Thanks to the advent of reconfigurable optical equipment, the traffic flows can be switched at the optical transport layer instead of consuming IP resources. However, in such multi-layer networks, it is necessary to efficiently combine the resources available from both layers in order to provide enhanced Quality of Service (QoS) to end-users.

This JA extends an earlier proposal of a multi-layer Bayesian decisor proposal. This algorithm finds a compromise between Quality of Service provided by both the optical and electronic resources and their relative utilization costs. During this JA, the mathematical formulation is reformulated and validated for a multi-hop scenario and for a complete network. Its behaviour is further analysed for different configurations found in realistic scenarios.

4.1.2 Main outcomes / Key results

At a given time, a multilayer router handles a number of LSPs (Figure 1). Typically, due to QoS constraints, optical switching is preferred due to the lack of queuing delay. In principle, many LSPs can be multiplexed in the electronic domain, whereas the lightpath bandwidth may be underutilized if LSPs are switched in the optical domain. Given a set of input LSPs, the question is to derive the number of LSPs that should be switched in the electronic domain and the amount of LSPs to be switched in the optical domain, on attempts to maximize utility. It is preferred to switch in the electronic domain because the availability of buffering in core nodes allows for a higher utilization, and the remaining optical bandwidth can be used for newly arriving LSPs.

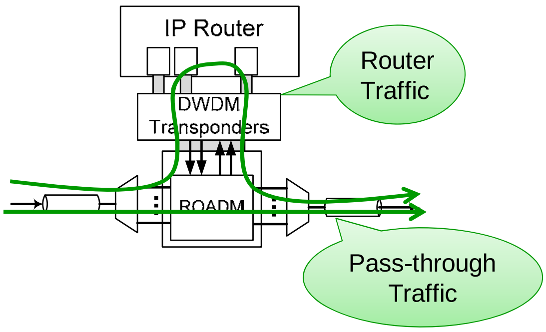


Figure 1: Multi-layer router

Figure 2 shows all kinds of connections in an IP over WDM architecture. If the LSPs are crossing IP routers, it is called a hop-by-hop connection. If there is an end-to-end lightpath, the LSPs are just using the optical resources, so their delay is close to zero. The last option is to use both, the IP and optical resources, which is a hybrid connection.

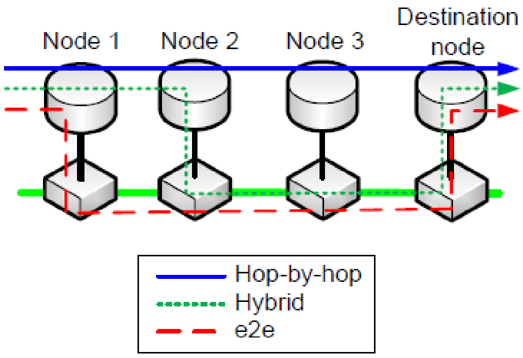


Figure 2: Possible connections in an IP over WDM architecture

We assume the situation where the network operator has a certain number of routers and cards deployed in their network. This IP equipment should be used while the network can provide the necessary QoS to the users. When the IP layer cannot absorb such demand, the incoming LSPs are sent using the optical layer. This proposal trades off two objectives, (1) provide an appropriate QoS definition for managing IP and optical switching; and (2) use electronic and optical switching efficiently. To do so, a risk function is defined as follows:

$$R(\vec{f}) = \sum_{\substack{d=1 \\ x_p^{e2e} \geq 0}}^{D} \sum_{p=1}^{P_d} K_c C_T(f_{dp}) - K_u \mathbb{E}_x \left[U(x_p^{e2e}) \right]$$

where x_p^{e2e} is the end-to-end delay of a path p. U(x) measures the QoS experienced (in terms of delay) by the switched packets. As the delay at a end-to-end lightpath is just the propagation delay, the utility is maximum for the optical connection while the IP hops reduce the utility perceived by the users. $C_T(f_{dp})$ introduces a metric for quantifying the utilization cost of optical switching with respect to electronic switching for the f_{dp} LSPs sent for the demand d using the path p. The cost function is defined:

$$C_T(f_{dp}) = C_e(f_{dp}) + R_{\text{cost}} C_o(f_{dp})$$

where $C_e(f_{dp})$ is the cost of transmitting f_{dp} LSPs due to the electronic resources in the path and $C_o(f_{dp})$ is the cost for the optical case. R_{cost} is the relative cost of using the IP or optical resources. We have considered a linear cost approach that evaluates the ratio at which the optical cost increases with respect to the electronic cost. Besides the longest the light-path the cheaper is, in order to encourage the creation of longer lightpaths.

The utility functions, U(x), measure the QoS experienced (in terms of queuing delay) by the electronically-switched packets. Three utility functions are proposed:

- **Mean utility (U_{mean}):** computes the mean delay of the LSPs in the electronic domain.
- **Hard-real time utility (U_{step}):** evaluates the probability that the delay in the router queue is lower than a given Tmax threshold.
- **Elastic utility (U_{exp}):** assesses the gradual degradation of elastic services.

The objective is to minimize the risk function and we have defined an optimization algorithm:

Algorithm 1 Optimization Problem

Indices:

- $d = 1, 2, \ldots, D$ demands
- $p = 1, 2, \ldots, P_d$ candidate paths for flows realizing demand d
- $l = 1, 2, \ldots, L$ links

Constants:

- $\delta_{ldp} = 1$ if link l belongs to path p for the demand d; 0, otherwise
- $R(\vec{f})$ risk function
- h_d volume of demand d
- c_l capacity of the link l
- N_{max} maximum number of LSPs in a wavelength

Variables:

- f_{dp} number of flows allocated to path p of demand d.

Objective:

- Find $\vec{f}^*$ such that $R(\vec{f}^*) = \min R(\vec{f})$

Constraints:

- $0 \leq f_{dp} \leq N_{max}$
- $\sum_p f_{dp} = h_d$
- $\sum_d \sum_p \delta_{ldp} f_{dp} \leq c_l$

Moreover a heuristic algorithm is defined:

Algorithm 2 Heuristic Algorithm

```
while traffic_to_allocate > 0 do
  d ← Generate_random_arrival
  for p = 1,...,P_d do
    f_dp update_load(p)
    R_p = Compute_System_Risk(f_dp)
  end for
  for p = 1,...,P_d do
    p* ← min(R⃗)
    f⃗* ← update_decision(p*)
    if ∑_d ∑_p δ_ldp f_dp ≤ c_l ∀ L then
      f⃗ ← f⃗*
      break
    else
      R_p* ← ∞
    end if
  end for
end while
```

The heuristic algorithm is assigning LSPs looking for the path which adds a minimum amount of risk, but it is not optimizing the complete risk function. The heuristic and the optimization algorithms are compared in a small scenario, achieving similar results. The heuristic algorithm is used into the NSFNET. Figure 3 shows the amount of LSPs transmitted using the IP and the optical layer, where the amount of traffic is increasing and the R_{cost} parameter varies. When the network is not congested most of the LSPs traffic are transmitted using the IP layer (Figure 3 left-size), but when the traffic is increasing the algorithm decides to transmit more LSPs using the end-2-end optical connections (Figure 3 right-size). Figure 3 illustrates that the R_{cost} parameter allows to tune the utilization of the electronic and optical resources.

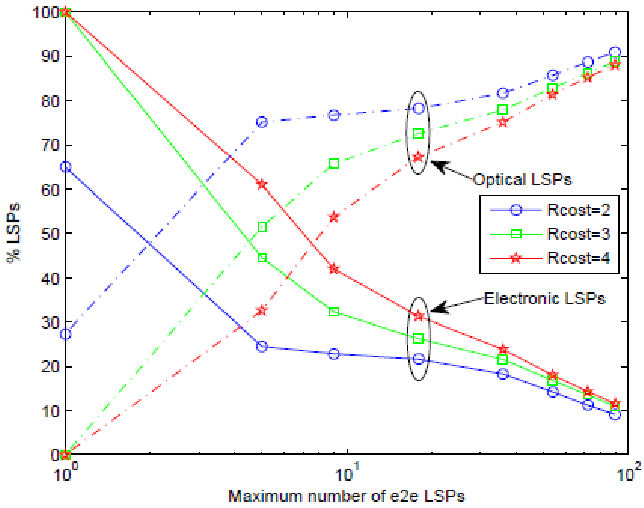


Figure 3: Percentage of LSP sent through the electronic or optical layer

T_{max} parameter defines the threshold for the utility functions elastic and hard-real time functions. When the QoS restrictions are coarser the system uses the IP layer for more connections. On the other hand, when the requirements are tighter, the flows are sent using the optical layer. Figure 4 shows this behaviour for the hard-real time function.

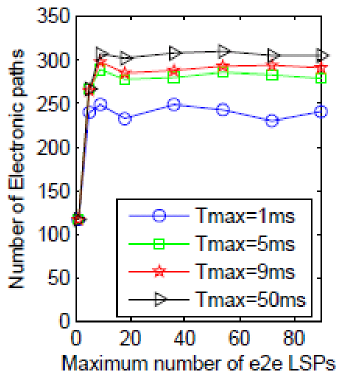


Figure 4: Number of electronic paths when T_{max} parameter varies (Hard-real time function)

To sum up the algorithm has been defined for a complete network and two algorithms are developed to solve the problem. In light of the results, the heuristic algorithm can efficiently use the resources of the IP and the optical layer.

4.1.3 Publications

Conference papers:

No.	Paper details	Participating partners
1	V. López, J.A. Hernández, J. Aracil, J.P. Fernández Palacios and O. González de Dios: Performance evaluation of a Bayesian decisor in a multi-hop IP over WDM network scenario, in Optical Networking Design and Modeling (ONDM), Feb 2009. **Abstract**: Network operators have understood the importance of migrating their backbone networks to IP over WDM architectures, whereby an underlying optical infrastructure can automatically set up and tear down direct optical connections (lightpaths), yet keeping electronic IP routers on top of it. In such multi-layer networks, it is necessary to efficiently combine the resources available in both electronic and optical layers, providing the necessary Quality of Service (QoS) to end-users at the minimum possible cost. This work defines a multi-layer Bayesian decisor in a multi-hop scenario which finds a compromise between the utility perceived by the users in terms of delay and the utilisation costs of the optical and electronic resources. The mathematical formulation of such a Bayesian decisor is formulated and its behaviour is further analysed for different configurations in realistic scenarios. Its behaviour shows that the algorithm is capable of adapting its decision according to traffic characteristics, while utilising only the necessary optical and electronic resources.	UAM, TID
2	V. López, O. González de Dios, J.A. Hernández, R. Duque, C. Garcia Argos, J. Jiménez, J.P. Fernández Palacios and J. Aracil: Performance evaluation of threshold-based multi-layer traffic engineering strategies, in Networks and Optical Communications (NOC), Jun 2009. **Abstract**: Current backbone networks are based on the IP paradigm, where the IP routers are interconnected through point to point high capacity links. Most of the IP traffic in core routers is pass-through, and may not be processed at the IP layer. Thanks to the advent of reconfigurable optical equipment, the traffic flows can be switched at the optical transport layer instead of consuming IP resources. This work proposes two “Thresholdbased” algorithms that aim to reduce the traffic at the IP layer, while efficiently using the optical resources. These algorithms firstly route the traffic using the IP layer, detect the congested links and search for candidate by-passes, which are classified in terms of length and amount of shared traffic. The “Longest” algorithm off-loads the candidate bypasses based on their length. On the other hand, the “Largest” algorithm uses the shared amount of traffic to decide which are off-loaded first. The performance of both strategies is studied in terms of network congestion.	UAM, TID
3	V. López, B. Huiszoon, O. González de Dios, J.P. Fernández Palacios and J. Aracil: Path Computation Element in Telecom Networks: Recent Developments and Standardization Activities, in Optical Networking Design and Modeling (ONDM), Feb 2010. **Abstract:** This paper provides an overview of the recent developments in research and the IETF standardization body on using a path computation element in telecom networks. The emerging impairment-aware routing and wavelength assignment is extensively treated for networks using lightpaths.	UAM, TID

Journal papers:

No.	Paper details	Participating partners
1	V. López, J.A. Hernández, J. Aracil, J.P. Fernández Palacios and O. González de Dios, "Multi-layer Traffic Engineering for IP over WDM networks based on Bayesian decision theory" submitted to a journal.	UAM, TID
2	J.E. Gabeiras, V. López, J. Aracil, J.P. Fernández Palacios, C. García Argos, Ó. González de Dios, F.J. Jiménez Chico and J.A. Hernández: Is Multi-layer Networking Feasible?, in Optical Switching and Networking, April 2009, Vol. 6, Issue 2, Pages 129-140. **Abstract**: IP traffic has been growing every year, bringing the need for deploying an IP backbone interconnected by links provided by the transport network. Thus, network operators have had traditionally divided its core network in two, the IP network and the transport network. Network planning and engineering tasks have been performed independently in both domains. Traditionally, the transport network has been quite inflexible, and changes have often required a long time to occur. However, recent developments in the control plane allow flexibility in the transport network, making it possible to set up and tear down circuits on demand. In this light, multilayer traffic engineering has been proposed to jointly manage both IP and transport layers, with the aim of optimizing the use of resources. This paper aims to describe the rationale behind multilayer traffic engineering, demonstrate its feasibility and quantify its advantages in terms of cost effectiveness. Also, this work takes a look at the different choices in performing the multilayer operation, in terms of control plane implementation and equipment integration. Finally, the paper presents a report on multilayer traffic engineer experimentation which proves its feasibility and show a preliminary techno-economic case study of the multilayer operation.	UAM, TID

4.1.4 *Meetings*

No.	Short Description (meeting/call conf.)	Participating partners
1	We have several meetings at TID or UAM premises and phone calls.	UAM, TID

4.1.5 *Joint Project proposals (Nations/ EU FP7)*

No.	Proposal title	Involved partners
1	EU FP7 – Metro ArchItectures eNabling Sub-wavelengths (MAINS)	UAM-TID

4.2 RWA (routing and wavelength assignment) and regenerator placement (RP) in semi-transparent networks.

4.2.1 Motivation and objectives

The main goal of this joint activity is to develop efficient mechanisms able to deal with physical impairments constraints in transparent and translucent optical networks. Different tasks have been identified:

(1) Collect and classify all related work proposed in the literature dealing with the problems of impairment aware routing and wavelength assignment (IA-RWA), regenerator placement (RP) and allocation (RA), and control plane (CP) extensions.

(2) Propose and compare novel offline IA-RWA algorithms for the case of static traffic demands with protection consideration.

(3) Propose and compare novel online IA-RWA algorithms for the case of dynamic traffic demands.

(4) Propose new predictive and deterministic IA-RWA algorithms taking into account the inaccuracy in the physical layer parameters.

(5) Propose and compare novel regenerator placement algorithms.

(6) Experimental evaluation of a subset of the proposed mechanisms along with validating and assessing the required translucent-based GMPLS protocol extensions.

4.2.2 Main outcomes / Key results

This section is organized in 6 subsection according to the different joint tasks carried out during this JA.

5.2.2.1 Related work on IA-RWA, RP/RA, and CP extensions

The result of this detailed literature survey is available in [1]. The key results can be summarised as follows.

