Benefits of Implementing a Dynamic Impairment-Aware Optical Network: Results of EU Project DICONET

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ABSTRACT

Dynamic optical networking allows operators to effectively maximize the capacity of their physical infrastructure and cope with the rapid growth rates of the Internet traffic. In the framework of the European DICONET project we proposed and developed a comprehensive solution that utilizes the dynamicity as well as the valuable physical layer information of a reconfigurable WDM core network to provide a smooth transition from the quasi-static networking of today to an intelligent reconfigurable and physical impairment-aware architecture. In this work we discuss the benefits of implementing the DICONET solution and present some of the major achievements of the project that support both the planning and operation phase of a core optical network.

INTRODUCTION

In old voice-centric telecom networks, planning and operation phases little resembled the equivalent functions of today's data-centric telecom networks. Nowadays, the indisputable growth of data traffic with dynamic usage patterns generated by novel capacity-demanding applications drives developments in communications worldwide. Core optical networks, occupying a fundamental piece of the Internet puzzle, evolved to networks that span over thousands of kilometers of fiber, carry high-capacity traffic, and switch connections all-optically. The evolution trend has followed a path toward higher spectral efficiency and lower total cost of ownership (TCO), facilitated first by the emergence of wavelength-division multiplexing (WDM) and optical add-drop multiplexers (OADMs) and later by reconfigurable all-optical nodes. The evolution path moved from an optical network with optical-electronic-optical regeneration at every node (opaque) to a translucent network where the regeneration takes place only in a small number of sites, or to a transparent network where the regenerators are totally omitted. This transition was driven and justified not only by high-bandwidth provision but also by the minimized TCO stemming mostly from elimination of the costly opto-electronic interfaces. In this context, though, new and more complicated implications were introduced in order to commercially realize an optical network that is fully-dynamic, robust and cost-effective. Optical transparency has a significant impact on network design and operation; the introduction of physical-layer considerations is mandatory in order to cope with the physical-layer effects that deteriorate the connections' quality of transmission (QoT). These challenges can be overcome by introducing additional rules for WDM systems, performance monitoring, and control plane-driven reconfiguration capabilities.

The European research project Dynamic Impairment Constraint Networking for Transparent Mesh Optical Networks (DICONET) successfully addressed these challenges. The consortium of the DICONET project, which consisted of seven academic partners, four equipment manufacturers, and one telecom operator, envisioned a comprehensive multilevel solution based on novel cross-layer algorithms for core optical networks [1]. The key concept of the solution makes use of the accumulation of the physical-layer effects that degrade the quality of the optical signal. Linear and nonlinear impairments that either affect every WDM channel individually or cause interference to neighboring channels render the optical reach finite. Current long-haul WDM networks tackle the limitations induced by the optical medium with careful link design, dispersion management, and power budgets. Beyond these offline techniques, DICONET actually exploits the knowledge of the impact of the single-channel and multichannel effects to introduce an intelligent and high-performance network with *impairment awareness* in the planning and operational processes. In addition, DICONET applies to dynamic optical networks and utilizes the *reconfiguration ability* of the optical switching components (reconfigurable optical crossconnects, R-OXCs) to support highly dynamic traffic in a flexible and economic manner [2]. As opposed to the current networks that employ OXCs with fixed configuration, reconfigurable optical nodes offer a clear advantage to the operators as they do not have to overprovision their network with costly equipment meant to serve future traffic variations. Hence, the network can react on the fly to traffic changes or failures, without the need for on-site interventions.

