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DICONET NPOT: An Impairments Aware Tool for Planning and Managing Dynamic Optical Networks

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Abstract The impact of physical layer impairments in the planning and operation of all-optical (and translucent) networks is the consideration of the DICONET project. The impairment-aware network planning and operation tool (NPOT) is the main outcome of the DICONET project, and is explained in detail in this paper. We describe the key building blocks of NPOT, consisting of the network description repositories, the physical layer performance evaluator, the impairment-aware routing and wavelength assignment (IA-RWA) engines, the component placement modules, the failure handling and the integration of NPOT in the control plane. Also, we present several experimental results for NPOT, evaluating the performance of its IA-RWA engines.

Keywords Routing and wavelength assignment (RWA) · Physical impairments · Planning and operation · Optical networks

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1 Introduction

Optical networking has undergone tremendous changes in recent years. The current trend clearly shows an evolution path towards lower cost and higher capacity networks, while other considerations such as energy consumption, heat dissipation, and physical space requirements are also gaining in importance. The optical network evolution has been governed by developments in the networking capabilities (e.g., more wavelengths, higher line rates, advanced modulation formats) and the emerging applications (e.g., tele-presence). With respect to the optical transmission systems, this evolution can be translated to denser WDM transmission systems (i.e., 80–160 wavelengths per fiber) operating at higher line rates (e.g., 40 or 100 Gbps), and coarser granularities at the switching level [7]. However, providing static and high-capacity pipes is no longer sufficient to address the demands of emerging dynamic applications. Dynamic and configurable optical and control planes that are able to serve dynamic requests in a cost-effective way are also required in order to support the mentioned trend.

Optical network architectures can be characterized as (a) opaque, (b) translucent (optical-bypass), or (c) all-optical (transparent), as depicted in Fig. 1. In opaque architectures, the optical signal carrying traffic undergoes an optical-electronic-optical (OEO) conversion at every switching or routing node on the path. The OEO conversion enables the optical signal to reach long distances, but this happens at a high cost, due to the number of regenerators required in the network and the dependency of the conversion process on the connection bit-rate and modulation formats. Transparent network architectures were proposed as a way to eliminate the OEO cost associated with opaque networks. In transparent networks, the signal is transported end-to-end optically, without any OEO conversions along its path. In extended networks, physical signal impairments limit the transparent reach distance and require all-optical regenerators in order to regenerate the signal in the optical domain that are not commercially available today. Translucent (optical-bypass)

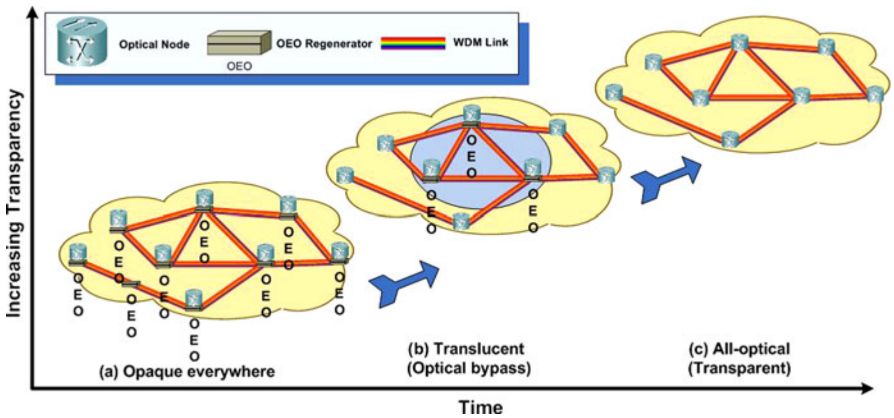

Fig. 1 Evolution of optical networks from (*a*) opaque, to (*b*) translucent (optical bypass), to (*c*) all-optical (transparent)

networks have also been proposed as a compromise between opaque and transparent networks [19]. In this approach, selective regeneration is used at specific network locations in order to maintain the acceptable signal quality from source to its destination. Optical transparency impacts network design, either by posing limitations on the size of WDM transparent domains so as to keep physical impact on the quality of transmission (QoT) below a certain level, or by introducing physical considerations in the network planning and operation process. In transparent optical networks, as the signal propagates in a transparent way it experiences 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 the overall QoT. The impact of failures also propagates through the network and therefore cannot be easily localized and isolated.