The RWA problem has been extensively examined in the literature; often it is tackled by dividing it into two different sub-problems, the routing sub-problem and the wavelength assignment sub-problem. With static traffic, the entire set of connection requests is known in advance, and the static (off-line) RWA problem of setting up these connection requests is known to be a NP-hard optimization problem. In a dynamic traffic scenario the connections are requested in some random fashion, and the lightpaths have to be set up as needed.

When the PLIs are introduced in the RWA algorithms (in so called IA-RWA algorithm), three main approaches have been considered in the recent literature: a) Blindly compute the route and the wavelength in the traditional way and finally verify the selected lightpath considering the physical layer impairments; b) Considering the PLI values in the routing and/or wavelength assignment decisions without further verification step; C) Considering the PLI values in the route and/or wavelength assignment decision and finally also verify the quality of the candidate lightpath (step needed when, for example, approximated physical models are adopted or the impacts on existing connections are not considered to speed up the IA-RWA algorithm). It is clear that approaches b) and c) provide better results than a); in addition, if a good algorithm is in place, a small number of wavelength conversion (either via OEO or all-optical conversion) is required to approximate the performance of opaque network architectures.

Some works in the recent literature address the problem of *regenerator placement* (RP) and *allocation* (RA). In semi-transparent or translucent networks, some of the nodes are equipped with OEO devices with regeneration capabilities. In a design phase of the optical network, the regenerator placement consists of selecting which nodes of the network have regeneration capabilities and how many signals can be regenerated at those nodes. In contrast, in the operation phase the regenerator allocation (or regeneration usage) tries to determine how the already placed regenerators are used in a dynamic scenario. It can be observed that by using a proper regenerator placement/allocation strategy in some nodes of the network, it is possible to obtain similar performance (in terms of blocking probability) of an opaque network with much lower cost. However, this topic is not enough investigated in the literature.

Although ASON/GMPLS CP for optical networks is relatively mature and key standards are already available, it does not include any information related to physical impairments and thus is unaware of quality of optical signals. Some recent works deal with the problem of encompassing the PLI constraints into the GMPLS CP functionalities. Three different models have been proposed, namely the path computation element (PCE) model, the signalling model and the routing model. The PCE model is able to provide optimal path computation in terms of both network utilization and optical signal quality. It also does not require any modification or extension to the current signalling and routing protocols. PCE has a global view of the network, which can speed up the service provisioning. Nonetheless, it suffers from scalability problems. Routing model seems less advantageous solution since it requires the global dissemination of the PLI performance data. The signalling model seems to be the easiest and fastest way to encompass the PLI performance into the RWA problem. On the other hand, it is not able to provide optimal resource utilization and signal quality. It may require high setup delay due to the re-attempts of failed lightpath establishment processes and possible sub-optimal route decisions due to impairment-unaware route computation.

The overall conclusion is that IA-RWA algorithms play important roles in maximizing the performance of an optical network design. These algorithms, when exploited in transparent or translucent networks planning and operation tools, can provide similar utilization as an opaque architecture, but with lower cost.

5.2.2.2 Novel offline IA-RWA algorithms with protection consideration

Since physical layer impairments accumulate as light propagates through a lightpath in the transparent optical networks, it is possible to provision a lightpath, while its quality of transmission (QoT) does not meet the required threshold. Considering the physical layer impairments in the network planning phase gives rise to a set of offline IA-RWA algorithms. However, as indicated in [1] very few works target the offline case; in addition, those proposed offline IA-RWA algorithms are evaluated for different metrics and network topologies, making them difficult to compare. None of these works tackle scenarios with protected demands. A recent study shows that the CAPEX difference of shared (e.g., 1:1) and dedicated (e.g., 1+1) path protection schemes is much lower in transparent optical networks comparing with its opaque counterpart [2], making dedicated protection attractive in transparent optical networks. For this reason, in this work, we tackle the problem of offline IA-RWA where some demands can require dedicated path protection.

The contribution of this work is three-fold. First, we propose a novel IA-RWA that natively accounts for dedicated path protection; second, we enhance the RS-RWA heuristic algorithm [3] from the literature to better include QoT related impairments (RS-RWA-Q) and to consider the dedicated path protection (RS-RWA-QP). Third, we enhance an ILP-based RWA formulation [4], also from the literature, to include QoT requirements (ILP-RWA-LU) and also to incorporate protected demands (ILP-RWA-LUP). Finally, we compare their performances under similar performance evaluation framework.

The simulation results can be summarised as follows. Our enhanced RS-RWA-Q heuristic reduced the blocking rate of demands by an average of 35% for different loads compared to the original scheme (i.e. RS-RWA). The performance of enhanced ILP-RWA-LU (1 sp) formulation is also improved by 71%. The Rahyab algorithm performs better than the other two algorithms with respect to the blocking rate performance metric. For instance when the offered load to the network is 80%, the blocking rate of Rahyab algorithm is decreased by 62% and 42% compared to RS-RWA-Q and ILP-RWA-LU algorithms respectively. When the number of wavelengths is limited only to 14 channels per link and the demand set included both the protected and unprotected demands, the performance of Rahyab algorithm is better than RS-RWA-QP and ILP-RWA-LUP by 23% and 15% respectively. ILP-RWA-LUP performs better than RS-RWA-QP, mainly thanks to the diversification of wavelength assignments, however the adaptive wavelength assignment and proper ordering of the demand set in Rahyab helps it perform better compared to its ILP-based counterpart.

5.2.2.3 Novel online IA-RWA algorithms

In all-optical networks the physical layer impairments accumulate along a lightpath and also vary dynamically, and a number of IA-RWA techniques have been proposed in order to mitigate the physical layer impairments and find lightpaths that meet a required Quality of Transmission (QoT) constraint predefined by the network operator.

One of the key building blocks in IA-RWA algorithms is a QoT estimator, which is a combination of theoretical models and/or interpolations of measurements, typically performed offline (in the lab, before the networks is deployed), but also possibly online. A practical QoT estimator should be fast to ensure that lightpaths can be established in real time. In addition, models by nature cannot capture all effects actually present in physical systems, resulting in QoT estimation inaccuracies. Inaccuracies are inevitable yet undesirable.

In this task, we work on a novel IA-RWA algorithm that not only consider the impact of physical impairments on RWA decisions, but also accounts for inaccuracy of the QoT estimators. In particular we address such inaccuracies directly within the decision steps of the IA-RWA algorithm in order to mitigate them and eliminate their effects.

The basis of the novel IA-RWA algorithm is the Rahyab algorithm developed for the offline case. In addition, we consider the availability of Optical Impairment Monitoring (OIM) or Optical Performance Monitoring (OPM) equipment to alleviate the inaccuracy of QoT estimations. Monitor equipment availability is mapped to QoT accuracy and is taken into account within a multi-constraint framework as a new constraint (the other constraint being a traditional QoT-related one), at the routing step of a proposed Rahyab heuristic. Doing so ensures that routes where monitors are available are preferred over routes with less monitoring capability, consequently increasing the accuracy of the QoT estimator and reducing the aforementioned issues associated with inaccurate QoT estimators.

The performance of the novel algorithm, which we call *Online Rahyab,* is compared with algorithms selected from the recent literature, namely k-SP-Q [5] and MmQ [6]. All algorithms are evaluated through simulations in a realistic scenario. The simulation results shows that our proposed novel algorithm is able to outperform the selected algorithms in terms of blocking rate and also the amount of required resource for achieving zero percent blocking rate under similar assumptions. In addition we see that accounting for QoT estimation inaccuracy changes the performance of the proposed IA-RWA substantially. For example, we observe that the admissible load for a given blocking rate is 11% higher than the one which is allocated by an algorithm that does not consider the OIM/OPM deployment in the network. We also observe that, due to the important impact of QoT estimator inaccuracies on network dimensioning (here, in terms of blocking rate), RWA algorithms need to incorporate those inaccuracies in order to appropriately reflect the actual behavior of monitored transparent optical networks.

5.2.2.4 Novel IA-RWA algorithms considering inaccuracies in the physical layer parameters

In this task we investigated the performance of translucent optical transport networks (OTNs) under dynamic traffic and uncertainties in the physical-layer parameters. The focus is on the regular operation of a translucent OTN, i.e., after the dimensioning and regenerator placement phase. The contributions can be summarized as follows. Based on the computation of the Personick's Q factor [7], we introduce a new methodology for the assessment of the optical signal quality along a path. In particular, three different conditions have been identified that can occur during the dynamic operation of a translucent OTN:

(1) *Perfect Knowledge and Perfect Matching* (PKPM) is the ideal condition. The Q factor used during the design phase is equal to the real Q on the network, and it is also the same factor currently used by the RWA process.

(2) *Perfect Knowledge and Imperfect Matching* (PKIM) is the condition derived from an uncertainty where the current values of in the OTN might be different from those estimated during the dimensioning phase. In this case, the network could suffer from an inadequate allocation of resources, e.g., because the design phase was done based on rather optimistic conditions.

(3) *Imperfect Knowledge and Imperfect Matching* (IKIM) is the worst condition, as it is the combined effect of the previous uncertainty and the uncertainty due to the drift suffered by the physical layer parameters from their nominal values during the operation of the OTN.

Under such different conditions, the performance of a deterministic (RWARP [8]) and a predictive (PB-Q [9]) RWA technique integrating this signal quality factor in the lightpath computation process have been analysed. The results confirm the effectiveness of predictive techniques to deal with the typical drifts and uncertainties in the physical-layer parameters, in contrast to the superior efficacy of deterministic approaches in case of perfect knowledge. Conversely to most previous works, where all wavelengths are assumed to have the same characteristics, we examine the case when the network is not perfectly compensated, so the Maximum Transmission Distance (MTD) of the different wavelength channels may vary. We show that blocking might increase dramatically when the MTD of the different wavelength channels is overlooked

5.2.2.5 Regenerator placement algorithms

In this task, we focused on the regenerator placement problem. Two different works have been carried out, namely the comparison between different strategies and the proposal of two new schemes.

5.2.2.5.1 Comparison of regenerator-placement strategies (i.e. opaque, sparse translucent, clustered translucent) in WDM networks under static and dynamic traffic

As well known, *translucent* or *semi-transparent* optical networks are effective and cost-effective at the same time, as they inherit the best features of both transparent and opaque networks. According to the translucent concept (introduced by Ramamurthy et al [10][11]), the optical signal is regenerated by the means of 3R units allowing O/E/O conversion (called *regenerators* or *transponders*). Thanks to regenerators, an optical signal can be transmitted over long distances preventing its quality falling below a certain quality threshold Q_{th} due to physical impairments; Q_{th} is strictly related to an expected BER threshold value at the receiver [12].

The *regeneration points* are usually located in the subset of the network nodes S3R that are provided with the regeneration capability. The *Regenerator Placement Problem* (RPP) is a sub-problem of translucent-network design: it aims at finding the minimum number of transponders and their best location so that all the desired optical communication paths can be established between every pair of source-destination nodes in the network. RPP has been proved to be NP-complete [13].

We can split a translucent-network design-procedure into two main steps: first we <u>choose the set S_{3R}</u> and then we perform the <u>quantification of resources</u> (3R units and DWDM systems) to satisfy a given set of demands for static optical circuits. In this study we have assumed a uniform static matrix of demands including one bidirectional request for a 10 Gbit/s connection between each pairs of nodes of the network.

Let us consider G(N,A) as the physical graph of the network where N represents the set of nodes and A the set of physical links. Being understood that the opaque implementation of the network is when all the nodes have at least one regenerator per transit lightpath, the translucent implementation of the same network can be conceived according to two different approaches:

- <u>Sparse translucent</u> approach: every network node can potentially host 3R units, which means $S_{3R} = N$. Regenerators are allocated to the nodes only when needed, trying to minimize their total number in the network. Obviously, this implies that not all the nodes necessarily have transponders at the end of the procedure;
- <u>Clustered translucent</u> approach: only a subset of network nodes are identified as regenerating nodes and are given the capability of hosting 3R units. All the other nodes are purely transparent. Thus, $S_{3R} \subset N$.

Several algorithms have been proposed in literature to identify the set of regenerating nodes in a clustered-translucent network. In this first study we have considered two of such algorithms, namely *Nodal Degree First* (NDF) [14] and *Central Node First* (CNF) [14]. They are both based on the physical topology of the network. The former sorts nodes in decreasing order of nodal-degree and starts building the set S_{3R} including nodes progressively taken from the list. S_{3R} continues to grow by adding more nodes to the set until it becomes a connected and dominating set [15]. As one node is added to S3R, it is removed from the sorted list and the nodal degree of all its neighbors is decremented by one. Then the list is resorted.

The CNF algorithm ranks the nodes according to their topological "centrality", i.e. a weight proportional to the number of times a node is crossed by the shortest paths between all the node pairs in the network. The more times a node is used the more central it becomes for the network. Then the procedure for constructing S_{3R} is the same as NDF. S_{3R} is increased adding nodes until the desired connectivity and dominating constraints are satisfied [15].

Once the S_{3R} has been generated, the quantification of resources is carried out solving the Routing and Wavelength Assignment with Regenerator Placement (RWARP) problem for each connection using a greedy algorithm described in the deliverable D2.1 of Nobel project [16]. The algorithm deploys transponders and DWDM systems on a per-path-basis, but 3R units are constrained to be placed only in those nodes belonging to the set S_{3R}. After all connections have been set up, nodes in which no transponder has been deployed, if any, are removed from the original S_{3R} set.

A number of design experiments have been performed using the well known PAN European network (28 nodes, 41 edges) as case-study example. Results of these experiments in terms of total number of regenerator nodes, installed 3R units and DWDM bidirectional transmission systems (assumed to carry 40 wavelength channels each) are reported in Table 3.3. Design experiments have been repeated for three different values of Q_{th}. Note that Q_{th}=17 dB roughly corresponds to a BER of 10^{-12} (assuming no FEC performed).

Algorithm/ Q_{th}=21 dB	Number of 3R nodes	Number of bidirectional 3R units	Number of bidirectional DWDM systems
OPAQUE	28	2360	59
SPARSE PLACEMENT	23	358	56
CNF	19	364	57
NDF	10	437	60
Algorithm/ Q_{th}=19 dB	Number of 3R nodes	Number of bidirectional 3R units	Number of bidirectional DWDM systems
OPAQUE	28	2480	59
SPARSE PLACEMENT	21	177	57
CNF	16	178	61
NDF	5	184	59
Algorithm/ Q_{th}=17 dB	Number of 3R nodes	Number of bidirectional 3R units	Number of bidirectional DWDM systems
OPAQUE	28	2480	59
SPARSE PLACEMENT	18	64	59
CNF	2	64	62
NDF	2	66	63

Table 3.3: Network-planning results with static traffic

Results show the clear advantage of the translucent approach (both sparse and clustered) over the opaque approach in terms of number of transponders, as well expected. In some cases sparse translucent allows to slightly reduce also the number of DWDM systems, thus achieving a clear CAPEX saving. This is due to a better distribution of load in the network compared to the opaque case, in which routing is purely shortest-path based. Shortest-path routing tends to overload few links, increasing the number of links in which two, instead of one, DWDM systems must be deployed.

