A Dynamic Impairment-Aware Networking Solution for Transparent Mesh Optical Networks

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ABSTRACT

Core networks of the future will have a translucent and eventually transparent optical structure. Ultra-high-speed end-to-end connectivity with high quality of service and high reliability will be realized through the exploitation of optimized protocols and lightpath routing algorithms. These algorithms will complement a flexible control and management plane integrated in the proposed solution. Physical layer impairments and optical performance are monitored and incorporated in impairment-aware lightpath routing algorithms. These algorithms will be integrated into a novel dynamic network planning tool that will consider dynamic traffic characteristics, a reconfigurable optical layer, and varying physical impairment and component characteristics. The network planning tool along with extended control planes will make it possible to realize the vision of optical transparency. This article presents a novel framework that addresses dynamic cross-layer network planning and optimization while considering the development of a future transport network infrastructure.

INTRODUCTION

Increasing traffic volume due to the introduction of emerging broadband services and bandwidth demanding applications with different quality of service (QoS) requirements are driving carriers to search for a cost-effective core optical networking architecture that is tailored to the new Internet traffic characteristics. The optical network evolution and migration should aim at improved cost economics, reduced operations efforts, scalability, and adaptation to future services and application requirements. The main drivers for this migration are:

- Requirement for high bandwidth and end-to-end QoS-guaranteed connectivity
- On demand (dynamic) technology-independent service provisioning

Optical network architectures can be characterized as either opaque, managed-reach, or all-optical (or transparent) networks (Fig. 1). In opaque architectures the optical signal carrying traffic undergoes an optical-electronic-optical (OEO) conversion at every switching or routing node in the network. The OEO conversion enables the optical signal to reach long distances; however, this is quite expensive due to the number of regenerators required in the network and the dependence of conversion process on the connection bit rate and modulation formats. Transparent network architectures were proposed to reduce the associated cost of opaque networks. In transparent networks the signals are transported end-to-end optically, without any OEO conversions along their path. In extended networks physical signal impairments limit the transparent reach distance, and in order to regenerate signal in the optical domain, all-optical regenerators are required, but are not commercially available today. Managed reach (semi-transparent, translucent, or optical-bypass) has been proposed as a compromise between opaque and transparent networks [1]. In this approach selective regeneration is used at specific network

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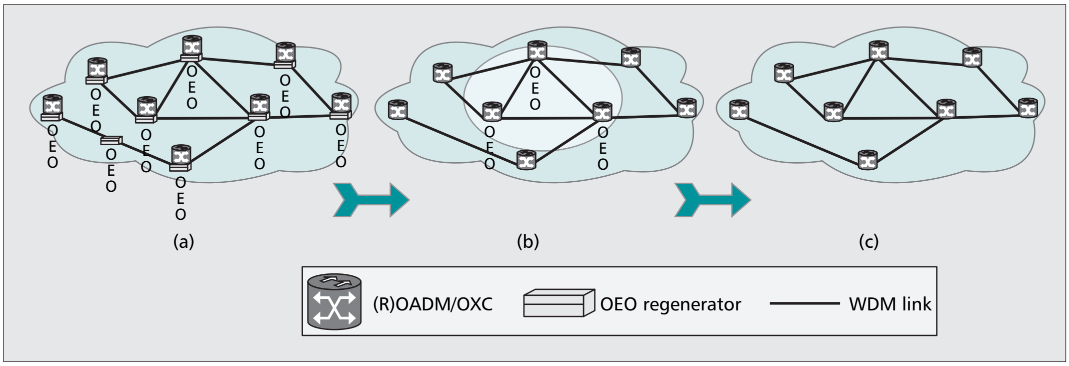


■ **Figure 1.** *Optical networks evolution: a) opaque everywhere; b) managed reach; c) all-optical.*

The placement of monitoring equipment to reduce the number of redundant alarms and to lower the capital expenses, and the design of fast localization algorithms are among challenges of fault localization in transparent optical networks.

locations in order to maintain the acceptable signal quality from source to destination.

All-optical core wavelength-division multiplexing (WDM) networks using reconfigurable optical add/drop multiplexers (ROADMs) and tunable lasers appear to be on the road toward widespread deployment and could evolve to all-optical mesh networks based on optical cross-connects (OXCs) in the future. In order to realize the vision of transparency while offering efficient resource utilization and strict QoS guarantees based on certain service level agreements, the core network should efficiently provide high capacity, fast and flexible provisioning of links, high reliability, and intelligent control and management functionalities. A very important aspect is also a high degree of performance management at the transparent intermediate nodes to enable fault localization in the case of a performance degradation of the optical channel.

The issues of core optical network planning and operation have been recognized within the Dynamic Impairment Constraint Networking for Transparent Mesh Optical Networks (DICONET) project. The DICONET project is funded by the ICT program, European Commission, and contributes to the strategic objective "The Network of the Future" by supporting innovative networking solutions and technologies for intelligent and transparent optical networks. In this article the existing static network planning procedures are extended toward equivalent ones for a flexible and dynamic networking paradigm. After introducing the main challenges involved in transparent optical networks, the DICONET vision and objectives are presented including physical layer modeling, optical performance and impairment monitoring schemes, impairment-aware path computation, failure localization, and control plane extensions.