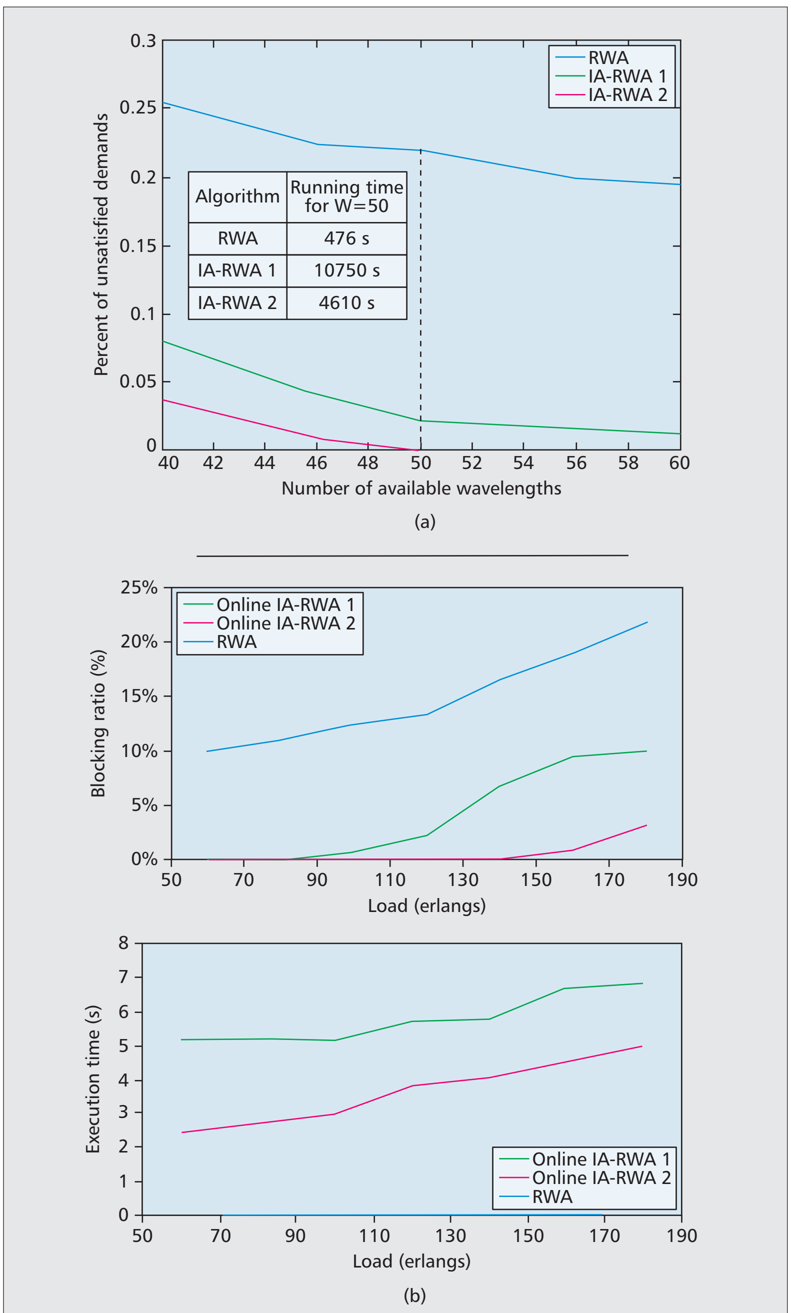


Figure 1. *a) Offline IA-RWA blocking ratio and running times as a function of the available wavelengths* W*; b) online IA-RWA blocking ratio and average execution time per connection in seconds presented as a function of the network load for a fixed number of wavelengths (*W = 20*).*

The goal of this article is to highlight the key features of the integrated DICONET solution via some of the achievements of the project. In the core of DICONET resides a set of cross-layer optimization algorithms designed to serve the network both during planning and operation. These algorithms are integrated in a common software platform, the DICONET Network Planning and Operation Tool (NPOT) [3], that considers the impact of physical-layer impairments (PLIs) on the decision making. The control plane effectively supports the DICONET networking solution through developed generalized multiprotocol label switching (GMPLS) protocol extensions, allowing the different entities to cooperate and run in an orchestrated manner. The project was completed with the implementation of the multilevel integrated solution in the DICONET testbed, practically realizing the vision for high end-to-end connectivity, dynamicity, and reliability.

The article is organized as follows. The following section gives an overview of the project by discussing the benefits of the DICONET solution. The remainder is dedicated to the main achievements that essentially enable the features of the solution, in turn including the NPOT, the developed cross-layer optimization modules, the control-plane-related developments, the testbed implementation, and the achieved capital resource optimization. The article concludes with some remarks about future research challenges.

Benefits

The DICONET project proposes a comprehensive solution that tackles issues in the planning or offline phase as well as the operation or online phase of an optical core network. The planning phase includes processes that are directly linked to the network capital. Transponders, monitors, and regenerators are costly equipment, whose associated capital and operational cost justifies the need for *resource optimization*. In the DICONET approach this challenge is addressed by dedicated resource optimization modules that minimize and efficiently allocate the available resources (i.e., monitor and regenerator placement) offline: impairment-aware routing and wavelength assignment — IA-RWA), exploiting the maximum transparent optical reach.

During operation, employing the dynamic and impairment-aware solution implies a situation where the network is *fully aware of the physical status* of its components and the QoT of the established connections. Optimum decision making is therefore achieved also during operation, utilizing intelligent online IA-RWA algorithms that serve the dynamic traffic. In addition, *dynamicity and high-performance end-to-end connectivity* strengthen the online operation as the lightpath provisioning is achieved in *low setup times*. Apart from the fast connection establishment the DICONET solution is capable of rapidly localizing potential physical failures and restoring the affected traffic, rendering the network intelligent and robust. Besides, operators always seek for Quality of Service (QoS) as it is an important revenue-generating attribute.

As a whole, DICONET is designed to work *independent of the scale* of the network topology as its tools are applicable to both core networks where regeneration of the optical signal is not necessary (transparent) and networks of bigger scale, where some strategically selected regeneration sites are required (translucent). Furthermore recognizing the importance of the *use of standardized protocols*, Generalized Multi-Protocol Label Switching (GMPLS) is adopted in the DICONET approach to control the transport plane. Indeed the control plane entities that run the optical transport employ the full GMPLS protocol suite, yet properly enhanced to support the PLIs. In what follows the main building blocks that induce these benefits are presented.