The clustered translucent approach requires more DWDM systems than the sparse approach, due to the fact that transponder locations are constrained. Thus, clustering transponders in a subset of nodes is economically effective only when fully-transparent network nodes have a lower cost than nodes with the capability of hosting 3R units, so to compensate the extra CAPEX for more DWDM systems. This scenario can become realistic when operational costs due to regenerator hosting are high (e.g. larger area occupation in node-housing infrastructures, much larger energy consumptions, need for special equipment for heat dissipation, maintenance costs, etc.).

Clustered and spares translucent implementations tend to converge in terms of number of deployed transponders when Q_{th} decreases. This lead to an enlargement of the *transparency island* of each node (i.e. set of nodes that can be reached from a node along the shortest path without using 3R).

CNF tends to select more 3R nodes adjacent one another and located at the “centre” of the network than NDF. NDF, on the other hand, reduces the cardinality of the set S_{3R} by placing 3R nodes far from one another, sometimes at the edges of the topology. In terms of number of transponders, NDF is more efficient than CNF.

If the semi-transparent implementation is less expensive in terms of CAPEX compared to the opaque, the drawback of the translucent approach is a worse behaviour in dynamic-traffic conditions. We have compared translucent and opaque network formerly designed for the same given static traffic under dynamic-traffic conditions (assuming a Poissonian model for lightpath setup and tear-down request generation). Dynamic traffic is correlated to the original static-traffic matrix used as input for the design phase: in fact we set the parameters of traffic generators so that on average the number of connections requested between each node-pair is the same as in the static case.

The following figure shows the results based on an extensive computer simulation campaign in which the confidence interval is 1% or better at 95% confidence level. It should be noted that blocking can occur for two reasons: lack of free resources and lack of free regenerators. The translucent implementation, no matter if sparse or clustered and regardless of the algorithm used to build the set S_{3R}, exhibits a large blocking-probability gap compared to the opaque implementation. Similar gaps have been obtained by carrying out simulations for other values of Q_{th}.

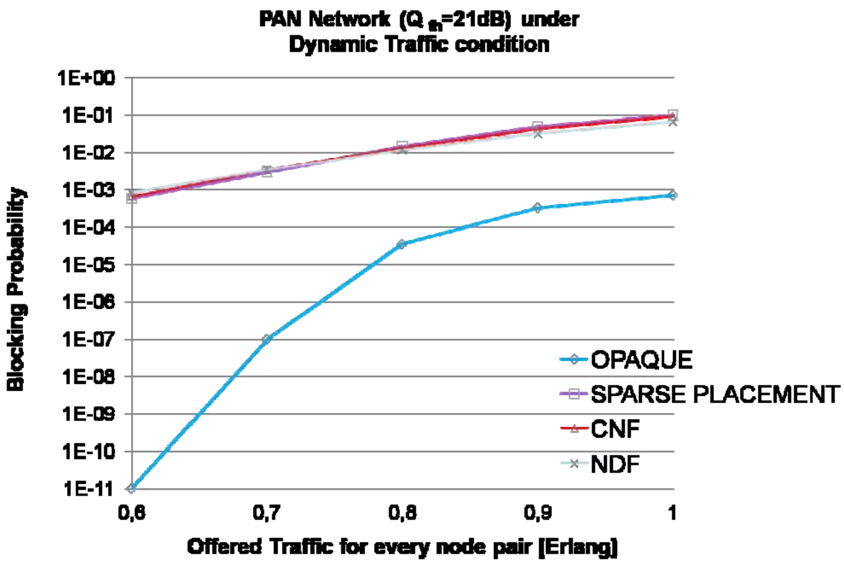


Figure 5: Blocking-probability results with dynamic traffic

These first results suggest us that more advanced transponder-clustering algorithms may be needed in selecting the set S_{3R} in order to preserve the advantages of a translucent network over opaque also with dynamic traffic. This will be the scope of our next research activity in this JA.

5.2.2.5.2 Novel regenerator placement strategies

We formalised the regenerator problem as follows.

Input parameters:

- Physical topology
- Traffic demand matrix
- (Static) physical layer impairment (PLI) information, which could be provided in whatever measure because the proposed formulations are independent on this measure.

Output parameters:

- Routing wavelength assignment
- Number of regenerators at each node.

Two formulations have been proposed in order to deal with this problem.

The first formulation considers that all the demands must be carried and receives as an input parameter a set of valid paths according to the physical layer impairments (P_q). Following this formulation is described:

Given:

N: set of nodes

M: set of fibres

W: set of wavelengths

$T(s,d)$: number of lightpaths to establish from node s to d

P_q: set of valid paths according to the physical layer impairments

Decision variables:

- x_{pwsd} {0,1}: is 1, if path p in P_q uses the wavelength w in W for carrying one lightpath in the demand from s to d.

Objective function:

$$\min \sum_{p,w,s,d} x_{pwsd}$$

Constraints:

(1) Flow conservation constraints for the lightpaths over the valid paths.

$$\sum_{p\in\delta^{+}(n),w} x_{pwsd} - \sum_{p\in\delta^{-}(n),w} x_{pwsd} = \begin{cases} T(s,d) \text{ if } \mathrm{n = s} \\ -T(s,d) \text{ if } \mathrm{n = d} \quad \forall \mathrm{n, s, d} = 1,\dots,\mathrm{N} \\ 0 \text{ otherwise} \end{cases}$$

where $\delta^{+}(n)$ and $\delta^{-}(n)$ are the sets of the paths which are initiated and ended at the node n respectively.

(2) Wavelength clashing constraints.

$$\sum_{p_e,s,d} x_{p_e wsd} \le 1 \, \forall \mathrm{w} \in \mathrm{W}, \mathrm{e} \in \mathrm{F}$$

The second formulation makes use of the decomposition of pre-computed end-to-end routing paths on transparent segments, for which PLI constraints are satisfied. The assumption is that between two consecutive transparent segments there is a regenerator placed so that the optical signal can reach the destination with an acceptable signal quality. Since an end-to-end routing path may be segmented in different ways, a decision problem is to select such a segmentation, among provided candidates, that meets given optimization objectives. At the same time, the RWA constraints, such as wavelength continuity, flow conservation, wavelength capacity, etc., have to be satisfied for all established lightpaths in the network. Although the formulation does not require that all the connection requests are accepted, still it aims at the minimization of the number of blocked requests. The second objective is the minimization of the overall regenerator usage. The problem is formulated as following:

Given:

V: the set of nodes

E: the set of links

W: the set of wavelengths

$T(s,d)$: the number of lightpaths to be established from node s to d

P: the set of all (end-to-end) paths

$P(s,d)$: a subset of paths between nodes s and d

P^r: a subset of paths requiring regeneration in some intermediate node(s)

P^{nr}: a subset of paths with no regeneration required

R_p: the set of candidate segmentations of path p

S_{pr}: the set of segments of candidate segmentation r on path p

Decision variables:

- $x_p \in Z_+$: a problem variable which represents the number of accepted lightpath requests on path p.
- $x_{(s,d)} \in Z_+$: a slack variable which represents the number of not-accepted lightpath requests of demand $T(s,d)$.
- $x_{pw} \in \{0,1\}$: a decision variable, equal to 1 if wavelength w on path p is assigned to a lightpath, and equal to 0 otherwise.
- $x_{pwrs} \in \{0,1\}$: a decision variable, equal to 1 if wavelength w on path p for candidate segmentation r and segment number s is assigned to a lightpath, and equal to 0 otherwise.

Constants

- δ_{ep}: a coefficient which is equal to 1 if link e belongs to path p, and equal to 0 otherwise.
- η_{pers}: a coefficient which is equal to 1 if link e belongs to segment s for given segmentation r of path p, and equal to 0 otherwise.
- θ_p: a number of regenerators required on path p.
- α: a big constant number used as a weighting coefficient in the multi-objective function to give a priority to the blocking objective over the regenerator usage objective.

(Multi)-objective function:

$$\min \alpha \sum_{s,d} x_{(s,d)} + \sum_{p \in P^r} \theta_p x_p$$

Constraints:

(1) Input traffic constraints.

$$\sum_{p \in P_{(s,d)}} x_p + x_{(s,d)} = T(s,d), \qquad \forall s,d$$

(2) Initial wavelength assignment.

$$\sum_{w \in W} x_{pw} = x_p, \qquad \forall p \in P,$$

$$\sum_{r \in R_p} x_{pwr1} = x_{pw}, \qquad \forall p \in P^r, w \in W.$$

(3) Flow conservation (assuming the wavelength conversion capability at regenerative nodes).

$$\sum_{w \in W} x_{pwr(s-1)} = \sum_{w \in W} x_{pwrs}, \qquad \forall p \in P^r, r \in R, s = 2 \ldots |S_{pr}|.$$

(4) Wavelength capacity.

$$\sum_{p \in P^{nr}} \delta_{pe} x_{pw} + \sum_{p \in P^r} \sum_{r \in R} \sum_{s \in S} \eta_{pers} x_{pwrs} \le 1, \qquad \forall e \in E, w \in W.$$

In Table 3.4 we present some numerical results of the regeneration placement obtained for a 9-node Internet2 topology [17] with 32 wavelengths per link and with uniform traffic demands, i.e., $T(s,d) = 1$ for each s, d pair of (distinct) nodes. The PLI model used to find valid paths P_q for the first formulation and candidate path segmentation for the second formulation is based on an OSNR impairment model (see [18] for details).

Formulation	Network Node									Overall regeneration usage	Request Blocking	Computation Time [sec]
	1	2	3	4	5	6	7	8	9			
1	0	1	2	15	5	1	0	0	0	24	0%	5.391
2	0	2	2	8	7	5	0	0	0	24	0%	2.828

Table 3.4: Number of regenerators required at each node comparing the two proposed formulations

Future work concerns preparing a conference paper and a journal paper which will present proposed solutions for the regenerator placement problem under static traffic demands. In the next step, the problem of regenerator placement under dynamic traffic demands will be studied.

5.2.2.6 Experimental evaluation of a subset of the proposed mechanisms

In this task, we concentrated on evaluating selected GMPLS-enabled IRWA algorithms within translucent wavelength switched optical networks (WSON) with sparse 3R regenerators. The performance evaluation is conducted within the CTTC ADRENALINE testbed® in terms of the connection blocking probability. In addition, translucent-oriented GMPLS protocol enhancements (i.e., signalling and routing) are evaluated and assessed within such an experimental platform.

The evaluated translucent-oriented IRWA algorithm presents the following characteristics:

- On-line source-and OSNR-based RWA algorithm satisfying two restrictions: the wavelength continuity constraint (WCC) and the adequate optical signal quality in terms of end-to-end OSNR. If either constraint is not fulfilled, sparse 3R regenerators placed throughout the network may be used.
- Shortest path computation based on a modified-Dijkstra algorithm. The IRWA algorithm uses a cost-model function according to two metrics: *link cost* and *node regenerator cost*.
- The objective of the IRWA algorithm is to dynamically compute paths satisfying the above constraints while minimizing / optimizing the number of used wavelength channels and 3R regenerators.

The architecture of the considered translucent node is composed of an NxN non-blocking optical switch with optical (de)multiplexers, being able to switch wavelengths from an input port to an output port without OEO conversions. Local tributaries (i.e., client equipment) are connected to the input/output ports of the optical switch through tuneable transceivers providing the proper wavelength channel and the signal power. A pool of 3R regenerators is located at given ports of the optical switch to perform 3R functions. A GMPLS-enabled control plane provides the intelligence to manage the lightpath provisioning. This is accomplished by means of distributed control protocols:

- The RSVP-TE signalling protocol for wavelength assignment/reservation and 3R regeneration allocation.
- The OSPF-TE routing protocol for network topology and network resource (i.e., wavelength channels and 3R regenerators) dissemination.

The GMPLS-enabled control plane executes several processes for the management of the optical switch, including the optical resources such as the wavelength channels and the 3R regenerators. Furthermore, the control plane is the responsible for computing the routes (executing the aforementioned IRWA algorithm) to serve incoming lightpath requests and the processing and exchange of RSVP-TE messages for the dynamic establishment of the connections.

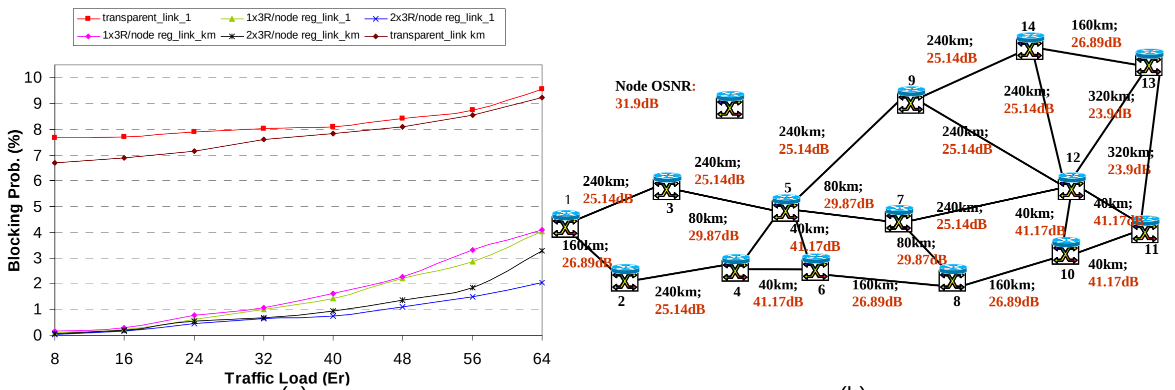
In the context of a translucent WSON, the longer the path an optical signal is transported on, the higher the number of amplifiers that are needed to compensate the power loss. This makes the ASE noise a significant signal impairment factor. The OSNR is commonly used as the main constraint to capture the impact of the ASE noise. There are two main components of the received OSNR level at a given node: *link_OSNR* and *node_OSNR*. Taking this into account, the received OSNR for a lightpath segment traversing *l* links and nodes is expressed as:

$$Total\_OSNR_l = 1/\left(\sum_{j=1..l-1} 1/Link\_OSNR_j + \sum_{j=1..l-1} 1/Node\_OSNR_j \right)$$

where the *link_OSNR* and the $Node\_OSNR_j$ are the OSNR for the j^{th} link and node, respectively. The *Total_OSNR* is then compared to an OSNR threshold (*OSNR_thr*) to determine whether the physical impairment constraint is fulfilled at the receiver node for a given transmission rate (i.e., *Total_OSNR* ≥ *OSNR_thr*). If not, an available 3R regenerator needs to be allocated at an intermediate node to improve the signal quality. Other relevant physical impairments such as chromatic dispersion, polarization mode dispersion and nonlinearities may be optically/electronically compensated at reception or integrated in the impairment constraint model as OSNR penalties.

For the performance evaluation of the translucent-oriented IRWA algorithm the following assumptions were considered:

- The network topology is formed by 22 links and 14 nodes (see Figure 6b).
- Each bidirectional link supports 10 wavelength channels per direction.
- ONSRthr was set to 19 dB.
- Lightpath-arrival is modelled according to Poisson traffic (average inter-arrival time 3 s) and the holding time follows a negative exponential distribution.
- Each data point is obtained requesting 104 lightpaths.
- Wavelength channels operate at 10Gbps.
- Several considered WSON scenarios: transparent (nodes with no regenerators), and translucent with 1 and 2 3R regenerators per node, respectively.
- Link cost set to either 1 or the fiber length expressed in km. Node regenerator cost set to 0.