The vision of the DICONET project [3] 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 and operation tool (NPOT) residing in the core network nodes that incorporates assessments of optical layer performance into various algorithms and is integrated into a unified control plane. In this work we, present the DICONET NPOT and its key building blocks along with control plane integration schemes. The performance of DICONET NPOT over a realistic 14-node network under static and dynamic traffic conditions, is also presented.

This paper is organized as follows. In Sect. 2, we present the architecture and key building blocks of the DICONET NPOT. The schemes that integrate NPOT into an impairment aware GMPLS-based control plane are explained in Sect. 3. The experimental setup and the performance results obtained are presented and discussed in Sects. 4 and 5, respectively. Section 6 draws the conclusions of this work.

2 DICONET NPOT

The main novelty of the DICONET project [3] is the design and development of a physical layer impairment-aware NPOT that incorporates the performance of the optical layer into impairment-aware routing and wavelength assignment (IA-RWA), component placement, and failure handling algorithms. The NPOT is integrated into a unified extended GMPLS-based control plane. The anatomy of the DICONET NPOT is depicted in Fig. 2. Network description repositories, a QoT estimator, IA-RWA engines, component placement modules, and a failure handling module are the key building blocks of NPOT. In the planning mode, the corresponding modules are accessible through a command line interface (CLI). On the other hand, in the operation mode, the communication of NPOT with the other entities of the DICONET's control plane integration schemes is materialized through a messaging protocol layer that is designed and implemented on top of the standard TCP/IP socket interface. The modular design of NPOT paves the way to enhance or upgrade each of its building blocks without affecting the overall functionality of the tool. In fact, the DICONET NPOT evolves as new modules or algorithms are replaced with

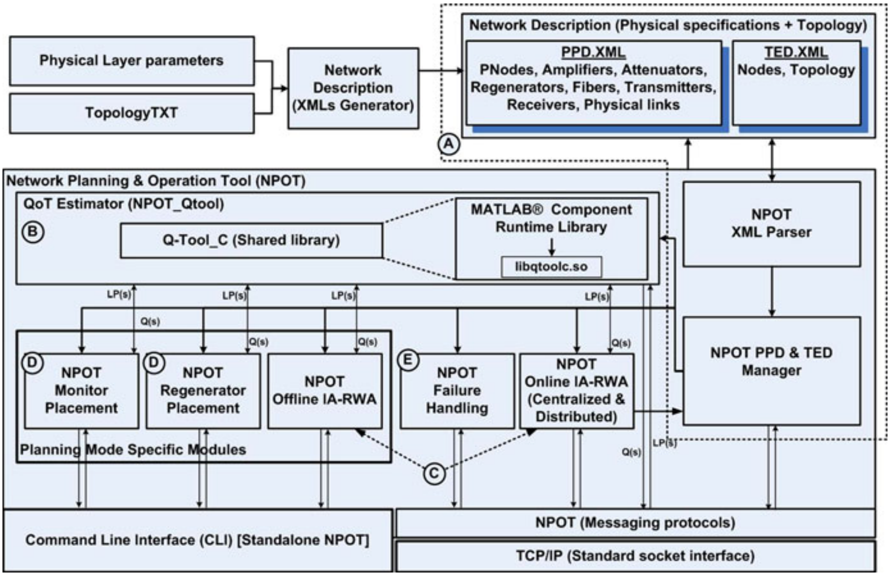

Fig. 2 Anatomy of DICONET Network Planning and Operation Tool (NPOT): (*A*) network description repositories, (*B*) QoT estimator, (*C*) IA-RWA engines, (*D*) component placement modules, and (*E*) failure handling module

the existing ones. In the sequel, we present an overview of each of the building blocks of NPOT.

2.1 Network Description Repositories

The network description (both at the physical layer level and topology level) is included in two main repositories that are kept as external databases to NPOT. The Physical Parameters Database (PPD) is the master repository, expressed in XML format that includes the physical characteristics of the links, nodes, and components on the network. More specifically, physical characteristics of nodes, amplifiers, attenuators, fibers (both transmission fibers and Dispersion Compensation Fiber, DCF, modules), transmitters, receivers, and eventually the definition of physical links are all kept in the PPD. The Traffic Engineering Database (TED) includes the nodes and a detailed network topology, in XML format. The NPOT XML parser is responsible to parse the XML repositories and transform the network description (content of PPD & TED) into the internal data structures that are stored inside the NPOT memory. The NPOT PPD and TED manager is responsible for managing these PPD and TED data structures.