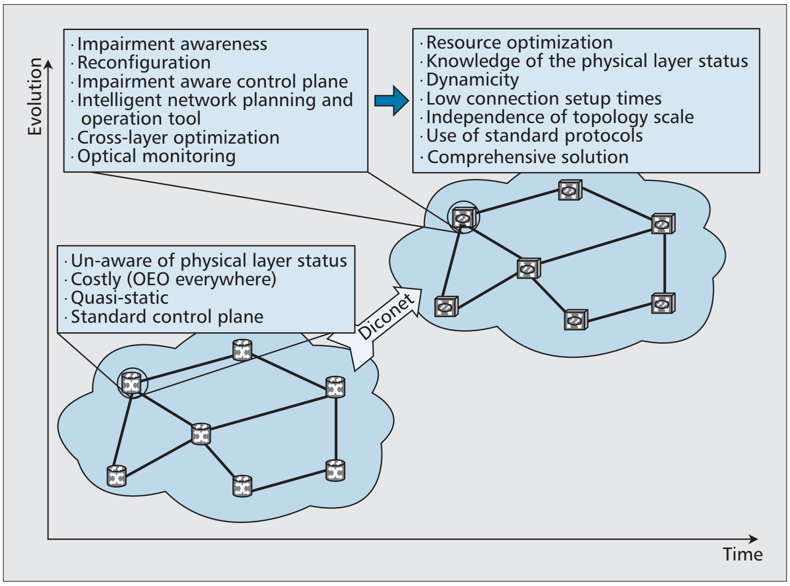


Figure 2. *Current core optical networks and DICONET.*

Network Planning and Operation Tool

The key innovation of DICONET is the design and development of NPOT that integrates in a common platform cross-layer algorithms that make use of physical-layer assessments, serving the network during planning and operation [3]. Following the development and testing of the various cross-layer techniques, the most suitable of each task was selected and all together were combined to act as the building blocks of NPOT. The most important of those are illustrated in the graphical representation in Fig. 2. The planning mode of NPOT consists of the Optical Monitor Placement, the Regenerator Placement and the offline IA-RWA modules, supporting the network manager before the actual network operation. In the operation mode the tool includes the online IA-RWA and the Failure Localization modules. The global network information, including the physical layer, the topology and the traffic parameters, populate two data repositories that are kept as external databases (Physical Parameters Database (PPD) and Traffic Engineering Database (TED)). All the input data are introduced to the two databases in a simple XML format.

In the core of the NPOT is situated a QoT estimator. The various components of the tool consult the QoT estimator to make physical-layer aware decisions. The RWA process, whether online or offline, uses the QoT estimator either as a quality metric during the routing and wavelength assignment process or after the routing and wavelength assignment has taken place to evaluate and validate the computed solution. In turn the regenerator and monitor placement algorithms invoke the QoT estimator in order to find the optimum location for these components. The QoT estimator utilizes the updated information stored in the databases to estimate in a single figure-of-merit (i.e. Q-factor) the quality of the signal travelling on a lightpath. It is noteworthy that the modular design of NPOT allows any of its building blocks to be upgraded or replaced by other algorithms in a seamless way.

Cross-Layer Optimization Modules

Network planning entails all the activities that are required to accommodate an initial traffic matrix with optimal resource allocation. The well-known problem of RWA constrained by the performance of the optical signal has received great attention from the research community [4]. IA-RWA refers to the process which given a set of demands, assigns a route and a wavelength to each of them always taking into account the physical impairments that degrade the QoT. During the planning phase, such an algorithm computes the routes and allocates the available resources –in this case the optical channels- for a static traffic in order to find the optimal strategy to accommodate it. This offline operation takes place before a network actually starts to operate.

Throughout the project the consortium dedicated significant effort to develop and study offline IA-RWA algorithms for transparent and translucent networks [5, 6]. Considering PLIs in offline RWA has a certain particularity, as it involves the joint assignment of routes and channels to the connection requests, and interference among the selected lightpaths is inevitable once the solution has been found. Extensive comparative simulations for transparent topologies were performed using the various offline IA-RWA algorithms under realistic network and traffic parameters, exploiting a common QoT estimator tool developed within the project [3]. Our experiments showed the applicability of these algorithms to real-scale experiments, as they demonstrated good performance characteristics