Transparent Optical Network Challenges

Optical transparency has an impact on network design, by either putting some limits on the size of WDM transparent domains in order to neglect physical impact on quality of transmission (QoT) or introducing physical considerations in the network planning process (e.g., extra rules for WDM systems or performance monitoring). The realization of dynamic and fully automated transparent optical core networks is an important task that is required in order to provide cost (capital and operating expenditures, CAPEX and OPEX) reduction and performance benefits. This goal has not yet been achieved in commercial exploitation due to:

- Limited system reach and overall transparent optical network performance
- Difficulties related to fault localization and isolation in transparent optical networks

In transparent optical networks, as the signal propagates in a transparent way, it experiences the impact of a variety of quality degrading phenomena that are introduced by different types of signal distortions. These impairments accumulate along the path, and limit the system reach and overall network performance. There are distortions of almost "deterministic" type related only to the pulse stream of a single channel, such as self-phase modulation (SPM), group velocity dispersion (GVD), or optical filtering. The other category includes degradations having a statistical nature such as amplified spontaneous emission (ASE) noise, WDM nonlinearities (four-wave mixing [FWM] and cross-phase modulation [XPM]), polarization mode dispersion (PMD), and crosstalk (XT).

In a transparent optical network, the impact of failures also propagates through the network and therefore cannot be easily localized and isolated. The huge amount of information transported in optical networks makes rapid fault localization and isolation a crucial requirement for providing guaranteed QoS and bounded unavailability times. The identification and location of failures in transparent optical networks is complex due to three factors:

- Fault propagation
- Lack of digital information
- Large processing effort

The placement of monitoring equipment to reduce the number of redundant alarms and lower the CAPEX, and the design of fast localization algorithms are among challenges of fault localization in transparent optical networks.

DICONET Solution

The most commonly adopted approach to overcome the mentioned issues is utilization of optoelectronic regenerators on a per channel basis on all (opaque architecture) or selected (managed-reach) optical nodes. A second approach

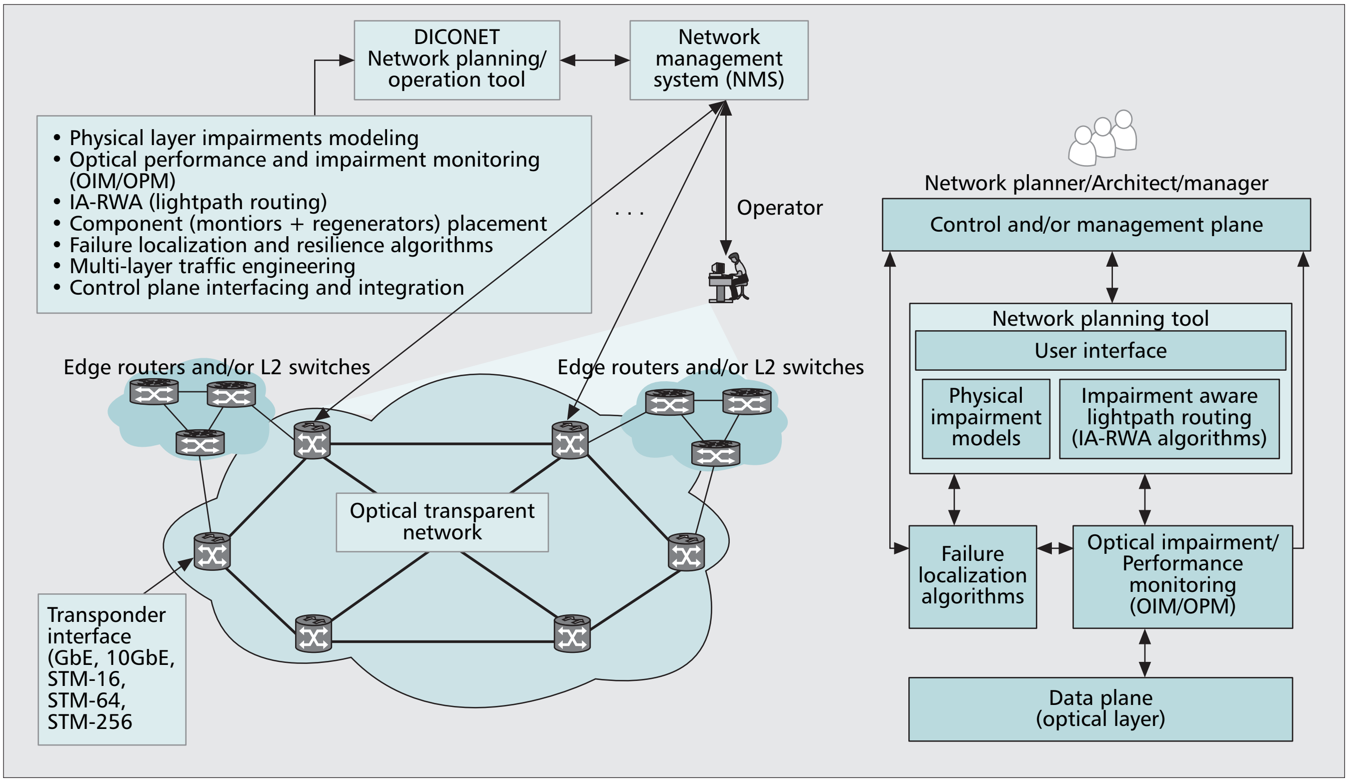


Figure 2. *The DICONET solution: a) the DICONET vision; b) the DICONET network planning/operation tool.*

uses impairment management techniques that may be implemented optically (i.e., optical means of impairment mitigation or compensation) or electronically at the optical transponder interfaces (i.e., electronic impairment mitigation). In addition, specific routing and wavelength aassignment (RWA) algorithms are used for lightpath routing while accounting for the physical characteristics of lightpaths. We categorize this class of algorithms as impairment-aware RWA (IA-RWA) algorithms. The vision of the DICONET project (Fig. 2a) is that intelligence in core optical networks should not be limited to the functionalities that are positioned in the management and control plane of the network, but should be extended to the data plane on the optical layer.