2.2 QoT Estimator

In the context of transparent optical networks, physical layer impairments can be categorized into “static” and “dynamic” impairments. Static impairments are topology-dependent, that is, they do not depend on the dynamic state of the network (established lightpaths). In particular, we account for the following static impairments: Amplifier Spontaneous Emission (ASE) noise, Chromatic Dispersion (CD), Filter Concatenation (FC), and Polarization Mode Dispersion (PMD). Dynamic impairments depend on the presence and characteristics of other established lightpaths in the network. We account for the following dynamic impairments: Self-Phase Modulation (SPM), Cross Phase Modulation (XPM), and Four Wave Mixing (FWM) [2].

To assess the QoT of a lightpath in NPOT, we have developed a "Q-Tool" that is able to compute the so-called "Q factor" for a lightpath, given the network topology, physical characteristics, and network state (i.e., set of active lightpaths in the network). The NPOT Q-Tool offers fast assessment of the QoT of a lightpath given a specific physical topology and set of established lightpaths, based on analytical models and numerical simulations. The building blocks of NPOT Q-Tool are presented in Fig. 3. The NPOT Q-Tool provides the required access to the physical layer performance evaluator. The NPOT Q-Tool receives a set of lightpaths (at least one lightpath), computes their Q-factor, and returns the computed values back to the calling module. The Q factor for a lightpath is a QoT indicator that is related to the signal's Bit-Error Rate (BER), assuming an On-Off modulated signal:

$$\mathrm{BER} = \frac{1}{2}\operatorname{erfc}\left(\frac{\mathrm{Q}}{\sqrt{2}}\right), \tag{1}$$

where the Q factor is defined as [1]:

$$\mathrm{Q} = \frac{P_1 - P_0}{\sigma_1 + \sigma_0}. \tag{2}$$

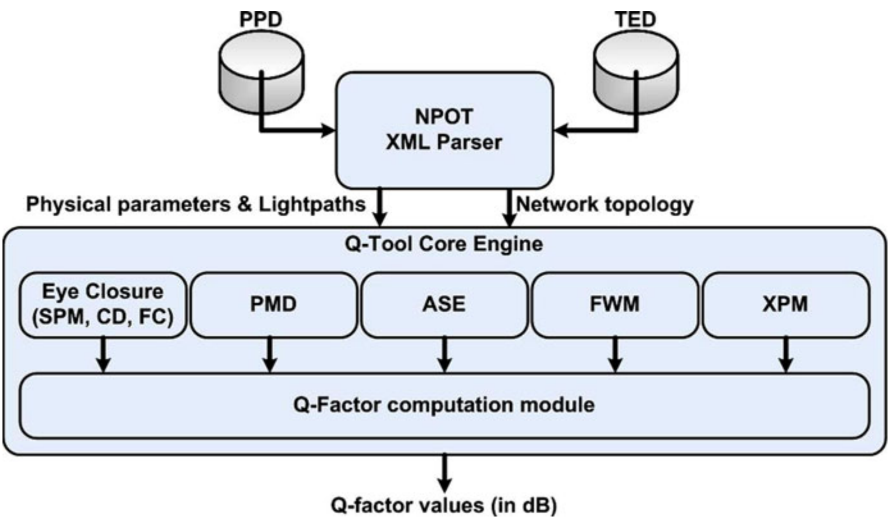

Fig. 3 Building blocks of NPOT Q-Tool module (Q-Tool core engine)

In (2), P_1 and P_0 are the mean of the distributions (assumed to be Gaussian) of the received samples corresponding to the sent "1" and "0" bits, and σ_1 and σ_0 are the respective standard deviations.

In order to quantify the impact of the static impairments (SPM, CD and FC) on the signal quality, the NPOT Q-Tool utilizes a detailed numerical Split-Step Fourier (SSF) method. During this process, every optical signal is treated as if there is only single-channel propagation, thus accounting only for SPM, CD, and FC. This approach achieves accurate computation of the state of the optical signal at the receiver-end, without considering the presence of neighboring channels that would impose a prohibitive time penalty on the process. Thus, contrary to various similar works [9, 16, 17] that rely solely on analytical or semi-analytical models to estimate the QoT, Q-Tool introduces a balance between speed and accuracy by numerically simulating the single-channel signal propagation.