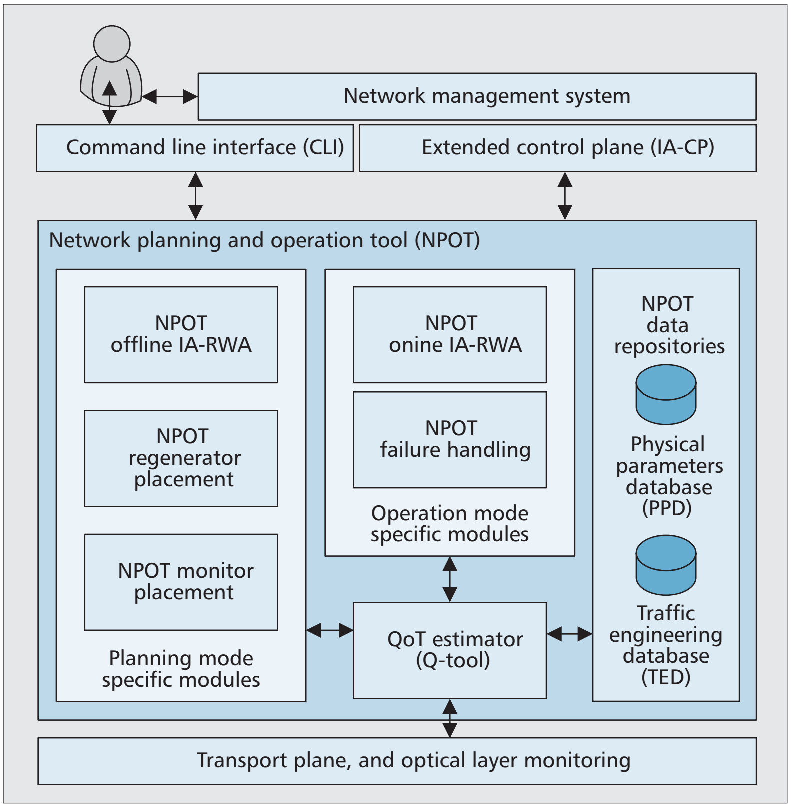


Figure 3. *Anatomy of DICONET network planning and operation tool.*

and implementation complexity, and relatively low execution times. Indicatively, we refer here to two of the developed impairment-aware algorithms and compare them with a standard k-shortest path RWA algorithm without physical-layer constraints in an effort to highlight the added value of impairment awareness. Figure 3a includes the blocking ratio of the three offline RWA algorithms with respect to the number of available wavelengths. The two IA-RWA algorithms use linear programming techniques and account for the interference among lightpaths in their formulation. The first algorithm (IA-RWA 1) takes the physical layer indirectly into account by limiting the impairment-generating sources. The second algorithm (IA-RWA 2) uses noise-variance-related parameters to directly account for the most important physical impairments [7]. The experiment used as reference topology the generic national backbone network of Deutsche Telekom (DT) and assumed a realistic traffic matrix corresponding to the yearly traffic of 2009 (2.8 Tb/s). Each traffic demand is assigned a channel at 10 Gb/s. The simulations of each algorithm were executed on a PC with Intel Core2 Duo at 3.GHz and 4 Gbytes RAM. Evidently the plain RWA cannot compete with the IA-RWA methods and yields very high blocking for the entire range of available channels.

In addition, offline RWA algorithms constrained by PLIs were also proposed for translucent networks, where regenerators are necessary in certain nodes to serve the traffic demands. Assuming a static traffic scenario with regenerators placed sparsely at certain a priori known locations, the solution consists of the routes and assigned wavelengths, and includes the decision of whether a connection will be served with or without the use of regenerators. In the former case also the sequence of regenerators is returned [6].

Before the RWA process, operators that employ the DICONET solution have additional cross-layer optimization tools at their disposal to support the planning phase. Regenerator and monitor placement refer to the modules developed to make optimized decisions on the number and location of the regenerating and monitoring equipment required in the network, by considering again the physical-layer performance [8]. This task has been specially focused on the regenerator placement techniques as those components imply significant capital and operational expenditures. Minimizing the particularly power-consuming opto-electronic interfaces of regenerators leads to the invaluable optimization of the total energy consumption of the network.

After the offline planning has been applied and the deployed network starts to operate, traffic demands may be requested or dropped in a dynamic fashion. Online IA-RWA algorithms specially designed for the operation phase process the new demands upon their arrival and one at a time, taking into consideration the current state of the network. Therefore, a new demand is served constrained by the traffic and physical-layer characteristics present at the time of arrival. The objective here is to assign routes and wavelengths to these dynamic demands taking PLIs into account, so as to satisfy their QoT requirements without disrupting the QoT of the already established connections. The time needed for making a connection assignment decision should be short so that the connection's establishment delay is also acceptably short. Similar to the offline case, we developed a number of online IA-RWA algorithms and performed simulation experiments to assess their performance under identical conditions and utilizing the same QoT estimator. Indicatively, Fig. 3b illustrates the capabilities of two multicost algorithms against a simple shortest-path-based that does not consider the QoT. In multicost routing, a vector of cost parameters is assigned to each link, from which the cost vectors of the paths are calculated. The first algorithm (online IA-RWA 1) utilizes cost vectors consisting of impairment-generating source parameters, so as to be generic and applicable to different physical settings. These parameters are combined into a scalar cost that indirectly evaluates the quality of candidate lightpaths. The second algorithm (online IA-RWA 2) uses specific physical-layer models to define noise variance-related cost parameters, so as to directly calculate the Q-factor of candidate lightpaths [9]. The comparison scenario assumed the DT reference topology and a dynamic input traffic. Connection requests (each requiring bandwidth equal to 10 Gb/s) are generated according to a Poisson process with rate $\lambda = 1$ (requests/time unit). The source and destination of a connection are uniformly chosen among the nodes of the network. The duration of a connection is given by an exponential random variable with average 1/μ (time units). Thus, λ/μ gives the total network load in Erlangs. In each experiment 2000 connection requests are generated. Figure 3b demonstrates two different performance metrics, blocking probability and execution time. Upon arrival of a traffic demand, fast response is essential together with accurate QoT-aware routing decisions. Moreover, an effort was made to develop IA-RWA algorithms for translucent networks. We proposed algorithms that jointly address the route, lightpath, and regenerator selection problems, attempting to minimize the usage of the available regenerators [10].

Another important building block of the overall networking solution is responsible for monitoring the network for failures and locating the exact link that needs to be recovered. Upon a failure, following the fault localization process, the network utilizes its reaction mechanisms and restores all affected traffic. The online IA-RWA module takes over to compute new lightpaths for the connections that have been disrupted. The result is a robust and reliable core network with guaranteed QoS. In the framework of the project, localization techniques for failures that cause complete interruption of a connection (e.g., fiber cut) or merely QoT degradation were developed and studied [11]. These techniques are fed with monitoring data from supervising devices (e.g., bit error rate [BER], power, or optical signal-to-noise ratio [OSNR] monitors) spread throughout the network that feed the restoration mechanisms.