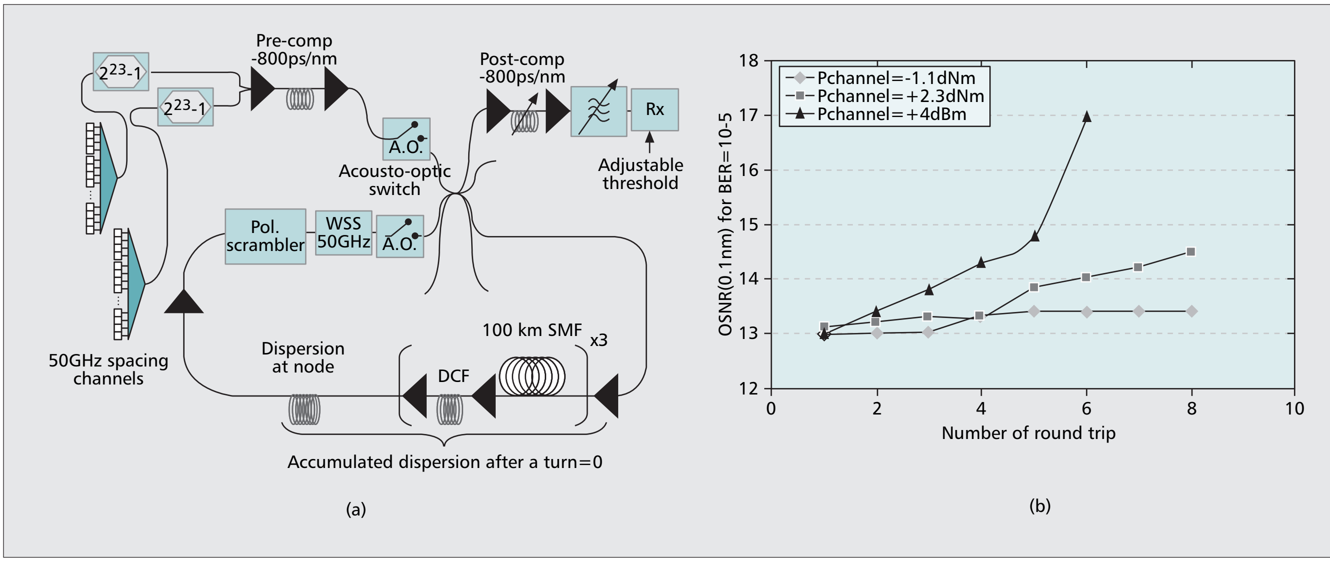
The key innovation of DICONET is the development of a dynamic network planning tool residing in the core network nodes that incorporates real-time assessments of optical layer performance into IA-RWA algorithms and is integrated into a unified control plane. In order to realize the DICONET vision, several building blocks should be considered in an orchestrated fashion, which are briefly presented in the sequel.

Physical Layer Modeling and Monitoring

In order to realize the IA-RWA algorithms covered later in this section, physical impairments should be carefully identified and modeled. Physical layer impairments may be classified as linear and nonlinear. Linear impairments are independent of the signal power and affect each of the optical channels (wavelengths) individually, while nonlinear effects scale with optical power levels and produce interdependencies of channels.

The important linear impairments that should be modeled and monitored are ASE, chromatic dispersion (CD)/GVD, XT, filter cconcatenation (FC), and PMD. Although also originating from transmitter laser diodes, ASE noise is principally brought by Erbium doped fiber amplifiers (EDFAs) and degrades the optical-to-signal-noise ratio (OSNR). CD or GVD is the impairment due to which different spectral components of a pulse (frequencies of light) travel at different velocities. When uncompensated, CD limits the maximum transmission reach and channel bit rate. The effect of CD can be minimized using dispersion compensation devices like dispersion compensating fibers (DCFs), chirped fiber gratings (CFGs), or periodic filter devices (Gires-Tournois interferometers, etc.). XT (interchannel and intrachannel) is the general term given to the phenomenon by which signals from adjacent wavelengths leak and interfere with the signal in the actual wavelength channel. FC is produced by signal propagation through multiple WDM filters between source and destination, and results mainly in the narrowing down the overall filter pass-band. Finally, PMD manifests itself in a difference of propagation velocities between orthogonal polarizations (differential group delay [DGD]), resulting in a broadening of the signal pulses. The DGD is a statistical parameter and evolves over time due to changes in stress and temperature conditions on the optical fibers.

There are two categories of nonlinear effects. The first arises due to the interaction of lightwaves with phonons (molecular vibrations) in the silica medium. The two main effects in this category are sstimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS).