The analytical model utilized in NPOT Q-Tool to estimate the power of the ASE noise of a cascade of inline (EDFA) amplifiers is similar to the models in [15, 18], and assesses the accumulation of this effect and its impact on the lightpath QoT. The Gaussian distribution of the ASE-signal beating noise facilitates the incorporation of its contribution to the Q-factor by considering the noise variances that are superimposed on the levels of marks and spaces. The NPOT Q-Tool considers the impact of XPM on the performance of a single link according to the Cartaxo analytical model [10] that is properly modified to match the specific link architecture. The analytical expression of σ^2_{XPM} is derived using the approach reported in [16]. NPOT Q-Tool treats XPM and FWM as random noise that affects the QoT in a way similar to ASE noise, imposing fluctuations that typically occur at the mark level. As shown in [20], this can be considered as a good approximation particularly at the regime of relatively high Q and at the same order of magnitude as ASE noise. In [20] the XPM-induced distortion is estimated using the frequency response of XPM-induced intensity modulation from a modulated pump channel to a continuous wave (CW) probe channel ([10] "Cartaxo model"), as in Q-tool. It was shown in [20] that FWM is well approximated with a Gaussian distribution. Assuming a random behavior is particularly applicable in FWM, since many independent channels contribute to the total FWM power. The work in [20] utilizes the model reported in [12] and is extended for a multi-span system that is implemented in the NPOT Q-Tool.

In order to estimate the PMD induced penalty on the Q-factor values, the NPOT Q-Tool utilizes the approach used in [8]. To calculate the PMD-induced penalty two different methods have been generally followed [23]. One of them relies on a sophisticated statistical modeling method that approximates the all-order PMD, while the other considers only the first-order PMD using an analytical or numerical approach. Despite the restriction of the analytical model to the first-order PMD, the comparison for a 10 Gb/s NRZ signal performed in [23] demonstrated that its penalty was in good agreement with the penalty obtained with the statistical modeling. In fact NRZ signals are primarily dominated by the first-order PMD, making the choice for the analytical approach appropriate for the purposes of DICONET NPOT.

The overall QoT of the signal, using NPOT Q-Tool, is reflected in the Q factor that considers the impact of the mentioned impairments as a single figure of merit (Q_{est}):

$$Q_{est} = 20\log\left(\frac{I_{1,min} - I_{0,max}}{\sigma_{0,\mathrm{ASE}} + \sigma_1}\right) - Q_{pen\mathrm{PMD}}, \quad (3)$$

$$\sigma_1 = \sqrt{\sigma^2_{1,\mathrm{ASE}} + \sigma^2_{\mathrm{XPM}} + \sigma^2_{\mathrm{FWM}}}. \quad (4)$$

The numerator of the fraction in (3) is the difference between the minimum detected current at the level of "1" and the maximum at the level of "0" that defines the distortion induced by SPM, CD and FC on the signal (Eye diagram closure effect). The summand in the denominator of the fraction in (3) includes the variances of all the noise impairments that add up to the total signal power variance. $\sigma_{0,\mathrm{ASE}}$ and $\sigma^2_{1,\mathrm{ASE}}$ in (3) and (4) refer to the variance of the detected spaces ("0"s) and marks ("1"s) due to ASE noise. XPM and FWM are assumed only to add noise at the level of "1"s and therefore the non-linear induced degradation is expressed by σ^2_{XPM} and σ^2_{FWM}. Finally, since the Q factor is in fact a figure of merit, the PMD-induced penalty ($Q_{pen\mathrm{PMD}}$) has to be subtracted from the total estimated Q-factor.

2.3 IA-RWA Engines

During the network planning phase, the demand set (traffic matrix) is already known, at least partially, enabling the network operator to perform the resource allocation task offline. Since, in all optical networks, bandwidth is allocated in the form of lightpaths (i.e., the combination of a route between two nodes, and a wavelength), the problem of a pre-planned resource allocation in such networks is called static or an offline RWA problem [2]. The offline IA-RWA algorithm utilized in NPOT is called offline "Rahyab" [4]. The offline Rahyab algorithm pre-processes the demand set and serves them sequentially. For each demand, a route and wavelength is selected in a way to minimize the impact of physical layer impairments (PLIs) on the already established lightpaths. This is done by computing a QoT margin of the candidate lightpath compared to the already established ones and selecting the lightpath with an optimum QoT margin [4]. On the other hand in the operational phase, new lightpath requests arrive dynamically, at random time instances, and they have to be established upon their arrival, one by one, taking into account the current utilization state of the network, that is, the previously established lightpaths. Connections may also terminate at random time instances, releasing the used links and wavelengths for future use. There are two IA-RWA engines for the operation (online) mode of NPOT. In the distributed integration scheme, which will be defined in more detail in Sect. 3, the NPOT IA-RWA module receives a demand, computes the *k* shortest routes from source to destination without consideration for PLIs. In case of demand with (1 + 1) protection requirement, this module computes *k* diverse pairs of primary and backup paths. If it is not possible to find complete disjoint paths then primary and backup paths with maximum disjointness will be computed. The caller module (i.e., Optical