Control Plane

Dynamic and impairment-aware networking relies heavily on a control plane enhanced with features that together with NPOT essentially enable the realization of this vision. Recently, the adoption of the GMPLS framework developed by the Internet Engineering Task Force (IETF) seems to prevail as the winning solution for the efficient control of an optical network. One of the main applications of GMPLS in the context of optical networks is the dynamic establishment and teardown of lightpaths. DICONET utilizes the GMPLS protocol set but is not limited to its standard capabilities. One of the key tasks of the project concerned the extension of the GMPLS protocols to carry physical-layer information [3]. Whenever a change in the physical-layer status occurs, it needs to be communicated to all responsible entities that have to take actions. The availability of this up-to-date information is essential so as to accurately evaluate the effect of PLIs and decide on the feasibility of a lightpath in the optical domain.

Various control plane architectures were evaluated for implementation in the dynamic and impairment-aware network, including centralized and distributed solutions. The centralized approach implies a central point of control accessible by all network entities and aware of the complete network topology, resource availability, and physical-layer information. In the distributed case all network entities are involved in the control plane signaling and routing processes, but are deprived of global data knowledge. Three distributed architectures were

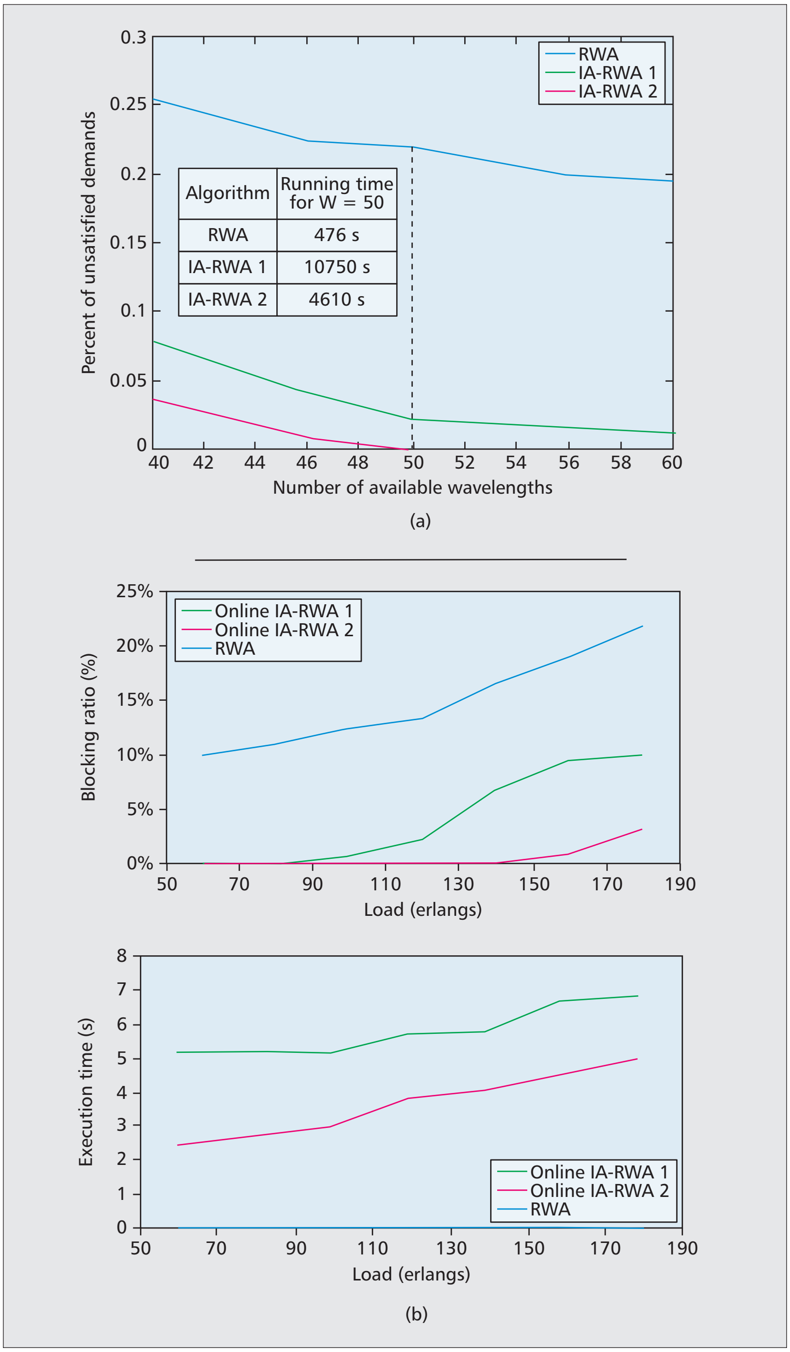
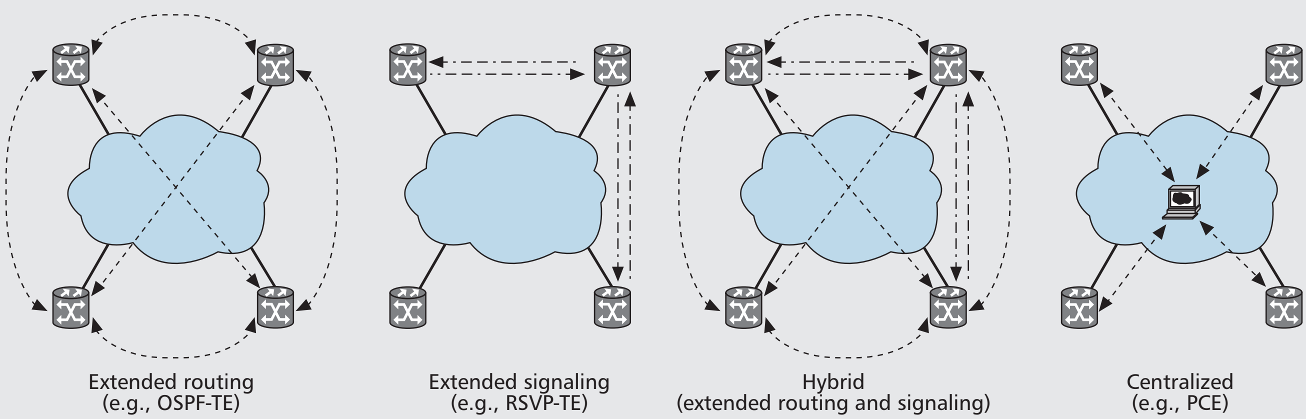