■ **Figure 3.** *Experimental setup and results: a) experimental testbed layout; b) measured OSNR vs. number of loops for several channels' power.*

The second set of nonlinear effects arises due to the dependence of the refractive index on the intensity of the applied electric field, which in turn is proportional to the square of the field amplitude. The effects in this category are SPM, XPM, and FWM. References [2, 3] provide good overall starting points.

For IA-RWA algorithms it is very important to be able to accurately predict the performance of the propagating channel considering all the impairments that can degrade the signal quality along the propagation. To establish an accurate analytical model for our performance estimator considering these impairments, an experimental testbed that emulates a transparent mesh optical network [4] will be used. It includes a recirculating loop with standard single mode fiber (SSMF), LEAF fibers, and nodes with wavelength selective switching (WSS). In Fig. 3a the section comprising SSMFs and WSS is displayed. With this testbed it is possible to propagate the channels several spans of SSMFs pass through a node. This scenario can be repeated several times before assessing the quality of the signal at the reception side. For this setup 21 channels were propagating, and we measured the central channel (1550.12 nm). The bit rate was 10.709 GHz and the modulation format was non-return to zero (NRZ). Odd and even channels are modulated by two modulators. Total power at the input of the DCF was 10 dBm. Polarization of odd and even channels is not controlled. Channel power at the input of each span is precisely monitored. Figure 3b depicts the measurement results for required OSNR for BER = 10^{-5} as a function of distance and channel power. Number of channels and EDFA output power have been kept constant.

In addition to analytical and simulation techniques for modeling these impairments, monitoring techniques are required for measurements, which finally enable the IA-RWA mechanism. The monitoring could be implemented on the impairment level (optical impairment monitoring [OIM]) or at the aggregate level where the overall performance is monitored (optical performance monitoring [OPM]) [4].

The development of a physical layer modeling and monitoring scheme will provide the intelligence to the DICONET platform to:

- Implement novel impairment-aware lightpath routing (i.e., IA-RWA) schemes
- Implement failure localization methods of single and multiple failures in transparent optical networks
- Construct and control complex network topologies while maintaining a high QoS and fulfillment of service level agreements

Impairment-Aware Lightpath Routing

Besides routing a path from source to destination, in optical networks the wavelength of the path should also be determined. The resulting problem is referred to in literature as the RWA problem, which is known to be NP-complete [5].

In most RWA proposals the optical layer is considered a perfect medium; therefore, all outcomes of the RWA algorithms are considered valid and feasible even though the performance might be unacceptable. The incorporation of physical impairments in transparent optical network planning problems has recently received some attention from the research communities. We can classify impairment-aware algorithms into two main categories:

- Those that consider separately the RWA problem and the effects of impairments
- Those that solve the RWA problem including impairment constraints in the problem formulation

In the literature several variations to the first case have been proposed. In the DICONET project, apart from this approach, we also plan to examine the feasibility and applicability of algorithms belonging to the second case that jointly consider the RWA problem and the impairment constraints. The objective of the corresponding joint optimization problem would be not only to serve the connection requests using the available wavelengths, but also to minimize the total accu-

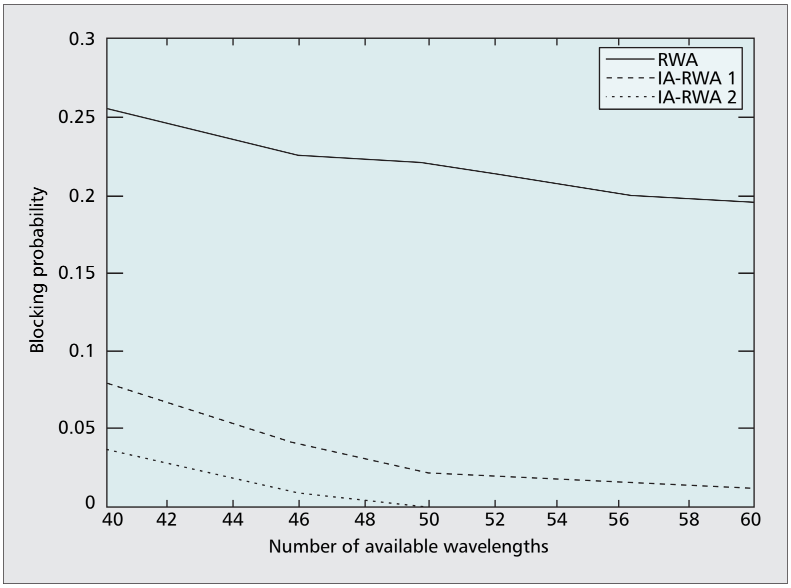


Figure 4. *Blocking probability vs. number of available wavelengths per link, for Deutsche Telekom reference network and realistic traffic demand.*

mulated signal degradation on the selected lightpaths.