(a) (b)

Figure 6. (a) Connection blocking probability (%),
(b) Network topology: link distance (km) and link OSNR (dB)

Figure 6a plots the blocking probability (%) versus the network offered load (Erlangs) for the three WSON scenarios, namely, transparent and translucent placing either 1 or 2 3R regenerators per node, considering the two link cost types. A connection is blocked if either the IRWA algorithm or the signaling mechanism fails. The path computation fails when either the WCC or the adequate optical signal quality restrictions cannot be satisfied. On the other hand, the signalling mechanism may fail when resource contention among connections being simultaneously set up occurs.

In the transparent scenarios, the link costs set to the fiber length lowers the connection blocking with respect to the link costs set to 1 (the reduction ranges the 3% and 9.8%). This is due to the fact that when using real distances, the computed routes are the shortest and, consequently, more likely to have an end-to-end OSNR above the threshold.

When a regenerator is placed at each node, in both cases (i.e., using cost link set to either 1 or the fibre length), the connection blocking is significantly reduced compared to the transparent WSON. Specifically, when the path computation uses the link cost set to 1, the attained reduction ranges between 58% and 98%. When the link cost is set to the fibre lengths, similar blocking improvements are achieved (from 55% to 97%). This is due to the fact that using a regenerator allows, on the one hand, regenerating the optical signal when needed and, on the other hand, reducing the blocking caused by the WCC. Note that the blocking performance between setting the link cost to either 1 or fibre length is not as significant as in the transparent WSON scenario. In particular, the path computation for the link cost set to 1 slightly outperforms the blocking results obtained by the link cost expressed as the fibre length. In the latter, the routing algorithm finds fewer problems to fulfil the optical signal quality constraint. However, most of the computed lightpaths are routed through a shortest link set in terms of distance (km). Thus, it is very likely that these connections contend for the wavelength resources, which does increase the signalling mechanism failures to satisfy the WCC. On the other hand, the path computation when the link cost is set to 1 allows balancing the connection establishment among all the network links. By doing so, the contention likelihood among connections is reduced, which improves the connection blocking.

When the optical nodes are equipped with 2 regenerators per node, further improvements are attained with respect to using a unique regenerator. The blocking reductions range between 49% and 70%, and 20% and 47% for the link costs set to 1 and the fibre length, respectively. Note that at low traffic loads, the blocking differences between both link costs are not appreciable. However, as the traffic load is increased, the link cost set to 1 achieves a lower connection blocking. The main advantage of using the link cost set to the fibre length is that the path computation encounters less difficulty to meet the optical signal quality constraint. However, the availability of two or more regenerators per node makes this constraint relatively easily satisfied. Thus, the main reasons of blocking a connection are the lack of wavelength resources and the WCC. In conclusion considering a link cost set to 1 achieves a better and more efficient utilization of the link and regenerator resources. As a result, more connections can be successfully established, reducing the connection blocking.

Future work involves evaluating the translucent-oriented IRWA algorithm within WSON infrastructures having a more optimized placement of the 3R regenerator resources. This will allow not only improving the connection blocking performance but also reducing the overall network cost.

4.2.3 Publications

Conference papers:

No.	Paper details	Participating partners
1	S. Azodolmolky, Y. Pointurier, M. Klinkowski, E. Marin, D. Careglio, J. Solé-Pareta, M. Angelou, I. Tomkos, "On the offline physical layer impairment aware RWA algorithms in transparent optical networks: state-of-the-art and beyond", in Proceedings of 13th Conference on Optical Network Design and Modeling (ONDM2009), Braunschweig, Germany, February 18-20, 2009. **Abstract**: In transparent optical networks with no regeneration, the problem of capacity allocation to traffic demands is called "Routing and Wavelength Assignment". Much work on this topic recently has focused on the dynamic case, whereby demands arrive and must be served in real-time. In addition, due to lack of regeneration, physical impairments accumulate as light propagates and QoT may become inappropriate (e.g., too high Bit Error Rate). Considering the physical layer impairments in the network planning phase gives rise to a class of RWA algorithms: offline Physical Layer Impairment Aware- (PLIA-)RWA. This paper makes a survey of such algorithms, proposes a taxonomy, and a comparison between these algorithms for common metrics. We also propose a novel offline PLIA-RWA algorithm, called POLIO-RWA, and show through simulations that it decreases blocking rate compared with other PLIA-RWA algorithms.	AIT, UPC

2	M. Yannuzzi, M. Quagliotti, G. Maier, E. Marin-Tordera, X. Masip-Bruin, S. Sanchez-Lopez, J. Sole-Pareta, W. Erangoli, and G. Tamiri, "Performance of translucent optical networks under dynamic traffic and uncertain physical-layer information," in Proceedings of the 13th IFIP/IEEE Conference on Optical Network Design and Modelling (ONDM 2009), Braunschweig, Germany, February 2009. **Abstract**: This paper investigates the performance of translucent Optical Transport Networks (OTNs) under different traffic and knowledge conditions, varying from perfect knowledge to drifts and uncertainties in the physical-layer parameters. Our focus is on the regular operation of a translucent OTN, i.e., after the dimensioning and regenerator placement phase. Our contributions can be summarized as follows. Based on the computation of the Personick's Q factor, we introduce a new methodology for the assessment of the optical signal quality along a path, and show its application on a realistic example. We analyze the performance of both deterministic and predictive RWA techniques integrating this signal quality factor Q in the lightpath computation process. Our results confirm the effectiveness of predictive techniques to deal with the typical drifts and uncertainties in the physical-layer parameters, in contrast to the superior efficacy of deterministic approaches in case of perfect knowledge. Conversely to most previous works, where all wavelengths are assumed to have the same characteristics, we examine the case when the network is not perfectly compensated, so the Maximum Transmission Distance (MTD) of the different wavelength channels may vary. We show that blocking might increase dramatically when the MTD of the different wavelength channels is overlooked.	UPC, POLIMI
3	E. Marín‑Tordera, R. Martínez, R. Muñoz, R. Casellas, J. Solé‑Pareta, "Improving IA-RWA algorithms in translucent networks by regenerator allocation", n Proceedings of 13th IEEE International Conference on Transparent Optical Networks (ICTON2009), Island of São Miguel, Azores, Portugal, June 28-July 2, 2009. **Abstract**: In this paper we present the impact of considering regenerator allocation when selecting routes and wavelengths in translucent networks. In the regular operation of translucent networks, i.e. with dynamic traffic, we assume that a certain number of 3R regenerators are installed in some nodes of the network. These regenerators break the optical transparency of the lightpaths, but allow establishing the optical connections with the required optical signal quality. We show the performance improvement of the MINCOD-Q IA-RWA algorithm when an efficient regenerator allocation policy is employed (optical regeneration is only performed when the signal quality goes bellow a pre-established threshold). Under this policy, the (extended) MINCOD-Q algorithm performs slightly better in terms of blocking probability, but and most important, this figure is obtained with a significant reduction of the number of 3R regenerators installed in the network.	UPC, CTTC
4	S. Azodolmolky, Y. Pointurier, M. Angelou, J. Solé-Pareta, and I. Tomkos, "An Offline Impairment Aware RWA Algorithm with Dedicated Path Protection Consideration," OFC/NFOEC 2009, OWI1, 22-26 March 2009, San Diego, California, USA. **Abstract**: We present excellent performance results for a novel offline physical layer impairment aware routing and wavelength assignment algorithm for various transparent all-optical networks, while considering dedicated path protection.	AIT, UPC
5	R. Martínez, R. Casellas, R. Muñoz and T. Tsuritani, "Experimental evaluation of the link cost impact in OSNR-based IRWA algorithms for GMPLS-enabled translucent WSON", in Proceedings of 13th IEEE International Conference on Transparent Optical Networks (ICTON2009), Island of São Miguel, Azores, Portugal, June 28-July 2, 2009. **Abstract**: This article addresses the dynamic provisioning of optical connections within a GMPLS-enabled translucent wavelength switched optical network with sparse 3R regenerators. To this end, an OSNR-based IRWA algorithm computes routes that aim at satisfying both restrictions: the wavelength continuity constraint and adequate end-to-end optical signal quality. If either constraint cannot be satisfied, the sparse 3R	CTTC

	regenerators placed throughout the network may be employed. Given the fact that 3R regenerators are considered a cost-expensive network resource, the IRWA algorithm is devised to optimize/minimize the utilization of available 3R regenerators when computing paths. This is accomplished through a cost-model function in which two metrics are defined, namely, the network link cost and the node regenerator cost. Thereby, the IRWA algorithm computes shortest paths considering those costs while fulfilling the above constraints. In this work, we present and evaluate the performance of the devised algorithm through varying the link costs. The numerical results are compared in terms of the connection blocking probability, which are experimentally obtained within the ADRENALINE testbed. For the sake of completeness, several scenarios with a different number of 3R regenerators are evaluated for the considered Japanese network topology.	
6	G. Franzl, S. Aleksic, B. Statovci-Halimi, S. Sarwar, "Quality of Transmission Management in Dynamically Routed All-Optical Networks", Proceedings of NOC2008, Krems, Austria, July 2008. **Abstract:** The paper discusses in general how to use control loops with impairments monitoring and mitigation for the control and management of dynamically routed all-optical networks. To do so the basic problem is outlined, constraint light-path provisioning reviewed, the cyclic performance optimisation problem discussed and control-loop demands derived. The view from the network-layer dominates as it is assumed the link between the connectivity sold to customers and the resources required for providing it. We conclude that dynamic all-optical networks are possible; impairments mitigation within control-loops effectively helps to increase the overall performance and reduces the demand for quality of transmission headroom to cope with transients from dynamic traffic assignments. Scenario independent control-loop specs are found too restrictive to be feasibly met and therefore a scheme with autonomous control-loop operation targeting on stabilization via the physical-layer control-loops and optimisation via an intelligent performance aware light-path routing is proposed.	TUW
7	Siamak Azodolmolky, Yvan Pointurier, Marianna Angelou, Josep Solé-Pareta, and Ioannis Tomkos, "Routing and Wavelength Assignment for Transparent Optical Networks with QoT Estimation Inaccuracy," OFC/NFOEC 2010, OMM4, 21-25 March 2010, San Diego, California, USA.	AIT-UPC

Journal papers:

No.	Paper details	Participating partners
1	S. Azodolmolky, M. Klinkowski, E. Marin, D. Careglio, J. Solé-Pareta, I. Tomkos, "A survey on physical layer impairments aware routing and wavelength assignment algorithms in optical networks", Computer Networks, vol. 53, no. 7, pp. 926-944, May 2009, ISSN: 1389-1286 **Abstract**: Optical networks are moving from opaque and translucent architectures towards all-optical (transparent) architectures. In translucent architectures a small amount of regeneration (e.g. optical–electronic–optical conversion) is available in the network. The incorporation of the physical impairments in the routing and wavelength assignment (RWA) problem in transparent optical networks has recently received some attention from the research communities. This work compiles a comprehensive survey of the proposed algorithms that address this issue. The physical layer impairments and related classification in optical networks are initially presented followed by physical layer impairments (PLI) constrained and aware RWA algorithms. Algorithmic approach, current PLI-RWA proposals, impact of wavelength conversion on these algorithms, protection and resilience considerations, and proposed extensions to control planes are covered in this work. Further research topics are presented in this study.	AIT, UPC

4.2.4 Mobility actions

No.	Brief Description of Mobility	Participating partners (Indicate the host institute)
1	Dates: 01.06 – 07.06.2008 Visitor: Mirosław Klinkowski (UPC) Host: Ioannis Tomkos and Siamak Azodolmolky (AIT) Start the collaboration between UPC and AIT on the physical layer impairment aware problem. Discuss the open issues and the preparation of a possible survey paper on the topic.	AIT
2	Dates: 06.07- 12.07.2008 Visitor: Siamak Azodolmolky (AIT) Host: Josep Solé-Pareta (UPC) Collect a comprehensive state of the art in physical layer impairment aware problem. Finalize the draft structure of a survey paper. Selection of the best representative papers for further performance analysis.	UPC
3	Dates: 01.09- 11.09.2009 Visitor: Marianna Angelou (AIT) Host: Josep Solé-Pareta (UPC) Discuss primarily the issues that were still open between UPC-AIT and in particular the implementation of the Q-tool and relative package in the UPC platform. Plan for future enhancement of the Q-tool.	UPC
4	Dates: 18.09- 20.11.2009 Visitor: María Belén García Manrubia (UPCT) Host: Josep Solé-Pareta (UPC) Collect a comprehensive state of the art in Regenerator Placement problem. Implement existing and new heuristic algorithm in regenerator placement. Integrate the algorithms in a new specific extension of MatPlanWDM for these tasks.	UPC

4.2.5 Meetings

No.	Short Description (meeting/call conf.)	Participating partners
1	Meeting on 15/7/2009 to discuss the collaboration between AIT, UPC and CTTC	UPC, AIT, CTTC
2	Second meeting on 8/9/2009 to discuss the collaboration between AIT, UPC and CTTC	UPC, AIT, CTTC
3	Meeting on 16/10/2009 to initiate the activity on the regenerator placement problem	UPC, UPCT, CTTC
4	Call Conference on 18/11/2009 to discuss the regenerator placement problem	UPC, UPCT

4.3 Algorithms for multi-layer optimization with ICBR constraints.

4.3.1 Motivation and objectives

The aim of this JA is addressing the multi-layer network optimization problems that appear in OCS networks with impairment constraints (ICBR), from an algorithmic point of view. The physical impairments appear as important constraints in the multi-layer network optimization problems on increasing the bit rate of the WDM channels. As the bit rate in the new optical communications systems is a parameter which tends to be increased, it is necessary to consider the physical layer in the muliti-layer optimization algorithms.

The main objectives of this JA can be summarised in these points:

- Collect and characterize different network scenarios (i.e. metro vs core, 2.5/10/40/100 Gbps) as different impairment constraints appear (and disappear).
- Take a (small) set of relevant multi-layer planning problems: i.e. joint flow routing and virtual topology optimization, converter placement, etc. and study them in network scenarios with impairment constraints.
- For the chosen ICBR + multi-layer problems, study the asymptotic bounds, known inequalities, sub-optimization algorithms etc.
- Finally, devise, implement and compare polynomial heuristics which make something better than an intuitive attempt of approaching to the optimum solutions.

4.3.2 Main outcomes / Key results

This section is organized in 4 subsection according to the different works carried out during this JA.

A4.3.2.1 Static planning with ICBR constraints

UPCT and AIT have been studying the static planning of OCS networks, subjected to the wavelength continuity constraint, and considering signal impairments. The interest is focussed on the design of optimization algorithms for this type of scenario, which make use of a common Q-evaluation tool. Such a function, developed by AIT, provides the Q factor for a given set of lightpaths, established in a given network topology.

A set of algorithms has been proposed, and tested. UPCT has proposed a global search optimization algorithm which combines ILP formulations and heuristic approaches, while AIT is more focussed on heuristic approaches based on sequencing the lightpath demand, and applying a greedy approach. The performance and the scalability of both schemes have been investigated. Results reveal great scalability properties of the global search algorithm, and a performance similar to or better than the sequential schemes.