Figure 4. *a) Offline IA-RWA blocking ratio and running times as a function of the available wavelengths W; (b) online IA-RWA blocking ratio and average execution time per connection in seconds presented as a function of the network loa, for a fixed number of wavelengths (W = 20).*

considered: a signaling-based approach where the signaling component (i.e., Resource Reservation Protocol with Traffic Engineering extensions [RSVP-TE]) is extended to consider the PLI information, a routing-based approach where the routing component is extended (i.e., Open Shortest Path First with Traffic Engineering extensions [OSPF-TE]), and also a hybrid one that overcomes the limitations of the other two by extending both the routing and signaling protocols. The distributed approaches along with a centralized architecture that employs a path-computation-element-based (PCE-based)



Metrics	Routing based	Signaling based	Hybrid	Centralized
Blocking rate	Medium	High	Low	Low
Average number of attempts	Medium	High	Low	Low
LSP setup time	Medium	High	Low	Low
Path computation complexity	High	Low	Very high	Very high

Figure 5. *Qualitative assessment of the various control plane options.*

method underwent a qualitative comparison to explore the performance and applicability of the four options using performance and engineering metrics (Fig. 4).

Two control plane schemes were eventually selected to implement and test for the purposes of the project. The two schemes differ with respect to the role of the NPOT in the overall multiplane architecture; one is hereafter referred to as the centralized (PCE-based) and the other as hybrid/distributed. In the former the NPOT is an engine common to all optical communication controllers (OCCs). The set of OCCs essentially realize the control plane, and each of them runs the full GMPLS protocol suite: RSVP-TE, OSPF-TE and Link Management Protocol (LMP). Apart from extending the OSPF-TE to disseminate the PLI information, the novelty of this approach lies in the PCE which in collaboration with the NPOT forms the so-called enhanced PCE (E-PCE) that deals with all the path computation and provision related actions. *Path Computation Reply* message of the standard Path Computation Element Protocol (PCEP) is extended and two novel messages, namely the *Path Allocation Result* and the *Path Tear-down Result* are defined to match the requirements of the PCE-based approach [12]. The standard RSVP-TE is deployed to establish, maintain, and tear down connections.

In the latter architecture all the network nodes run their own instance of the NPOT and extended versions of OSPF-TE and RSVP-TE. OSPF-TE is extended to disseminate wavelength availability information, while RSVP-TE carries the PLIs information for the QoT feasibility check. Due to the distributed nature of this implementation, upon receiving a new connection request from the network management system (NMS) the lightpath computation and the QoT estimation processes take place in the local NPOTs of the source and destination nodes. Prior to final integration and validation of the DICONET concept, emulation experiments were conducted to explore the capabilities of both selected control plane architectures under dynamic conditions and traffic load.

Implementation, Testing and Demonstration

Following the development of the different pieces, all were eventually integrated in a multiplane testbed spanning from the transport to the management plane. Both the centralized and distributed architectures were implemented in the 14-node experimental testbed bearing 1 or 14 NPOTs respectively. Each of the 14 OCCs consists of three different modules: the link resource manager (LRM), routing controller (RC), and connection controller (CC). Briefly, the LRM is a module responsible for the management of the resources available at the optical node through the Connection Controller Interface (CCI), while the RC and CC implement OSPF-TE and RSVP-TE, respectively. The transport plane of the DICONET testbed represents the same 14-node topology, and bears both emulated and physical optical nodes. Specifically, three 2° reconfigurable OADMs (ROADMs) based on wavelength selective switching (WSS) technology were used. Each ROADM has been equipped with one optical performance monitor able to perform both optical power and OSNR measurements. The DICONET testbed is also equipped with an NMS which interfaces with the control and optical nodes and provides a graphical representation of the network that allows its manager to monitor the traffic or potential failures.