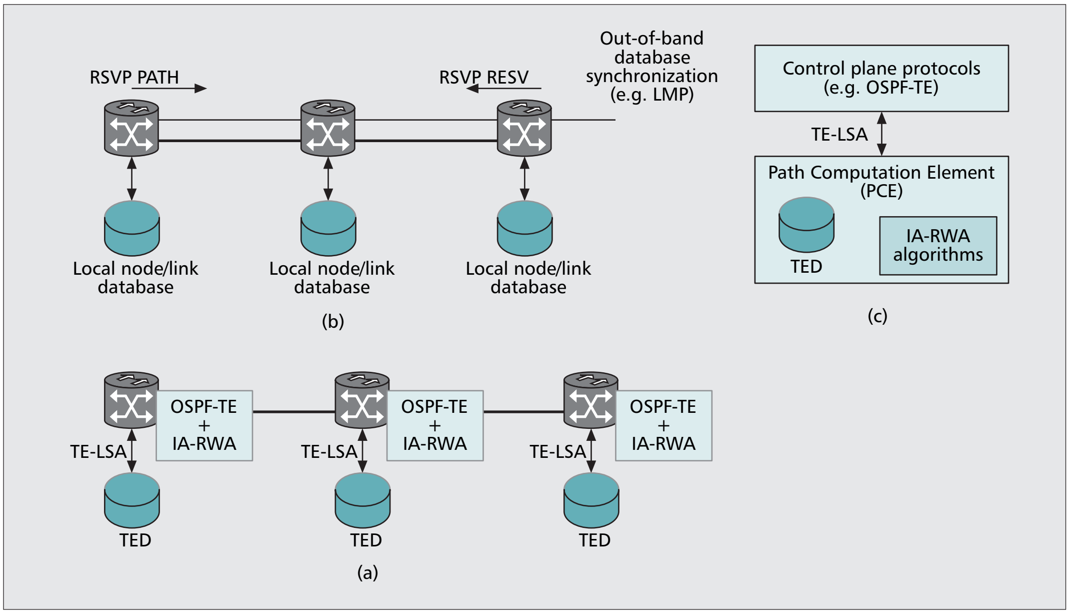
The IA-RWA algorithms can also be classified as static and dynamic depending on whether or not the impairments and overall network conditions are assumed to be time-dependent. Physical impairments may vary over time (i.e., dynamic network conditions) and thus change the actual physical topology characteristics. In the static traffic case (aka offline) the optimization of all connection requests can be performed, while in the dynamic case (aka online), the optimization of a single request has to be considered. Offline RWA is known to be NP-complete. Making these algorithms impairment-aware (IA-RWA) is even more difficult; thus, various heuristics have been proposed in the literature. However, the offline algorithmic approaches proposed fail to formulate the interference among lightpaths. Moreover, when considering online traffic, the great majority of algorithms proposed in the literature only consider static network conditions (time invariant impairments). IA-RWA algorithms in the DICONET proposal try to address further possible scenarios. In particular, the formulation of the interference among lightpaths in offline RWA is a significant problem from a theoretical and practical perspective that will be carried within the scope of DICONET. Regarding the offline problem, in Fig. 4 the performance of two impairment-aware algorithms (IA-RWA-1 and IA-RWA-2) based on LP relaxation formulations that model the interference among lightpaths as additional constraints on RWA is compared to a typical algorithm that solves the pure RWA problem and considers impairments only in the post-processing phase. The network topology used was the DT optical network, using a realistic traffic scenario, and 10 Gb/s wavelengths. For assessing the feasibility of lightpaths we used a Q factor estimator that takes into account all the most known impairments through detailed analytical models. The Q factor estimator takes as input the lightpaths found by the algorithms, calculates the Q factor of all active lightpaths, and returns how many of them have unacceptable transmission quality. This graph shows that considering the impairments in RWA decisions leads to better performance than an impairment-unaware approach. Also, the case in which dynamic traffic demands may induce a different impairment behavior is the most realistic situation for the dynamic network paradigm envisioned by the DICONET project. For this scenario, apart from typical scalar algorithms, we plan to examine multicost algorithms. In the multicost case the cost of a link is a vector, not a single cost value, with entries corresponding to individual impairments (or a combination of impairments). The real "cost" (in €, $, …) of a path is also another important optimization parameter for the IA-RWA algorithms.

Failure Localization

Failure management is one of the crucial functions and a prerequisite for protection and restoration schemes. All-optical components are not by design able to comprehend signal modulation and coding; therefore, intermediate switching nodes are unable to regenerate data for all channels, making segment-by-segment testing of communication links more challenging. As a direct consequence, failure detection and localization using existing integrity test methods are made more difficult.

In the DICONET framework an algorithm that solves the multiple failures location problem in transparent optical networks is proposed where the failures are more deleterious and affect longer distances. The proposed solution also covers the non-ideal scenario, where lost and/or false alarms may exist. Although the problem of locating multiple faults has been shown to be NP-complete, even in the ideal scenario where no lost or false alarms exist, the proposed algorithm keeps most of its complexity in a precomputational phase. Hence, the algorithm only deals with traversing a binary tree when alarms are issued. This algorithm locates the failures based on received alarms and the failure propagation properties, which differ with the type of failure and the kind of device that are in the network. Another algorithm has been proposed to correlate multiple security failures locally at any node and discover their tracks through the network. To identify the origin and nature of the detected performance degradation, the algorithm requires up-to-date connection and monitoring information of any established lightpath, on the input and output side of each node in the network. This algorithm mainly runs a localization procedure, which will be initiated at the downstream node that first detects serious performance degradation at an arbitrary lightpath on its output side. Once the origins of the detected failures have been localized, the network management system can then make accurate decisions to achieve finer-grained recovery switching actions.