The Quality of Transmission (QoT) of a lightpath has been evaluated by a *Q*-tool developed by AIT. This *Q*-tool computes the so-called *Q*-factor of the lightpaths of a virtual topology, given the physical characteristics of the network. This *Q-tool* considers both *static* and *dynamic* physical impairments. Static impairments are topology-dependent, and independent from the routing state of the network. The static impairments considered are Amplifier Spontaneous Emission (ASE) noise, filter concatenation, and Polarization Mode Dispersion (PMD). Dynamic impairments depend on the presence and characteristics of other lightpaths already established in the network. This work accounts for the following dynamic impairments: node crosstalk, originating from signal leaks at nodes, and nonlinear effects: Cross Phase Modulation (XPM) and Four Wave Mixing (FWM).

The global search algorithm proposed is based on an iterative search of PLIA (Physical Layer Impairment Aware)-solutions, in which each iteration rearranges parts of the lightpath demand carried through a Binary Integer Linear Programming (BILP) approach. The algorithm is organized in 4 sequential phases. Three different types of BILP formulations are applied in different phases of the algorithm.

Phase 1 is a pre-processing stage. In this phase, it is computed the set of candidates lightpaths whose static Q factor (computation of the Q factor without considering dynamic impairments). It is also computed other parameters like the degradation matrix *D*. Both calculations depend only on the physical topology (e.g. do not depend on the traffic demand). Note that computing all the possible paths in the network is not needed, but only the PLIA-valid paths.

Phase 2 searches for the feasible solution which carries the maximum number of lightpaths, without considering dynamic impairment constraints, but just wavelength clashing. It is conducted by solving a BILP formulation. The QoT of the lightpaths in the virtual topology found V is evaluated invoking the Q-tool function. Let V_{best} be the subset of lightpaths evaluated to be over the signal quality threshold. Along the algorithm, V_{best} will store the Q-feasible virtual topology found at this moment with the maximum number of lightpaths. This defines an upper bound (L_{ub}) and a lower bound (L_{lb}) to the number of lightpaths of the optimum Q-feasible virtual topology: $L_{ub}=|V|$, $L_{lb}=|V_{best}|$.

Phase 3 and 4 try to find solutions with an improved number of Q-feasible lightpaths. This is done by searching solutions in which the number of established lightpaths is forced to be exactly L, for different values of L. During phase 3, solutions are searched for decreasing values of L. Each phase 3 iteration, searches for a solution with an L value in the middle of the range [L_{last},L_{lb}], where L_{last} is the L value tested in the last iteration of phase 3, and L_{lb} is the number of Q-feasible lightpaths in the best solution found up to this moment. Phase 3 ends when the L value is equal to or lower than L_{lb}. During phase 3, the list of L values already tested are stored (in order that they are not repeated during the phase 4), and the best solution found is updated.

Phase 4 starts with an initial value of L equal to the Q-feasible lightpaths in the best solution found, plus 1. Its objective is try to find better solutions, increasing 1 by 1 the L values to test, skipping the L values that have been already tested (as they provided worse solutions in the past). The procedure stops if after G_L consecutive tests of increasing L values, the solutions found did not improve the best existing solution.

The heuristic approaches are based on a pre-processing ordering of the traffic demand, and a subsequent sequential processing of individual lightpath demands. The first stage in the sequential algorithms is a *demand pre-processing ordering* module. We propose two different strategies to order the demands. Both are based on assessing the a-priori distance between two nodes i and j by the length of the shortest path between i and j. Then, we order (i,j) node pairs according to the aforementioned shortest distance, multiplied by the number of lightpaths to be established between i and j, T_{ij}. Two orderings are considered: ascending and descending order. Ascending order prioritizes (i,j) node pairs with shortest paths and smaller demands, while descending order prioritizes (i,j) node pairs with longest paths and larger demands.

The sequential processing stage processes one by one the ordered list of (i,j) pairs. For each (i,j) pair, the T_{ij} lightpath demands are processed sequentially. If a route and wavelength assignment is found for the lightpath demand, so that all the previously established lightpaths and the new one are Q-feasible, then the lightpath and its associated route are added to the current virtual topology V. If not, the lightpath is blocked.

A lightpath demand is processed by first finding a candidate list of possible routes and wavelength assignments for the lightpath. For each lightpath demand all the possible routes and wavelength assignments in the candidate list are tested. If more than one route passes the QoT test, the route chosen is the one with the maximum worst Q-factor (the Q-factor of the lightpath with the lowest Q-factor).

The performance and scalability of the global optimization approach and the heuristic algorithm were assessed by means of several experiments. All the tests were done in the MatPlanWDM tool (developed by UPCT), which interfaces with the TOMLAB/CPLEX solver. The algorithms have been tested for two different network topologies displayed in Fig. 1. They correspond to the Internet2 network (9 nodes, 26 unidirectional links, and average node degree 2.89) and the European Optical Network (EON) (18 nodes, 66 unidirectional links, and average node degree 3.67). The average shortest path length is 1266 km for Internet2 and 1203 km for EON topology respectively.

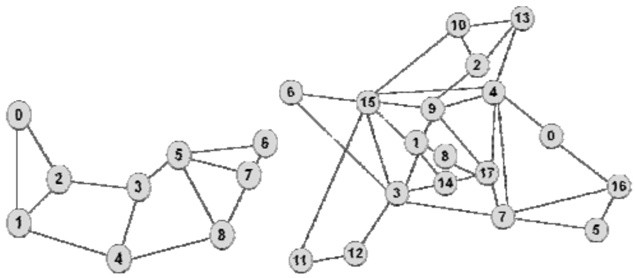


Figure 7: Internet2 (left side) and EON (right side)

We have conducted two experiments to compare the performance of the proposed approaches. In the first experiment, the blocking rate (percentage of blocked lightpath demands versus total number of offered lightpath demands) is evaluated for each physical topology (Internet2 and EON) considering 8 and 16 wavelengths per fibre (Figure 8, Figure 9). The graphs illustrate the evolution of the blocking rate, varying the traffic load.

Each plot in Figure 8, and Figure 9 includes five curves. Three curves correspond to the three algorithms described in this paper (global search, and the two sequential approaches: the shortest path first (SPF) and longest path first (LPF) ordering). In addition, one more algorithm, named sLERP, is added to the comparison. The sLERP algorithm is a simplification of the LERP algorithm (Lightpath Establishment and Regenerator Placement) proposed by M. A. Ezzahdi, et al. The fifth curve named as stat-PLIA in the graphs, is included also for comparison. It is the blocking rate of a MILP algorithm that solves the RWA problem by including only static signal impairments.

Results show that the blocking rate obtained by the global optimization and the sequential algorithms considered are similar in the smaller topology Internet2. However, the global optimization algorithm outperforms the sequential schemes in the EON topology. Both approaches are in a significant number of occasions far from the upper bound calculated, also for small topologies. No strict conclusion can be extracted from this, as the tightness of this bound cannot be calculated. Finally, the comparison between the sequential approaches shows a better behaviour in most of the situations with the shortest path ordering. The sLERP algorithm exhibited the worst performance in all the tests.

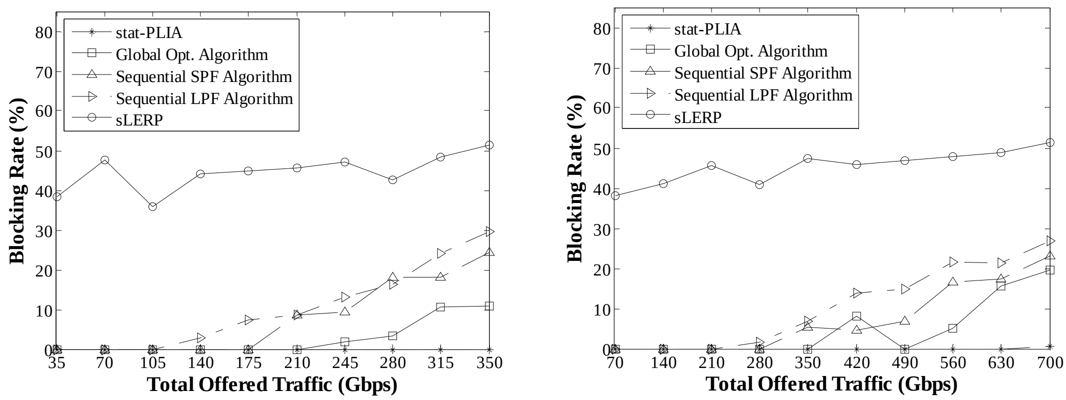


Figure 8: (a) Blocking Rate vs. Load Internet2 8 wavelengths.

(b) Blocking Rate vs. Load Internet2 16 wavelengths.

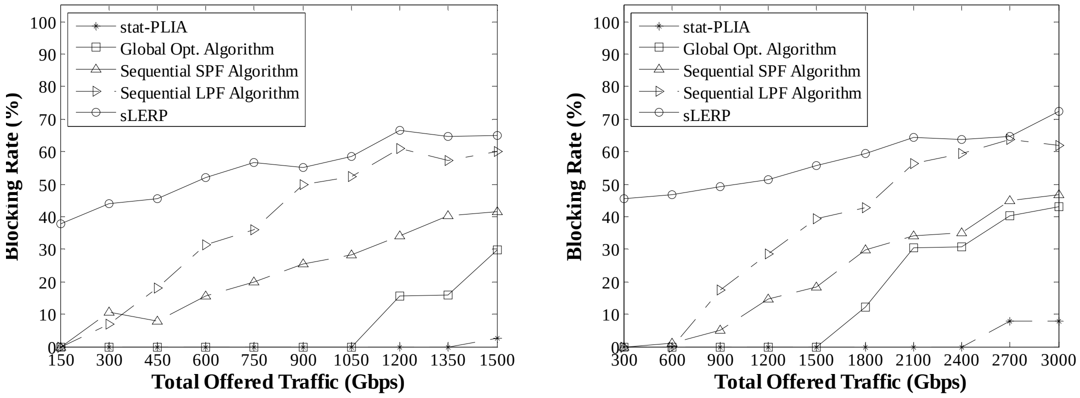


Figure 9:(a) Blocking Rate vs. Load EON 8 wavelengths.

(b) Blocking Rate vs. Load EON16 wavelengths.

The second experiment consists of an evaluation of the blocking rate when the number of wavelengths per fibre is increased from 8 up to 32. This experiment is repeated for the Internet2 topology and a total offered traffic of 490 Gbps, and the EON topology for a total offered traffic of 2100 Gbps. The results from this experiment are presented in Figure 10. They can be interpreted in the same way as in previous graphs. The performance of the sequential algorithms is similar to the global search in Internet2. For EON, a significant performance gap appears favouring the global search algorithm. This performance gap is slightly decreasing for a growing number of wavelengths per fibre.

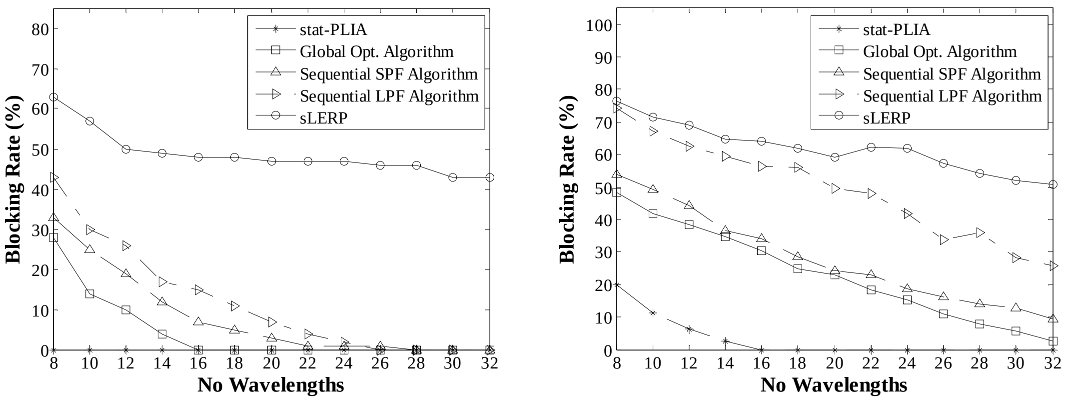


Figure 10:(a) Blocking Rate vs. Number of wavelengths Internet2.

(b) Blocking Rate vs. Number of wavelengths EON.

The scalability of the proposed algorithms is assessed by attending to the evolution of the running time of the different tests presented in the previous section. In Figure 11 the running times of the algorithms are compared when the traffic load is increased from the 10% of the maximum load to the 100% for the four simulation scenarios (EON and Internet2, 8 and 16 wavelengths). In the global search algorithm, the execution time is quite small for low loads, and has an abrupt rise at medium to high loads. This is because for low loads the algorithm can find a solution which carries all the traffic demand during its phase 1. For medium and highs loads the algorithm enters in the iterations inside phases 2 and 3, which are more time consuming. It is quite noticeable that at this moment, algorithm response time remains approximately constant, independent from the traffic load, the number of wavelengths, and the topology size.

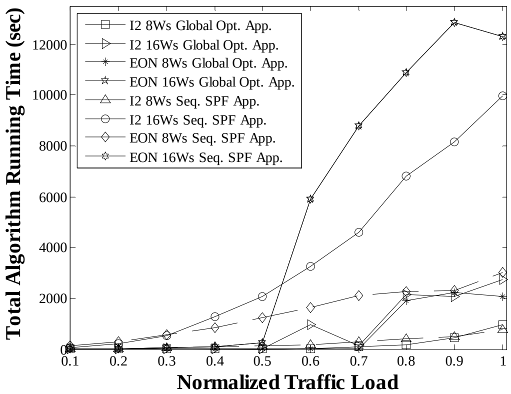


Figure 11: Total Algorithm Running Time (sec) vs. Normalized Traffic Load.

A joint publication has been presented (journal paper 1) with this work . The collaboration work was promoted by the mobility actions from UPCT to AIT of Ramon Aparicio Pardo (from the 15th to the 26th of April 2008) and of Pablo Pavon-Marino (from 15th to 18th of April 2008).

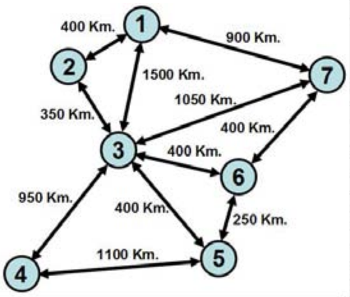
A4.3.2.2 Static planning in multifibre networks

UPCT and TID collaborated in investigating the static planning of multifibre networks, where two neighbour nodes are connected with a bundle of K fibres, $K>1$. On one hand, the multifibre approach adds the cost of amplifying, equalizing, monitoring, switching, etc. more fibres. On the other hand, the WC approach involves the cost of one WC device per wavelength conversion (we assume that the WCs are shared per node). UPCT and TID compared in this work the interest of both approaches in the static planning case. For this, a binary ILP (Integer Linear Programming) formulation was proposed which simultaneously includes the cost of both alternatives. Then, we obtain the minimum cost solution under different conditions, and evaluate the actual use of WCs (wavelength converters) and/or multifibres.