In [3] the testbed was used to experimentally

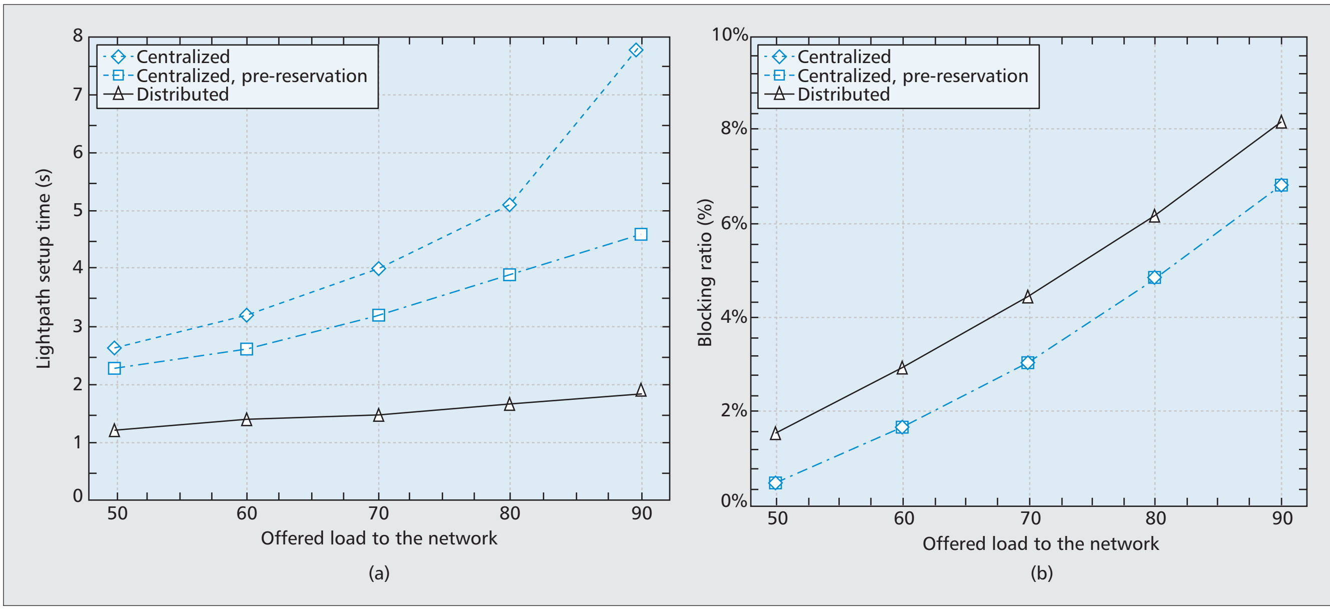


Figure 6. *a) Measured lightpath setup time of the two schemes for an operational scenario with the traffic load varying from 50–90 Erlangs; the setup time of the centralized approach is improved using an alternative strategy (square marks, dashed line) where the wavelengths are pre-reserved to avoid waiting for the OSPF-TE flooding; b) corresponding blocking ratio results of the two schemes.*

test the performance of the two architectures in a scenario with lightpath requests arriving and departing dynamically. It was demonstrated that the distributed scheme yields lower setup times in highly dynamic traffic conditions (Fig. 5a), benefiting from the parallel lightpath establishments. The centralized scheme, on the other hand, experiences better blocking ratio justified by the sophisticated impairment-aware routing process it employs (Fig. 5b). The centralized nature of this architecture allows the routing engine to have a complete picture of the physical layer and traffic conditions, yet only one connection request may be served at a time, thus affecting the connection setup times.

In these initial NPOT implementations, a guard time was left between two consecutive route computations, leaving enough time for the GMPLS OSPF-TE protocol to disseminate the new PLI and wavelength availability information in order to update the PPD and TED databases. This forces the NPOT to remain idle some seconds between route computations (i.e., the OSPF-TE flooding time), which affects the overall lightpath setup times.

In this article we implemented an alternative strategy to improve the lightpath setup time for the centralized scheme. Specifically, once a lightpath is selected, the involved wavelength is directly pre-reserved in order to avoid its usage in upcoming lightpath requests; this eliminates the waiting time for the OSPF-TE flooding. The state of the pre-reserved resources can be changed to "reserved" or "free" based on the information of the OSPF-TE updates. By applying this strategy, as shown in Fig. 5a, the lightpath setup time is significantly reduced, particularly for high offered load. In addition the centralized scheme with the pre-reservation strategy maintains the same low blocking ratio as depicted in Fig. 5b.

There have been various other research efforts that also employ an impairment-enabled control plane, focused on either centralized [13, 14] or distributed approaches [15]. Table 1 reports the lightpath setup time reported in some of these works to highlight the potential of the DICONET architecture which not only utilizes algorithms that incur low blocking ratio but also manages to achieve low setup times; lower than 5 s are achieved in the centralized case and lower than 2 s in the distributed case for all traffic scenarios.

Reference	Description	Lightpath Setup Time
T. Tsuritani *et al.* [13]	Centralized PCE-based approach	Within 10 s
F. Cugini *et al.* [14]	Centralized PCE-based approach	Within 10 s
R. Martinez *et al.* [15]	Distributed approach	8–9 s

Table 1. *Relevant works.*

In addition to the dynamicity offered by the integrated solution, DICONET enables continuous and robust operation by properly reacting to potential failures and restoring the affected traffic in a transparent fashion. In the effort to evaluate these capabilities we utilized the centralized configuration in a scenario where failures occur randomly throughout the network. The network was loaded with a set of predetermined active lightpaths, and then independent failures were caused by emulating link cuts in random locations. The results showed fast restoration times, despite the sequential processing of the disrupted lightpaths due to the centralized architecture. Indeed, it was shown in [16] that 72 percent of the lightpath restorations were performed in less than 5 s.