Connection Controller "OCC") tries to establish the lightpath from source to destination using the extended GMPLS signaling protocol. If a lightpath (or a pair of lightpaths) is (are) established the NPOT updates its global data structure (via TED & PPD manager). If none of the *k* candidate routes are feasible, the caller (i.e., OCC) sends the proper status code back to the NPOT. In the centralized integration scheme (defined in Sect. 3) the NPOT IA-RWA engine, based on Multi Parametric algorithm [14], computes the lightpath from source to destination, assigns a wavelength for it and returns it back to the caller (i.e., OCC). In the multi-parametric approach, a vector of cost parameters is assigned to each link, from which the cost vectors of candidate lightpaths are calculated. The cost vector includes impairment generating source parameters, such as the path length, the number of hops, the number of crosstalk sources and other inter-lightpath interfering parameters, so as to indirectly account for the physical layer effects. For a requested connection, the algorithm calculates a set of candidate lightpaths, whose QoT is validated using a function that combines the impairment generating parameters. For selecting the lightpath different optimization functions are utilized. OCC tries to establish the lightpath using the GMPLS signaling protocol and returns the result of lightpath establishment process back to the NPOT. If the establishment is successful, NPOT updates the list of active lightpaths in the network and also updates the topology data structure (i.e., TED). If the lightpath establishment is not successful, the source OCC notifies the NPOT accordingly.

2.4 Component Placement Modules

Regenerator and monitor placement are two component placement modules of NPOT that are mainly designed for the planning mode. The main assumption in all-optical networks is that the network is truly transparent (all-optical), where all intermediate OEO conversion is eliminated. However, given that the longest connections for instance in a North American backbone network are on the order of 8,000 km, clearly some regeneration is still required. The NPOT regenerator placement module receives a demand set (traffic matrix) along with the network description and optimizes the regeneration sites and regenerators that are going to be deployed in the network. This module is developed according to the COR2P (Cross Optimization for RWA and Regenerator placement) algorithm [21, 22] specifications. The COR2P algorithm utilizes the NPOT Q-Tool in order to evaluate the performance of the physical layer. In addition to the regenerator placement, NPOT exploits a special purpose monitor placement algorithm that deploys optical impairment/performance monitors (OIM/OPM) on the network links. The OIM/OPM equipments can be utilized for enhanced QoT estimation, compensation of QoT estimation inaccuracy [5], and failure localization.

2.5 Failure Handling

When a failure occurs, the optical transparency leads to a propagation of Loss of Light (LoL) alarms, with all nodes that are downstream from the failure point detecting LoL in their incoming ports. This makes additional failure localization functionalities necessary in networks where transport plane devices operate in transparent mode. There are two main approaches for failure localization: (1) monitoring cycles (m-cycle) and (2) monitoring trails (m-trail). Both techniques utilize a set of out-of-band lightpaths that are organized either as optical loops (cycles) or as an open optical circuit (trial). The NPOT failure localization engine is designed and developed based on a novel heuristic algorithm called MeMoTA ("Meta-heuristic for Monitoring Trail Assignment") [11]. This algorithm aims at designing an m-trail solution that is able to exactly localize the broken link in the network with a low monitoring deployment CAPEX.

3 Integrations

Two control plane integration schemes have been investigated and assessed within the DICONET project, namely, a distributed and a centralized scheme. In this section, we present the details of these control plane integration schemes.