We tested three networks of 7 nodes: a mesh network (Figure 12), a ring and a star with centre in node 3 (last two cases with fibres of 100 km length). In all the cases, links have two fibres, and 8 wavelengths per fibre. One fibre in the link is already pre-activated at cost 0. The cost of activation of the other fibre, normalized to one transmitter plus one receiver cost, is taken from NOBEL cost model: $20+0.96036(d/80)+1.585(d/360)$, where d is the link distance in km. Divisions are rounded to the floor, and correspond to optical line amplifiers, and dynamic gain equalizers per each 80 km and 360 km spans respectively.

The formulation has been implemented in the MatPlanWDM tool, which interacts with a TOMLAB/CPLEX solver. Let T be the 7x7 traffic matrix in Figure 7, obtained from traffic forecast studies for a national optical backbone (measured in Gbps). All the traffic matrixes used are calculated multiplying T, by a real factor. For each topology we made 20 tests with different traffic matrixes, from the higher traffic carried at 0 cost, to the higher carried traffic feasible found. As the WC technology is not fully mature, WC prices were estimated sweeping the WC cost from 0.01 (1% of a transmitter plus a receiver), to a sufficiently high value. Naturally, we expected a lower preference for WCs, as the WC cost grew. Surprisingly, as it is shown in Figure 7, WCs were not used in any case, even considering the lower WC cost of $c_{WC}=0.01$. As traffic grew, a higher number of fibres were activated. But always happened, that given a set of active fibres, if a solution with WCs was found, a solution without WCs and the *same active fibres* was found (obviously at a lower cost).

Previous studies showed that multifibre networks could reduce at a great extent the need of WCs for *dynamic planning* scenarios. Our tests correspond to static planning. It seems that the advantage of a deterministic knowledge of the traffic (in contrast to dynamic planning), greatly *favours* finding minimum solutions without WCs. After these results, we conducted more tests in these topologies which confirmed that minimum cost solutions with WCs in static planning are largely infrequent, and appear in very narrow intervals of traffic demands.



	1	2	3	4	5	6	7
1	0	13.30	23.53	8.10	13.52	22.81	20.59
2	4.28	0	22.91	7.89	13.16	22.24	20.07
3	23.53	73.69	0	43.03	71.88	121.47	109.70
4	8.10	25.28	43.03	0	24.66	41.69	37.67
5	13.52	42.26	71.88	24.66	0	69.66	62.90
6	22.81	71.41	121.47	41.69	69.66	0	106.30
7	20.59	64.50	109.70	37.67	62.90	106.30	0

	MESH net - 7 nodes			RING net - 7 nodes			STAR net - 7 nodes		
Matrix Index	Carried Traffic (Gbps)	No. Used WCs	No. Extra Activ. Fibres	Carried Traffic (Gbps)	No. Used WCs	No. Extra Activ. Fibres	Carried Traffic (Gbps)	No. Used WCs	No. Extra Activ. Fibres
1	953	0	0	368	0	0	338	0	0
2	1005	0	2	397	0	1	356	0	1
3	1057	0	3	425	0	3	375	0	2
4	1109	0	4	454	0	4	393	0	3
5	1160	0	5	483	0	4	412	0	3
6	1212	0	6	512	0	5	431	0	3
7	1264	0	6	540	0	6	449	0	4
8	1316	0	6	569	0	6	468	0	5
9	1367	0	7	598	0	7	486	0	5
10	1419	0	7	627	0	7	505	0	5
11	1471	0	8	655	0	9	523	0	6
12	1523	0	10	684	0	10	542	0	6
13	1574	0	11	713	0	10	561	0	6
14	1626	0	11	742	0	11	579	0	6
15	1678	0	13	770	0	11	598	0	7
16	1730	0	13	799	0	11	616	0	7
17	1781	0	15	828	0	12	635	0	7
18	1833	0	16	857	0	13	653	0	7
19	1885	0	16	885	0	14	672	0	7
20	1937	0	18	914	0	14	691	0	7

Figure 12: Topology, Traffic Matrix and Results

A mobility action was carried out from UPCT to TID, focussed on this topic: from 6th to 12th July 2008 by Ramon Aparicio Pardo. A joint publication has been presented (conference paper 1).

A4.3.2.3 Multicost Approach to Online Impairment-Aware RWA

In the context of this JA, RACTI performed a joint work with AIT and proposed a multicost algorithm to online impairment-aware routing and wavelength assignment (IA-RWA) [2].

In particular, to serve a connection, the proposed algorithm finds a path and a free wavelength (a lightpath) that has acceptable quality of transmission (QoT) performance by estimating the corresponding Q factor. Figure 13 shows the approach we have adapted in order to calculate the corresponding Q factor of a path.

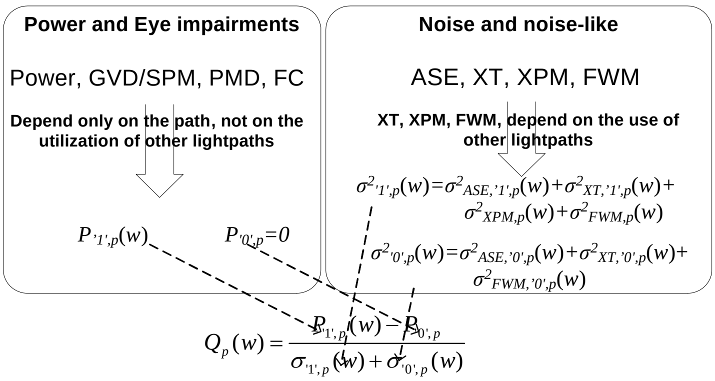


Figure 13: Q factor calculation

Assuming that there are m available wavelengths, the cost vector of a link l is given by

$$V_l = (d_l, G_l, \overline{\sigma^2_{'1',l}}, \overline{\sigma^2_{'0',l}}, \overline{W_l}),$$

where, (i) d_l is the delay of the link– or its length (scalar), (ii) G_l (in dB) is the gain of the link (scalar), (iii) $\overline{\sigma^2_{'1',l}} = (\sigma^2_{'1',l}(1),\ldots, \sigma^2_{'1',l}(m))$ is a vector with the noise variances of signal 1 for each of the wavelengths, (iv)

$\overline{\sigma^2_{'0',l}} = (\sigma^2_{'0',l}(1),\ldots,\sigma^2_{'0',l}(m))$ is a vector with the noise variances of signal 0 for each of the wavelengths, and (v) $\overline{W_l} = (w_l(1),\ldots,w_l(m))$ gives the availability of wavelengths in the form of a Boolean vector (element $w_l(i)$ is equal to 0 (false) when wavelength λ_i is used and equal to 1 (true) when λ_i is free (available)).

Similarly to a link, the cost vector of path p can be calculated by the cost vectors of the links l=1,2,..,k, that comprise it:

$$V_p = \left(\sum_{l=1}^{k} d_l,\ \sum_{l=1}^{k} G_l,\ \sum_{l=1}^{k} \left(\overline{\sigma^2_{1,l}} \cdot \prod_{i=l+1}^{k} 10^{G_i/10} \right),\ \sum_{l=1}^{k} \left(\overline{\sigma^2_{0,l}} \cdot \prod_{i=l+1}^{k} 10^{G_i/10} \right), \mathop{\&}_{l=1}^{k} \overline{W_l},\ (1,2,\ldots,k) \right),$$

where the operator & denotes the bitwise AND operation.

The proposed multicost algorithm consists of two phases. In the first phase, the algorithm finds the set of so called non-dominated paths from the given source to all the nodes of the network, including the given destination.

In the second phase, an optimization function is applied to the cost vector of the paths, in order to find the optimum solution. More specifically, we have evaluated the following cost functions:

i) Most Used Wavelength (MUW)
Given the connections already established, we order the wavelengths in decreasing utilization order and choose the lightpath whose wavelength is most used. Note that this approach does not differentiate between the Q factors of the solutions, as long as they are feasible. So the chosen lightpath can have a Q value close to the threshold, which can become unacceptable when new connections are established.

ii) Better Q performance (bQ)
For each path and wavelength we calculate its Q factor and select the lightpath with the higher Q value. This approach does not consider the utilization of wavelengths in the network, making it more difficult for future connections to be served due to network-layer blocking.

iii) Mixed better Q and wavelength utilization (bQ-MUW)
We start by finding the highest Q, as in (ii). Then, we obtain the set of lightpaths that have Q close to that highest value. From this set we select the lightpath whose wavelength is used more in the network, as in (i).

Note that the noise variances corresponding to XT, XPM and FWM impairments depend on the utilization of the other lightpaths. Therefore, when a lightpath is established, the quality of transmission (QoT) of some already established lightpaths may become unacceptable, and the corresponding connections will have to be rerouted

To evaluate the performance of the proposed algorithm we conducted simulation experiments in Matlab. The experiments were performed assuming the DT network topology. To evaluate the feasibility of the lightpaths we use a Q-factor estimator that uses detailed analytical models to account for the most important impairments.

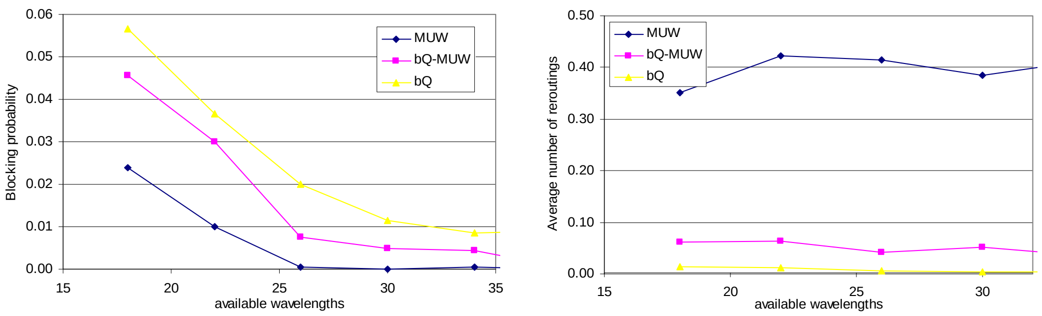


Figure 14: (a) blocking probability and (b) rerouting probability for uniform span length equal to 100 km.

In Figure 14(a) we graph the blocking probability for the three examined optimization policies. We can observe that the most used wavelength (MUW) policy exhibits the best performance. However, as Figure 14(b) indicates, MUW exhibits a high number of reroutings. On the other hand, the bQ policy has the worse blocking probability performance, since it wastes a lot of wavelengths trying to establish a lightpath that is not affected by the others. However, since the established lightpath has the highest Q value and future connections do not appreciably affect its feasibility, bQ exhibits the best rerouting performance. The mixed bQ-MUV algorithm that combines the good blocking probability of MUV algorithm and the low rerouting probability of bQ algorithm seems the best solution since it gives the most balanced results.

Concluding, our results indicate that the proposed multicost algorithm with an optimization function that accounts for both the availability of wavelengths and the Q performance of the chosen solution exhibits a superior performance, combining good physical-layer blocking and low rerouting rate of older connections. The execution time of the proposed algorithm is small, making it appropriate for serving online connections.

A4.3.2.4 Signal power based routing

In this section we propose a new ILP based RWA algorithm where the control plane handles the routing and the signal power allocation jointly. Nowadays in nearly all types of ROADMs the signal power can be tuned with variable optical attenuators (VOA) from the management system. The proposed method can be used in existing WDM optical networks where the nodes support signal power tuning. The method also finds global optimum if it exists. To present the benefits of the algorithm, we calculate the maximum number of demands which can be routed in one network scenario. The absence of solution can have two reasons: the RWA does not succeed or the distance between the source and destination node is too long (i.e. the signal quality will be inadequate). It has to be mentioned that the proposed algorithm finds the global optimum of the routing problem which is an NP-hard problem. Therefore in some cases to find the maximum demands which can be routed takes long time, approximately one week for the COST 266 network with 8 wavelengths (W=8) and n=8 – where n means the maximum allowed deviation of signal power from the traditional power allocation. The “maximum routed demands” means the number of successfully routed demands from a randomly generated demand set. If a certain number of demands could be routed, we increase the number of demands and route it again. This process continues until it is not possible to route more demands anymore. This way it is possible to find the maximum number of demands which can be routed. The bandwidths of the demands were equal to the capacity of one channel. The source and destination pairs were chosen randomly. This timescale problem is not a significant drawback of the proposed algorithm since in real networks this kind of routing problem will not occur. Finding the global optimum (e.g., for COST 266 network with 8 wavelengths, n=1.5 and 60 demands), takes approximately 10 minutes, which is a really fast RWA solution.

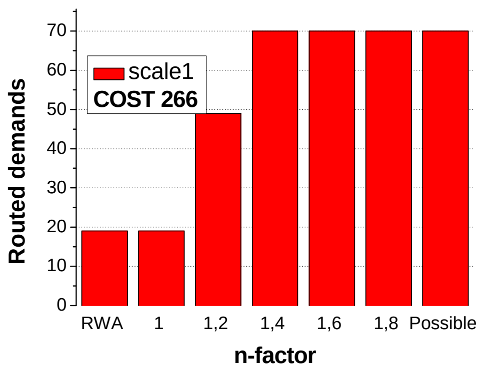


Figure 15: Maximum number of routed demands versus n-factor parameter in case of COST 266 topology

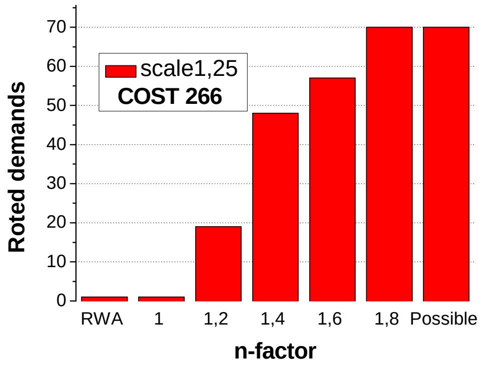


Figure 16: Maximum number of routed demands versus n-factor parameter in case of COST 266 topology, scale 1.25

We compared the proposed algorithm with the traditional RWA algorithm (Figure 15, Figure 16). On the y-axis the maximum number of routed demands is depicted, while on the x-axis the used routing schemes. *RWA* means that we used the traditional routing scheme where each channel has the same signal power. The $n = 1$ routing scheme is similar to the *RWA* routing scheme. The only difference is that in case of $n = 1$ the channel powers can be lower than the average of the powers. In *RWA* case this variation is not allowed. In $n > 1$ cases we used the proposed routing algorithm with n equal to the depicted numbers. The result marked as "possible" is the number of maximum routed demands in case when physical effects are neglected. The *scale parameters* mean that we changed the lengths of the used network link by multiplying the original lengths with the scale parameter. In Figure 15 the scale is 1, i.e., we used the original link lengths (geographical distances). In Figure 16 the scale parameter is 1.25.

In Figure 15 and Figure 16 it can be seen that the traditional RWA algorithm can route 19 and 1 demands, respectively. While by increasing the n-factor more and more demands can be route until we reach a limit, where the RWA problem is infeasible in itself (without considering physical effects).