In cases where efficient use of network capacity is important and restoration times on the order of hundred(s) of milliseconds are acceptable, shared protection schemes are desirable. However, as reported in [6], the CAPEX gain of shared path protection compared to dedicated path protection is much less in transparent opti-



■ **Figure 5.** *Control plane extensions: a) routing protocol extensions; b) signaling protocol extensions; c) path computation element.*

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cal networks than the same metric in opaque optical networks. Considering the dynamic network condition in IA-RWA algorithms and control plane integration make the fast response time (50 ~ 100 ms) of the network operation tool a key requirement for addressing the failure recovery and resilience issues. Thus, dedicated 1 + 1 protection, with one primary (i.e., working) path and one backup (hot standby path), is clearly a good protection candidate. Two reference networks, the Deutsche Telekom (DT) national network and pan-European research network (GEANT2), are selected for different studies. Based on the characteristics of the DICONET reference networks, we computed the link and node disjoint shortest paths considering physical layer impairments. On average, the protection paths for the DT network and GEANT2 reference network are 46 and 37 percent longer than their respective primary paths. We also observed that the average hop count for primary and protection paths for both reference networks (DT and GEANT2) are 46 and 30 percent more than the hop counts of the working paths, respectively.

Network Planning Tool

The key innovation of DICONET is the development of a dynamic network planning tool residing in the core network nodes that incorporates real-time measurements of optical layer performance into IA-RWA algorithms and is integrated into a unified control plane. As depicted in Fig. 2b, this tool will integrate advanced physical layer models with novel IA-RWA algorithms. It will serve as an integrated framework that considers both physical layer parameters and networking aspects, and will optimize automated connection provisioning in transparent optical networks.

The network planning tool has two operational modes:
- Offline mode
- Online (or real-time) mode

The offline mode is selected in the planning phase of a network. In this phase a full map of network traffic and network conditions is fed into the tool in order to produce the planning outcomes. Since offline computation time is not the main issue, optimization routines are allowed to have high numerical complexity. The gained results can be disseminated to the network management system, controlled by an operator. For online use of the network planning tool, an online traffic engineering solution is required utilizing an interface between the control plane and the management plane so that the network situation could be evaluated in real time and its results periodically disseminated into the network. In online mode this dynamic network planning tool can be used to support optimum network operation and engineering under dynamically changing traffic and physical network conditions.

Control Plane Extensions

In order to realize an impairment-aware control plane (impairment-aware light path routing, topology and resource discovery, path computation, and signaling), existing protocols should be extended properly. The extended control plane will in turn address traffic engineering, resiliency, and QoS issues, and support automated and rapid optical layer reconfiguration. The generalized multiprotocol label switching (GMPLS) protocol suite [7] has gained significant momentum as a candidate for a unified control plane [8]. Figure 5 shows three proposals to address the integration of physical layer impairments into the GMPLS control plane.

One direction deals with enhancement to the interior gateway routing protocol (IGRP) (e.g., Open Shortest Path First with Traffic Engineering [OSPF-TE]), as shown in Fig. 5a. By flooding link state advertisements (LSAs) enhanced with physical layer information, all nodes populate their traffic engineering database (TED)

Using the information of the global topology stored in the TED, the PCE constructs a reduced topology of the network, based on which the IA-RWA algorithms proceed to the path computation taking into account the physical layer parameters.

with network-wide information, which can provide updated and accurate inputs to the IA-RWA algorithms. For a connection request, the source node can interact with the TED to compute a proper route, taking into account the physical layer information by using the IA-RWA algorithms. Standard Resource Reservation Protocol with Traffic Engineering (RSVP-TE) is used for lightpath establishment. We call this approach the routing-based optical control plane (R-OCP). This approach has some issues:

- TED inconsistency, scalability, and stability when the link information changes very frequently [9]
- Requiring a powerful CPU at each node and taking more time to solve the multiconstraint routing problem since not only the network layer but also the physical layer must be considered at the same time
- Difficulty in selecting unified mathematical models for computing the effects of physical impairments since some of these models are based on measurements and empirical formulations

In the second approach, GMPLS signaling (e.g., RSVP-TE) is extended to include physical impairments information, as shown in Fig. 5b. Routes from source to destination are dynamically computed using standard routing protocols (e.g., OSPF-TE) without knowledge of the optical layer impairments. Only during the signaling process does the enhanced RSVP-TE protocol compute the amount of impairments along the route; based on the results, the lightpath setup request can be either accepted or rejected. Following this approach a local database in each node (e.g., OXCs or ROADM) is required to store the physical parameters that characterize the node and its connected links without requiring full knowledge of physical layer information of the whole network. We call this approach the signaling-based optical control plane (S-OCP). This approach can handle frequent changes of optical parameters, and does not require global flooding of physical impairments information, thereby minimizing scalability problems. Due to the lack of complex path computation algorithms, the load on the nodes' CPUs is minimized. The main drawbacks of this approach are longer path setup time due to the increased number of setup attempts and possible suboptimal route decisions due to impairment-unaware route computation algorithms.