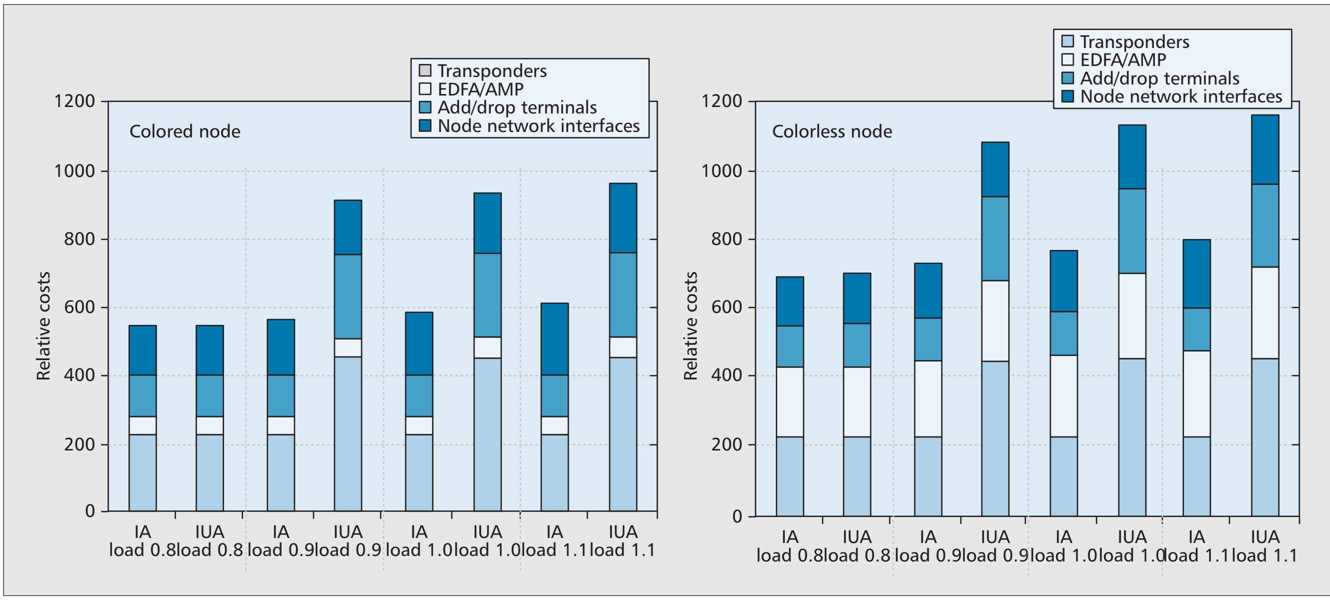


Figure 7. *CapEx of IA vs. IUA for two different types of node architectures, a colored and a colorless one.*

CAPITAL RESOURCE OPTIMIZATION

In addition to having strong technical features, it is essential for any venture requiring investment to be coupled by a viable business case that highlights the advantages over other existing methods. Intelligent RWA, optimized component placement, failure localization and resilience, all integrated in a unified control plane, provide the network with an extended level of optimization. Indeed the networking solution that DICONET proposes is realized through a set of resource optimization algorithms that also introduce a cost benefit. The cost benefit that is gained with the DICONET solution was studied and quantified, focusing on the concepts of impairment awareness and reconfiguration ability.

The DICONET RWA algorithms were utilized to define the required network resources and compare an impairment-aware solution to an impairment-unaware solution in financial terms. Furthermore, in the analysis different commercially available reconfigurable node architectures were considered since R-OXCs account for a large fraction of the capital cost of the transport plane. Each type of R-OXC bears a different degree of flexibility in their add/drop capabilities (bearing or not the features directionless, colorless, contentionless) and therefore impact in a different way the network planning [17]. The capital and operational cost associated with each type is essentially determined by its physical implementation.

The analysis covered scenarios with transparent and translucent topologies [18], and utilized the offline IA-RWA and pure RWA algorithms developed in the project to estimate the cost of the required components (i.e., amplifiers, add/drop terminals, transponders, network interfaces, regenerators) of each planning solution and each node architecture. Figure 6 illustrates results indicative of this analysis. In particular, it corresponds to the capital cost estimations of a transparent network for both cases — impairment-aware (IA) and impairment unaware (IUA) — with respect to the traffic load. Evidently, the IUA solution lacks the optimization capabilities of a QoT-aware process and requires additional capital investment sooner than the IA solution as the traffic increases. For the same topology a comparison between a colorless (Fig. 7, right) and a colored (Fig. 7, left) node is presented. Colorless add/drop ports, unlike colored add/drop ports, do not have permanently assigned channels. This feature leads to higher capital expenditures for the case of the more flexible architecture (colorless) that are dominated by the number of add/drop terminals. Nevertheless, in the presence of dynamic traffic, deploying a flexible node facilitates online connection provisioning and minimizes manual interventions. Overall, the techno-economic analysis gave promising indications for the feasibility of the DICONET solution in commercial networks.

CONCLUSION

Extensive simulations, emulations, and experiments shaped DICONET to bear all the attributes the consortium sought after to fulfill the vision of dynamic and impairment-aware networking that maximizes the utilization of the existing WDM infrastructure. More than an architectural enhancement, DICONET empowers operators with useful tools applicable to both the planning and operational phases of a core optical network that is either transparent or translucent with features not limited to the control and management planes but that actually take advantage of the optical layer in an integrated cross-layer manner. Resource optimization, dynamicity, and resilience outline a network that offers not only quality of service but also cost effectiveness.

DICONET effectively utilizes today's technologies to optimize the network and paves the way for a smooth migration to the next generation core. Driven by technological evolution, the future core network is going to enjoy an increased degree of dynamicity with higher bit rates, mixed transmission characteristics, and gridless network components. To also achieve resource optimization in the future flexible networks, issues such as the evaluation of signals with advanced transmission parameters and dynamic bandwidth allocation ought to be investigated.

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