4.3.3 Publications

Conference papers:

No.	Paper details	Participating partners
1	P. Pavon-Marino, R. Aparicio-Pardo, B. Garcia-Manrubia, J. Fernandez-Palacios, O. Gonzalez, F. Martin, J. Garcia-Haro, "Balancing Multifibre and Wavelength Converter Cost in Wavelength Routing Networks", *ECOC* Brussels, Sept. 2008. **Abstract**: This paper evaluates the balance between the cost of multifibres and the cost of wavelength converters in multilayer networks. A novel ILP formulation of the static planning problem is applied.	UPCT, TID
2	K. Manousakis, K. Christodoulopoulos, E. Varvarigos, M. Angelou, I. Tomkos, "A Multicost Approach to Online Impairment-Aware RWA", *ICC* 2009. **Abstract:** We design and implement a multicost impairment-aware routing and wavelength assignment algorithm for online traffic. In transparent optical networks the quality of a transmission degrades due to physical impairments. To serve a connection, the proposed algorithm finds a path and a free wavelength (a lightpath) that has acceptable signal quality performance by estimating a quality of transmission measure, called the Q factor. We take into account channel utilization in the network, which changes as new connections are established or released, in	RACTI, AIT

	order to calculate the noise variances that correspond to physical impairments on the links. These, along with the time invariant eye impairment penalties of all candidate network paths, form the inputs to the algorithm. The multicost algorithm finds a set of so called non-dominated Q paths from the given source to the given destination. Various objective functions are then evaluated in order to choose the optimal lightpath to serve the connection. The proposed algorithm combines the strength of multicost optimization with low execution time, making it appropriate for serving online connections.	
3	Szilárd Zsigmond, Marcell Perényi, Tibor Cinkler "ILP formulation of Signal Power Based Routing for Single and Multilayer Optical Networks", *BROADNETS 2008* September 8-11 2008 London **Abstract**: {In both metropolitan optical networks (MON) and long haul optical networks (LHON) the signal quality is often influenced by the physical impairments, therefore a proper impairment based routing decision is needed. In this paper we propose new routing and wavelength assignment (RWA) methods where the control plane has influence on the signal power of the Wavelength Division Multiplexed (WDM) channels. Nowadays in nearly all kinds of reconfigurable optical add-drop multiplexers (ROADM) the signal power can be tuned via variable optical attenuators (VOA) from the control plane. We give the exact integer linear programming (ILP) formulation of the method for both single and multilayer networks. In the first case we assume that no signal regeneration is allowed along the path, while in the more complex multilayer case 3R signal regeneration, grooming and wavelength conversion can all be done in the electronic layer. The proposed algorithm can be used in existing WDM optical networks where the nodes support signal power tuning. The algorithm finds the global optimum, if it exists, for a certain network topology, physical constraints and demand set.}	BME

Journal papers:

No.	Paper details	Participating partners
1	P. Pavon-Mariño, S. Azodolmolk, R. Aparicio-Pardo, B. Garcia-Manrubia, Y. Pointurier, M. Angelou, J. Solé-Pareta, J. Garcia-Haro, I. Tomkos, "Offline Impairment Aware RWA Algorithms for Cross-LayerPlanning of Optical Networks," *IEEE/OSA Journal of Lightwave Technology*, Vol.27(12), pp. 1763-1775, June 2009 **Abstract**: Transparent optical networks are the enabling infrastructure for converged multi-granular networks in the Future Internet. The cross-layer planning of these networks considers physical impairments in the network layer design. This is complicated by the diversity of modulation formats, transmission rates, amplification and compensation equipments, or deployed fiber links. Thereby, the concept of Quality of Transmission (QoT) attempts to embrace the effects of the physical layer impairments, to introduce them in a multi-criterium optimization and planning process. This paper contributes in this field by the proposal and comparative evaluation of two novel offline impairment aware planning algorithms for transparent optical networks, which share a common QoT evaluation function. The first algorithm is based on an iterative global search driven by a set of binary integer linear programming formulations. Heuristic techniques are included to limit the binary programming complexity. The second algorithm performs different pre-orderings of the lightpath demand, followed by a sequential processing of the lightpath demands. The performance and the scalability of both approaches are investigated. Results reveal great scalability properties of the global search algorithm,	UPCT , AIT, UPC

	and a performance similar to or better than the sequential schemes.	
2	K. Christodoulopoulos, K. Manousakis, M. Angelou, E. Varvarigos, “Considering Physical Layer Impairments in Offline RWA”, IEEE Networks Magazine, 23(3), pp. 26-33, May-June 2009. **Abstract**: We consider the offline version of the routing and wavelength assignment problem in transparent all-optical networks. In such networks and in the absence of regenerators, the signal quality of a transmission degrades due to physical layer impairments. Certain physical effects cause choices for one lightpath to affect and be affected by the choices made for other lightpaths. This interference among lightpaths is particularly difficult to formulate in an offline algorithm, since in this version of the problem we start without any established connections, and the utilization of lightpaths are the variables of the problem. For this reason the majority of work performed in this field either neglects lightpath interactions or assumes a worst case interference scenario. In this article we present a way to formulate interlightpath interference as additional constraints on RWA and show how to incorporate these constraints in an IA-RWA algorithm that directly accounts for the most important physical layer impairments. The objective of the resulting cross-layer optimization problem is not only to serve the connection requests using the minimum number of wavelengths (network layer objective), but also to select lightpaths that have acceptable quality of transmission performance (physical layer objective).	RACTI, AIT
3	K. Manousakis, K. Christodoulopoulos, E. Kamitsas, I. Tomkos, E. Varvarigos, "Offline Impairment-Aware Routing and Wavelength Assignment Algorithms in Translucent WDM Networks", IEEE/OSA Journal of Lightwave Technology, Vol. 27(12), pp. 1866-1877, June 2009. **Abstract**: Physical impairments in optical fiber transmission necessitate the use of regeneration at certain intermediate nodes, at least for certain lengthy lightpaths. We design and implement impairment-aware algorithms for routing and wavelength assignment (IA-RWA) in translucent optical networks. We focus on the offline version of the problem, where we are given a network topology, the number of available wavelengths and a traffic matrix. The proposed algorithm selects the 3R regeneration sites and the number of regenerators that need to be deployed on these sites, solving the regenerator placement problem for the given set of requested connections. The problem can be also posed in a slightly different setting, where a (sparse) placement of regenerators in the network is given as input and the algorithm selects which of the available regenerators to use, solving the regenerator assignment problem. We formulate the problem of regenerator placement and regenerator assignment, as a virtual topology design problem, and address it using various algorithms, ranging from a series of integer linear programming (ILP) formulations to simple greedy heuristic algorithms. Once the sequence of regenerators to be used by the non-transparent connections has been determined, we transform the initial traffic matrix by replacing non-transparent connections with a sequence of transparent connections that terminate and begin at the specified 3R intermediate nodes. Using the transformed matrix we then apply an IA-RWA algorithm designed for transparent (as opposed to translucent) networks to route the traffic. Blocked connections are re-routed using any remaining regenerator(s) in the last phase of the algorithm.	RACTI, AIT

4.3.4 Mobility actions

Please fill the following table to report the performed mobility actions (if any):

No.	Brief Description of Mobility	Participating partners (Indicate the host institute)
1	**Visiting Researcher:** Ramon Aparicio-Pardo **Start-End Dates**: 15/04/2008 – 26/04/2008 It was advanced in the integration between the MatPlanWDM Tool and physical layer impairments models developed by the AIT to be able to test and compare different Impairment-Aware Routing and Wavelength Assignment (IA-RWA) Algorithms. Some IA-RWA algorithms have been developed by both sides. These algorithms use the physical layer model provided by the AIT to estimate the signals at the receivers. The algorithms have been evaluated and compared. The results of the algorithms comparison were published in the paper Journal Paper 1.	UPCT, AIT (host institute)
2	**Visiting Hosted Researcher:** Ramon Aparicio-Pardo **Start-End Dates**: 6/07/2008 – 12/07/2008 We have introduced a basic Physical Layer Impairment-Aware planning in a case of study considered in a previous work between both institutions. This case consist of a multifibre study carried out using the MatPlanWDM tool over network scenarios provided by TID. We have done several studies from this collaboration and the results were published in the paper Conference Paper 1.	UPCT, TID (host institute)

4.3.5 Meetings

No.	Short Description (meeting/call conf.)	Participating partners
1	BONE Plenary Meeting - Jan 2008 Turin, Italy, 29/01/2008 - 30/01/2008	UPCT, TID, AIT, RACTI, BME, UPC,CCTC,UAM, BILKENT.
2	Joint Plenary meeting WP11 WP12 WP21 WP22 WP24 WP26 - June 2008 AIT facilities, Athens (Greece), 27/06/2008 - 27/06/2008	UPCT, TID, AIT, RACTI, BME, UPC,CCTC,UAM, BILKENT.
3	BONE Plenary Meeting - Oct 2008 Rome (Italy), 20/10/2008 - 22/10/2008	UPCT, TID, AIT, RACTI, BME, UPC,CCTC,UAM, BILKENT.

4.4 ICBR algorithm taking into account traffic grooming

4.4.1 Motivation and objectives

There is no doubt, that the near future info-communications will be based on optical networks. In general for networks of practical size, the number of available wavelengths is lower by a few orders of magnitude than the number of connections to be established. The only solution here is to join some of the connections to fit into the available wavelength-links. This is referred to as traffic grooming. The aim of this JA is the joint optimization of traffic grooming and Impairment Constraint Based Routing (ICBR). It is assumed that in the optical layer, there is no signal regeneration, and the noise and signal distortion accumulate along a lightpath.

The main objective of this joint work can be summarized as follows:

- Investigation the traffic grooming in an ICBR environment
- Define new node architectures, new traffic grooming methods
- Discuss and present results obtained for defined architectures and by using the developed models

4.4.2 Main outcomes / Key results

Several results have been obtained from different network scenarios and different network parameters. We have considered a two-layer architecture, an electrical layer and an optical layer. The electrical layer supports some features such as traffic grooming and λ-conversion. The routing is realized by a shortest path algorithm. Each link and node has its own cost. In this way it can be chosen the lowest cost path by implementing Dijkstra's algorithm. This algorithm can route demands dynamically. The input of the optimization is the network topology and the demands. The output of the algorithm is the set of optimal routes and statistical data on the blocking in the network. The routing parameters contain information about the blocking ratio and the reason why the route has been blocked. A route can be blocked due to the RWA problem, or because of the physical impairments. A route is blocked due to RWA problem if there is not enough resource to route the demand between the source and destination node. This happens when all the wavelengths are used or in case of grooming there is not enough free capacity to groom the demand We consider a route blocked due to physical impairments if Q value of the route is lower than 3.5 which is still acceptable if using coherent detection schemes.

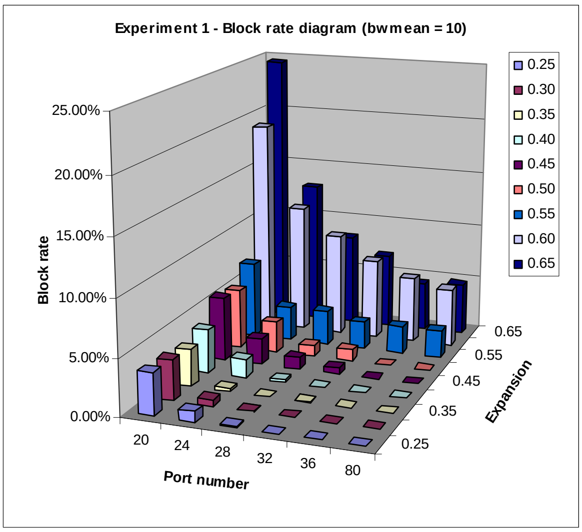


Figure 17 Blocking ratio vs. port number vs. expansion at 10 Mbit/s average demand bandwidth

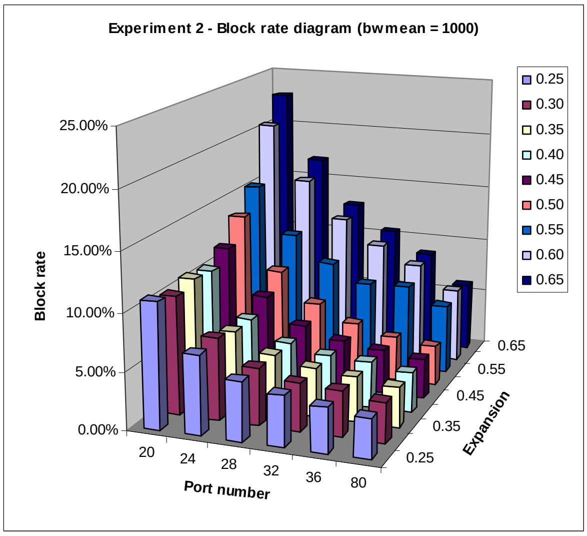


Figure 18 Blocking ratio vs. port number vs. expansion at 1 Gbit/s average demand bandwidth

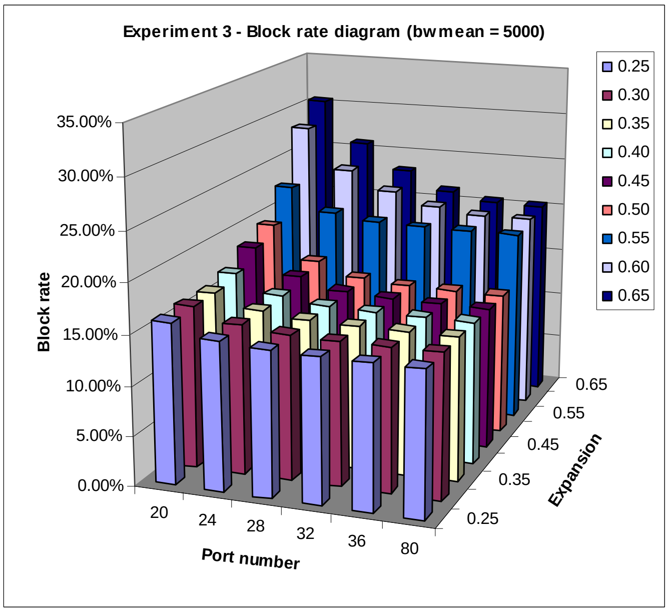


Figure 19: Blocking ratio vs. port number vs. expansion at 5 Gbit/s average demand bandwidth

To investigate the effects of Grooming in an ICBR environment it has been defined three crucial parameters. The first one is the scale of the network. We changed the used network link lengths by multiplying the original lengths with the scale parameter thus triggered the influence of physical impairments. The other parameter was the port number which means the number of electrical port in one optical node, e.g. the grooming capability of the node. The third parameter was the average bandwidth considering a fix bandwidth for every lightpath. The third parameter is also a metric of the grooming capability of the network. This means a 3 dimensional simulation space, whit a huge computation request. As a solution, a Hungarian supercomputer has been used to perform these simulations.

The results show that while increasing the network size or decreasing the port number or increasing the average bandwidth of demands the blocking ratio decreases.

As conclusion in this JA we have shown how the physical impairments and the limited number of O/E/O ports can be taken into account while routing the demands in a grooming capable two layer network. We have turned attention to the mutual impact of grooming and physical impairments, i.e. of using the electronic time- and space-switching capable layer for signal regeneration and better resource utilization. We have shown, that having too few O/E/O ports leads to a significant performance deterioration, while having more O/E/O ports than a certain number does not change the performance at all, since they will not be used at all. The outcome of the joint research activity are reported in [24], [25].