In order to address the scalability requirements while maintaining TE support, path computation element (PCE) architecture is also considered, as shown in Fig. 5c. The PCE can reside within or external to a network node in order to provide an optimal lightpath and interact with the control plane for establishment of the proposed path. The PCE could represent a local autonomous domain (AD) that acts as a protocol listener to the intradomain routing protocols (e.g., OSPF-TE). Using the information on global topology stored in the TED, the PCE constructs a reduced topology of the network, based on which the IA-RWA algorithms proceed to path computation taking into account the physical layer parameters.

The DICONET control plane uses extended GMPLS to facilitate IA-RWA and fault localization, which makes the software stack even more complex than in standard GMPLS implementations. Therefore, to improve performance of the control plane, DICONET will undertake a hardware implementation of some control protocol procedures. The DICONET control plane is implemented in reconfigurable hardware: field programmable gate array (FPGA) and network processors (NPs). To overcome complexity of the control plane stack, only time-critical procedures of the DICONET control protocols are implemented in the FPGA and NPs in the form of a control protocol hardware accelerator.

The main control plane aspects addressed by the DICONET relate to:

- Multilayer network control
- Routing and signaling-related mechanisms and physical network characteristics information dissemination
- Design and implementation of a hardware accelerator for impairment-aware forwarding and path selection

We have conducted preliminary studies on the S-OCP and R-OCP approaches dealing with static network conditions and dynamic traffic where only linear impairments (loss, ASE, CD, PMD, and XT) are considered; the mathematical models can be found in [9].

In the S-OCP approach, for a connection request, the source node computes *K* explicit routes. The signaling process starts checking the optical feasibility of the first explicit route by sending out a PATH message containing signal properties information and a list of available transmitters/wavelengths along the route. Upon reception of the PATH message, each intermediate node updates these fields and checks the wavelength availability. If there is no free wavelength on its outgoing link, the node sends a PATH_ERR message toward the source node. If the destination node receives the PATH message, it will evaluate the impairments, and check for optical feasibility and a suitable transponder for the connection request. If path establishment is feasible, the destination node sends an RESV message along the first explicit route to the source node with a selected transponder pair; otherwise, the destination node sends back a PATH_ERR message. If the source node receives a PATH_ERR message, it will send the PATH message on the second explicit route and repeat the process for the next route out of all *K* routes.

In the R-OCP approach the source node will compute *K* routes through the IA-RWA algorithm, which takes into account wavelength availability as well as physical impairments. Once the source node receives the specific wavelength availability information per link, it can compute the optical feasibility through its physical layer module implementing the equations described in [9]. The optically feasible computed path would then be set up through standard RSVP-TE selecting one of the available wavelengths according to a First-Fit policy.

AT&T and Daisy networks (Figs. 6a and 6b) have been used to evaluate the performance of the S-OCP and R-OCP architectures. The maximum length of a Daisy network is 80 km. The