3.1 Centralized Approach

In the centralized approach (Fig. 4), NPOT carries out the IA-RWA and failure handling functionalities, while the OCCs execute the extended GMPLS protocols and interface to the actual optical nodes. A TCP-based messaging protocol has been developed to facilitate the communication between the OCCs and the centralized NPOT. Upon the arrival of a new connection request, the source OCC contacts the online IA-RWA module of the centralized NPOT to request an impairment-aware lightpath computation. During the lightpath computation, the online IA-RWA module utilizes the QoT estimator (NPOT Q-Tool) and the information of the gPPD and gTED (global PDD and global TED) that completely describes the network topology and the physical layer characteristics. When the NPOT finds a lightpath with a guaranteed QoT (Q-factor value above a pre-defined threshold), the lightpath is returned back to the source OCC that triggers the *standard* RSVP-TE signaling protocol. Upon successful establishment of a lightpath, the global PPD and TED in

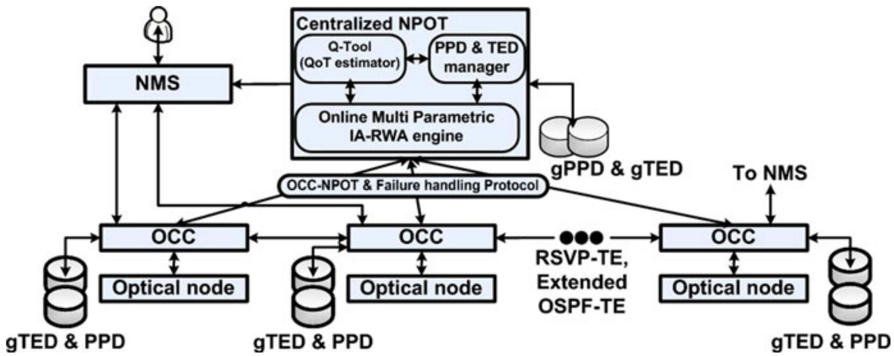

Fig. 4 Centralized control plane integration scheme

the NPOT and the local PPDs and TEDs in every OCC in the network are updated using the *extended* OSPF-TE protocol. Finally, the source OCC updates the Network Management System (NMS). In case of a lack of resources/wavelengths or an unacceptable QoT, the demand is blocked and the source OCC informs the NMS, accordingly.

When a link failure occurs, the downstream optical nodes detect it and send alarms to their OCCs, which forward the failure notification to the centralized NPOT. In order to restore the failed lightpaths and to avoid using the failed network resources, the centralized NPOT localizes the failure, updates both gTED and gPPD, and computes the backup paths. Then, the source OCCs trigger the signaling protocol for the actual lightpath establishment as explained earlier (Sect. 2.5)

3.2 Distributed Approach

In the distributed approach (Fig. 5), both RSVP-TE [6] and OSPF-TE [13] protocols were extended to consider the impact of the PLIs, providing different compromises between network performance, control overhead, and complexity. The OSPF-TE protocol was extended to disseminate the wavelength availability information. The RSVP-TE signaling protocol was extended to collect real-time information of the PLIs during the PATH message traversal from source to destination. In the distributed approach, each node in the network runs an instance of NPOT that is connected to an OCC via the NPOT-OCC communication protocol, specifically developed for the NPOT integration schemes. Upon receiving a new connection request, the source OCC node requests from the online IA-RWA module of the NPOT to compute the *k*-shortest routes from source to destination without the PLIs knowledge. Once these *k*-routes are computed, the source OCC node triggers the *extended* RSVP-TE protocol to initiate the RSVP-TE signaling on the first candidate route. The RSVP-TE PATH message collects the PLIs information from source to destination along the path. Upon the reception of the PATH message, the destination node requests from its NPOT the QoT estimation of the corresponding candidate lightpath. If the QoT of the lightpath is acceptable (i.e., above a given threshold), then the destination nodes of the potentially affected lightpaths (i.e., those lightpaths