4.4.3 Publications

Please fill the following two tables:

Conference papers:

No.	Paper details	Participating partners
1	Szilárd Zsigmond, Marcell Perényi, Tibor Cinkler „Cross-Layer Optimization of OSNR-Constrained RWA in WDM Optical Networks" COST 291 workshop on The role of optical networking in the future Internet Vilanova i la Geltrú, Catalonia, Spain, Spain, March 11, 2008.	BME
2	Szilárd Zsigmond, Marcell Perényi, Tibor Cinkler "Traffic grooming and power level tuning for physical impairment constrained routing" Transparent Optical Networks, ICTON 2008. 10th 22-26 June 2008 Athens Greece.	BME

4.5 Traffic Engineering in Integrated and Interconnected Control Plane Models in the Presence of Physical Impairments

4.5.1 Motivation and objectives

This study focuses on Traffic Engineering (TE) applications for different inter-operation models for electronic and optical layers. The control plane architectures proposed for inter-operation of the electronic and optical layers can be categorized in two main models. The first one is the vertical interconnection model where the electronic and optical layers are controlled by separate control planes and the interaction between the control planes is provided through interfaces. Three classes of integration model are defined depending on the interaction between the control planes: overlay, peer and augmented [26]. The second inter-operation model is the vertical integration model, in which a unified integrated control plane is used to control both layers. The control plane treats both layers as a single integrated network.

TE methods that can be applied on the network differ according to the assumed inter-operation model. In the overlay vertical interconnection model, there is a client/server type relation between optical and electronic layers. Electronic layer requests optical connections from the optical layer, and optical realizes the establishment of these connections in the physical topology. In the vertical integration model, the common control plane collects the information from both layers and performs TE actions jointly on both layers. Both approaches have their advantages and disadvantages. In the vertical integration model, the total usage of network resources can be better optimized, but the complexity is high since information from both layers is processed, and too frequent changes of the optical layer topology can disrupt the traffic flows in the electronic layer. TE in the vertical interconnection model requires collection and processing of less amount of information and easier to implement in that perspective, however it may not use network resources as efficiently as in the vertical integration model.

In this study, we propose and evaluate TE schemes for these two inter-operation models. We also consider the effect of physical layer impairments. Our aim is to compare the TE applications proposed for these two models in terms of blocking performance and network resource usage and demonstrate their cons and pros.

4.5.2 Main outcomes / Key results

The first results of this joint activity, comparing two of the proposed TE schemes for overlay vertical interconnection model and vertical integration model, without the consideration of physical layer impairments are published in [27]. In this report, we present the performance evaluation of three different TE schemes under physical layers impairments. Main physical layer impairments considered are ASE noise, intra-channel crosstalk, Polarization Mode Dispersion (PMD) and shot noise and thermal noise at the photo-detector. Feasibilities of the lightpaths are verified by calculating the Bit Error Rate (BER) using the Q factor approach. The impairment penalties are classified as Eye Related and Noise Related, and calculated separately [28].

The implemented TE schemes are referred as Fixed WDM Topology (FT), Adaptive WDM Topology (AT) and Shared Intelligence (SI) schemes. FT and SI schemes are suitable to employ in the overlay and augmented vertical interconnection models and AT is suitable for the vertical integration model.

The FT scheme consists of two phases. In the first phase, a fixed WDM layer virtual topology is designed and established. This is achieved by employing a Topology Design Tool (TDT) that uses a heuristic topology design algorithm using Tabu Search meta-heuristic, in the electronic layer. Establishment of the requested lightpath set is performed in the WDM layer by the so called Wavelength Graph Tool (WGT). TDT requests lightpath connections with full wavelength bandwidth, from WGT and WGT serves or denies these requests and announces the result to TDT. Depending on the reply, TDT may request other lightpath establishment or tear down actions. The interaction scheme between TDT and WDT tools represents an example of the overlay model. The second phase of the FT scheme is an online TE method based on rerouting of MPLS

LSPs using a dynamic cost function [29]. As their bandwidth requirements change, the LSPs are rerouted to use the resources on the WDM layer virtual topology, more efficiently.

In the AT scheme, the lightpath topology is not fixed. Lightpaths are added, dropped, fragmented or concatenated dynamically to accommodate changing traffic demands. The demands are routed by using the wavelength graph Model [30]. Each physical link corresponds to as many links on the wavelength graph, as the number of wavelengths. Each node is modelled by a sub graph whose topology is based on the function of the modelled node. The lightpath set is exploited as far as possible and a demand is not refused if there are available resources in the network. However, frequent fragmenting/concatenating of lightpaths causes delay of the traffic or even traffic loss. Therefore, weights of wavelength graph are set; so that traffic grooming is preferred against lightpath fragmentation. By using a well-constructed cost-function fragmentation and hereby opto-electronic conversion is applied as few times as possible.

In the third scheme, SI, a fixed WDM layer topology is designed similar to the FT scheme. Differently from FT, the optical connections requested from WGT are with sub-wavelength bandwidth. The TE scheme routes the demands on the fixed WDM topology first. If any demand cannot be satisfied on the fixed topology, a new temporary connection is requested from WGT between the source and the destination of the corresponding demand. If reply of WGT is positive, the demand is routed on the temporary connection. Each time the bandwidth of the demand changes, the fixed WDM topology is searched for a path with sufficient capacity to route the demand. If an available path is found, the demand is rerouted on that path and the temporary connection is torn down.

The implemented TE schemes are evaluated on a network based on the NSFNET topology with 14 nodes and 21 bidirectional links [28], for wavelength numbers (*W*) of 4,8 and 16. Traffic demands over a one day period are generated by using a traffic model that considers the time zone and population of the nodes [29]. The traffic loss ratios of the TE schemes are calculated for changing values of '*Traffic Magnitude*', which is the ratio of the maximum demand between two nodes to a single wavelength capacity. The results are presented in Figure 20. W=16 is not included in Figure 20, since no loss is observed for this wavelength number for the implemented TE schemes. As can be seen from the results, for W=4, SI has the lowest traffic loss ratio. As the number of wavelengths increase, FT outperforms AT and SI. The performances of FT and AT can are close, compared to SI.

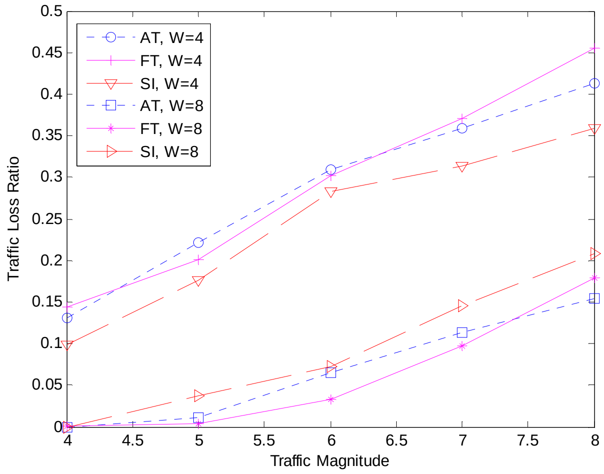


Figure 20: Traffic loss ratio for AT, FT and SI TE schemes.

The resource usage statistics of the TE schemes are presented in Table 5. The uppermost row represents the number of λ-connections (optical connections) established in the WDM layer. The second row shows the average hop lengths of the λ-connections. The third row is wavelength utilization ratio, the ratio of the number of utilized wavelengths to the total number of wavelengths on all the links. The results show that FT establishes higher amount of λ-connections than the other TE schemes and with smaller lengths. This implies that FT scheme is generally not successful in establishing direct optical connections between the source and destinations of the demands, which is an expected result since it does not have the physical layer information. The wavelength utilization ratio is also highest for FT. Among the three TE schemes, SI establishes the smallest number of λ-connections. Its wavelength utilization ratio is also the lowest. AT is between FT and SI for all three parameters.

	FT	AT	SI
# of λ connections	210.650	184.988	157.202
average λ length	1.415	1.518	1.643
wavelength utilization (%)	90.861	88.685	84.366

Table 5: Resource usage statistics for AT, FT and SI TE schemes.

In conclusion, in this study three TE schemes are proposed for the vertical interconnection and integration models under physical layer impairments. The performances of these schemes are evaluated in terms of traffic loss ratio and utilized network resources. The traffic loss ratio is close for the FT and AT schemes. SI performs better than the other two TE schemes for lower number of wavelengths and worse for higher number of wavelengths, in terms of traffic loss ratio. However the average number of λ-connections is the lowest for SI. This is a significant feature since it implies that a smaller number of optical add/drop multiplexers are needed in this TE scheme, which reduces the total network cost.

4.5.3 Publications

Please fill the following two tables:

Conference papers:

No.	Paper details	Participating partners
1	P. Hegyi, N. Sengezer, E. Karasan, T. Cinkler, "Traffic Engineering in Case of Interconnected and Integrated Layers", 13th International Telecommunications Network Strategy and Planning Symposium, Budapest, Hungary, September 2008. **Abstract**: {In this paper, we compare two routing scenarios for grooming-capable optical-beared two-layer networks that are capable of meeting the Traffic Engineering (TE) objectives. The first one applies completely dynamic WDM layer that adapts instantly to all traffic changes. The second one is based on fixed WDM topology ("lower layer"). To achieve the best performance, the fixed lightpath system is optimized in advance according to the characteristics of the expected traffic. In both cases, the upper layer is assumed to be dynamic. We perform extensive simulations to compare these two multi-layer Routing and Traffic Engineering approaches that are currently both of particular practical interest with their inherent advantages and drawbacks.}	BME BILKENT

5. Conclusions

This deliverable presented the final report on the activities that have been performed within the duration of the work package “Topical Project on Alternatives for multi-layer networking with cross-layer optimization” (BONE WP26).

In total there were 5 Joint Activities comprising 15 partners of the BONE project consortium. The scientific outcome of these Joint Activities has produced 19 joint publications out of which 13 were in major international and refereed conferences and 6 in international journals. There were also 3 conference publications, which was performed by individual partners. Moreover, 6 mobility activities were implemented with scientists meeting physically together and working collaboratively over the set activity targets. Finally, the Joint Activities has been supported by 6 independent meetings and numerous call conferences.

Two out of the 5 Joint Activities had a more general scope and covered the following research areas: a) the development, study and comparison of RWA (routing and wavelength assignment) algorithms for semi-transparent networks and the associated optimized regenerator placement (RP), b) the development of algorithms for multi-layer optimization with ICBR constraints. Both of those Joint Activities had a wide number of participating institutes (6 and 9 partners respectively) and covered in detail a great mass of critical aspects producing also novel optimization algorithms in their related subjects. This is evident also by the large number of the resulted joint publications.

In the framework of JA2, which was dedicated to the RWA algorithms for transparent networks and also regenerator placement, several studies and objectives were achieved through close collaboration between involve partners. The first outcome was the compilation of a comprehensive literature survey in order to collect and classify all related works dealing with the problems of impairment aware routing and wavelength assignment (IA-RWA), regenerator placement and extensions for control plane. The next important out come was the investigation of offline case (or planning mode) of IA-RWA problem. In addition to comparative studies, novel algorithms were also proposed and benchmarked with the already proposed algorithms. The similar studies were also performed for the dynamic traffic case (online mode) and furthermore the impact of inaccuracy of the physical layer performance evaluation (e.g Q-Tool) was investigated. The next set of studies were dedicated to the regenerator placement algorithms in translucent (semi-transparent) optical networks and in addition to proposing novel algorithms, comparative studies with existing algorithms were also performed. The last major outcome of this joint activity was the experimental evaluation of GMPLS protocol extensions for the translucent optical networks.

In the framework of JA3, three important outcomes can be summarized. The first outcome was a comparative study on planning of optical networks with consideration of physical layer impairments. In this study the impact of physical layer impairments was considered for the planning of optical networks with a given demand sets. Two algorithms (one heuristic and the other based on global optimization) proposed and their performance were compared in this joint activity. The second outcome was the investigation of the static planning of multi-fibre optical networks, where two neighbour nodes are connected with a bundle of K fibres, K>1. Previous studies showed that multi-fibre networks could reduce at a great extent the need of (Wavelength Converters) WCs for dynamic planning scenarios. It seems that the advantage of a deterministic knowledge of the traffic (in contrast to dynamic planning), greatly favours finding minimum solutions without WCs. After these results, we conducted more tests on other topologies which confirmed that minimum cost solutions with WCs in static planning are largely infrequent, and appear in very narrow intervals of traffic demands. The next activity was the investigation of multi-cost algorithms for operation mode (dynamic traffic case) of optical networks. The obtained results indicate that the proposed multi-cost algorithm with an optimization function that accounts for both the availability of wavelengths and the Q performance of the chosen solution exhibits a superior performance, combining good physical-layer blocking and low rerouting rate of older connections. The execution time of the proposed algorithm is small, making it appropriate for serving online connections.

The rest 3 of the Joint Activities covered more specialized topics related with a) the implementation of the Bayesian decision theory in multi-layer optimization, b) the study of traffic grooming in relationship with ICBR algorithms and c) the inclusion of traffic engineering in integrated and interconnected Control Plane Models in the presence of physical impairments.

In the framework of JA1 two novel algorithms were proposed and benchmarked. Most of the IP traffic in core routers is pass-through, and may not be processed at the IP layer. Consequently, network operators are moving their backbone networks to IP over WDM architectures. Thanks to the advent of reconfigurable optical equipment, the traffic flows can be switched at the optical transport layer instead of consuming IP resources. However, in such multi-layer networks, it is necessary to efficiently combine the resources available from both layers in order to provide enhanced Quality of Service (QoS) to end-users. This work proposes two “Threshold-based” algorithms that aim to reduce the traffic at the IP layer, while efficiently using the optical resources. These algorithms firstly route the traffic using the IP layer, detect the congested links and search for candidate by-passes, which are classified in terms of length and amount of shared traffic. The “Longest” algorithm off-loads the candidate bypasses based on their length. On the other hand, the “Largest” algorithm uses the shared amount of traffic to decide which are off-loaded first. The performance of both strategies is studied in terms of network congestion.

The main goal of JA4 was the joint optimization of traffic grooming and Impairment Constraint Based Routing (ICBR).We have shown how the physical impairments and the limited number of O/E/O ports can be taken into account while routing the demands in a grooming capable two-layered network. We have turned attention to the mutual impact of grooming and physical impairments, i.e. of using the electronic time- and space-switching capable layer for signal regeneration and better resource utilization. We have shown, that having too few O/E/O ports leads to significant performance deterioration, while having more O/E/O ports than a certain number does not change the performance at all, since they will not be used at all.

The main focus of JA5 was on Traffic Engineering (TE) applications for different inter-operation models for electronic and optical layers. In this study three TE schemes were proposed for the vertical interconnection and integration models with consideration for physical layer impairments. The performances of these schemes are evaluated in terms of traffic loss ratio and utilized network resources.

The aforementioned Joint Activities has created the basis for the first detailed studies and novel algorithmic developments in the field of multi-layer optimization and efficient routing and wavelength assignment algorithms. As a result these efforts has delivered a platform upon which the participants can develop further innovative algorithms according to well defined requirements and being also in many cases comparable to each other. This allows strong future collaborations among the leading research groups in these topics.

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