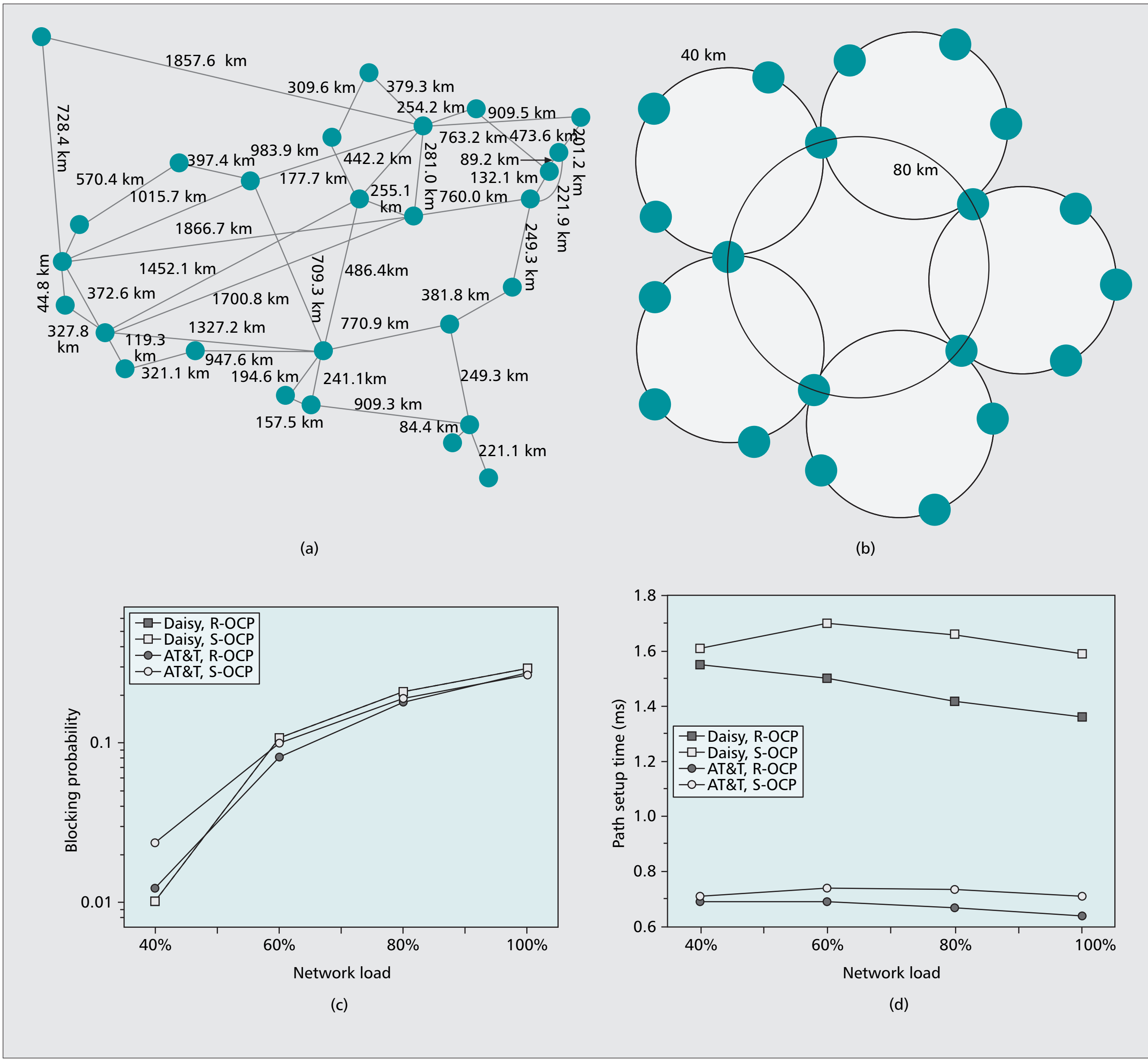

Figure 6. *Network topologies and blocking probability and path setup time performance: a) AT&T network topology; b) Daisy network topology; c) blocking probability vs. network load for Daisy and AT&T networks; d) path setup time vs. network load for Daisy and AT&T networks.*

AT&T topology has been scaled down by a factor of 1:23. The purpose is to avoid in-line optical amplifiers in all fiber links, and only pre- and booster optical amplifiers are used inside each node. Several modifications/extensions are made to RSVP-TE and OSPF-TE protocols on the GMPLS Lightwave Agile Switching Simulator (GLASS) [10]. The traffic and simulation scenarios used in the simulation experiments are same as described in [9]. The simulation results have a confidence level of 95 percent.

Figure 6c compares the blocking probability of R-OCP and S-OCP architectures for AT&T and Daisy networks. In the AT&T network, it can be found that the blocking performance of S-OCP architecture is very close to R-OCP. In the Daisy network, the blocking performance of S-OCP is slightly worse than R-OCP. Figure 6d compares the average lightpath setup time of R-OCP and S-OCP architectures for AT&T and Daisy networks. Lightpath setup time is defined as the elapsed simulation time between the first PATH message sent and the RESV message received at the source node. This metric reflects how fast a connection request can be established. It can be seen that, in general, the lightpath setup time for R-OCP and S-OCP architectures does not change much with traffic load. S-OCP has the higher setup time, mainly because the source node tries all K-explicit paths sequentially until the lightpath is established or blocked.

SUMMARY

Transparent dynamic optical networks are the next evolution step of translucent optical networks. Both of them have been recognized as the evolution of static WDM networks. In order

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to provide high-speed and QoS guaranteed connectivity with high reliability, considering the realistic optical layer, the DICONET vision was presented in this article as a disruptive and novel solution for optical networking. Two main challenges of transparent networks are identified:

- Limited system reach and overall network performance due to physical impairments
- Challenges related to failure localization and isolation

Solving these challenges is the main goal of the DICONET project. It is the vision of DICONET that intelligence in the core optical networks should not be limited only to certain functionalities of control and management planes, but also be extended to the physical layer. Following this vision, the main physical impairments as well as the essential role of optical performance and impairment monitoring schemes, IA-RWA algorithms, and failure localization algorithms complemented with an impairment-aware control plane are discussed in this article.

Acknowledgments

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Biographies

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IOANNIS TOMKOS (itom@ait.edu.gr) is the associate dean of AIT (since 2004), having the rank of full professor and adjunct faculty at the Information Networking Institute of Carnegie-Mellon University. At AIT he founded and serves as head of the High Speed Networks and Optical Communication (NOC) Research Group that participates in many EU funded research projects (including five running FP7 projects) in which he represents AIT as principal investigator and has a consortium-wide leading role (e.g., project leader of the EU ICT STREP project DICONET, technical manager of the EU IST STREP project TRIUMPH, chairman of the EU COST 291 project, WP leader). He has received the prestigious title of Distinguished Lecturer of IEEE Communications Society on the topic of transparent optical networking. Together with his colleagues and students he has co-authored over 75 peer-reviewed articles published in international scientific journals, magazines, and books, and over 175 presentations at conferences, workshops, and other events. He has served the scientific community as Chair of the International Optical Networking Technical Committee of IEEE Communications Society and Chairman of the IFIP Photonic Networking working group. He is currently Chairman of the OSA Technical Group on Optical Communications. He has been General Chair, Technical Program Chair, Subcommittee Chair, Symposium Chair, and/or member of the steering/organizing committees for major conferences (OFC, ECOC, IEEE GLOBECOM, IEEE ICC, ONDM, etc.) in the area of telecommunications/networking (more than 50 conferences/workshops). In addition, he is a member of the Editorial Boards of the *IEEE/OSA Journal of Lightwave Technology*, *OSA Journal of Optical Networking*, *IET Journal on Optoelectronics*, and *International Journal on Telecommunications Management*. His current work focuses on optical communications/networking, network planning, future Internet, and techno-economic studies of broadband networks

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