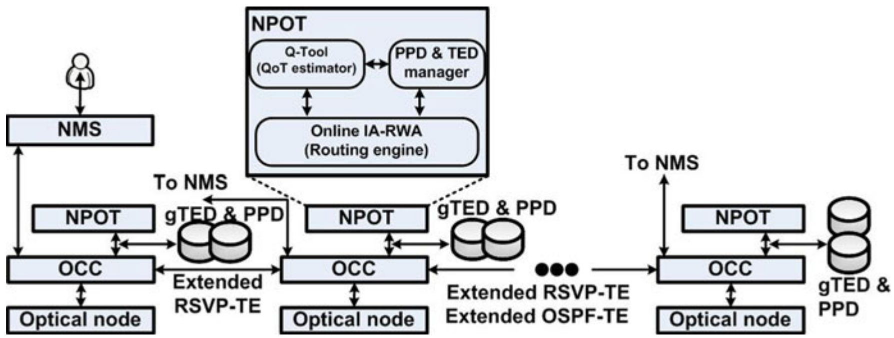

Fig. 5 Distributed control plane integration scheme

that share at least one optical section with the candidate one) are notified to request for a QoT estimation from their respective NPOTs. The information of already established lightpaths are maintained in the global TED. Since a global view of the TED is available in each node (using extended OSPF-TE), it is possible for nodes to identify the affected lightpaths. This verification step makes sure that the Q-factor of the affected active lightpaths will remain above the required threshold after the establishment of the new lightpath. If there is no violation, the destination nodes of these affected active lightpaths update their local databases with the new lightpath information and respond back to the destination node of the candidate one. Next, an RSVP-TE RESV message is sent back to the source node and the actual cross-connections are properly configured. Otherwise, an RSVP-TE PATH_ERR is sent back to the source node, which then tries to establish a lightpath based on the next candidate route. If all the *k*-candidate routes fail, the connection request is blocked.

4 Experimental Setup

We selected Deutsche Telekom's national network (DTNet) for our simulation studies. This network has 14 nodes and 23 bidirectional links, with an average node degree of 3.29 and an average link length of 186 km. The physical characteristics of DTNet is shown in Table 1. In Fig. 6, the Q-factor value (computed by Q-Tool) of 10 shortest paths between all possible pairs of the nodes is depicted. Without considering the impact of other established lightpaths, there is no lightpath with a length longer than 1,500 km and an acceptable QoT. There are short lightpaths with a Q value lower than the threshold (Region 1) and long lightpaths with acceptable Q values (Region 2). This demonstrates the benefit of IA-RWA engines that are able to find long but feasible lightpaths. For the evaluation of NPOT in the planning mode, we define the offered load in the network as the ratio between the number of lightpath demands divided by the number of pairs of nodes in the network. The unit traffic load corresponds to the demand set where there is, on average, one lightpath

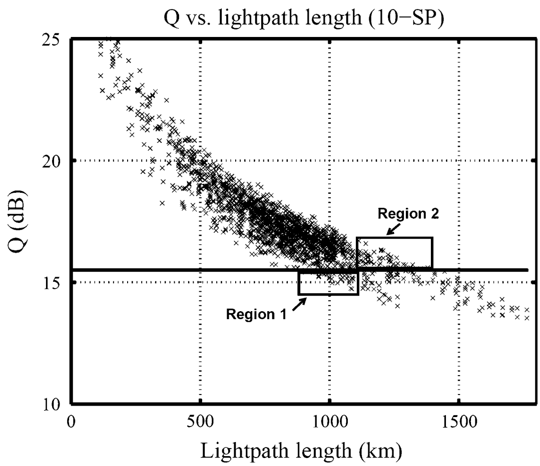

Fig. 6 Benefit of IA-RWA and different solution spaces. Region 1 shows the short lightpaths that are not feasible (unacceptable QoT) and Region 2 shows the long feasible lightpaths. The QoT threshold is set at 15.5 dB level

request between each pair of (distinct) source-destinations. We studied three traffic load values, namely, 0.3, 0.6, and 0.8, corresponding here to the establishment of 56, 110, and 146 lightpaths, respectively. In order to evaluate the performance of the IA-RWA engines in the operation mode an "arrival only" scenario is assumed. In this scenario, connection requests have an infinite duration and arrive one by one. The requests have to be served efficiently and fast upon their arrival. Under this scenario, the exact arrival times of the requests do not affect network performance; instead, their characteristics (source, destination nodes) are important. In our tests, the number of requested connections varies. The characteristics of these demands were based on the traffic of the DTNet for 2009, by scaling it up by a factor L (0.2, 0.4, 0.6, 0.8, 1, 1.2). In what follows, we refer to this factor L as the network load for operation mode. These traffic loads are used to evaluate the performance of the IA-RWA engines in terms of success rate. This means that for the incremental traffic, the rate of successfully served demands over the total number of demands for the given load is measured and reported as the success ratio.

Parameter	Value
Input power	−4 (SSMF), 3 (DCF) dBm
Pre-dispersion compensation	−85 ps/nm
Span length	70 km
Dispersion parameter	17 (SSMF), 80 (DCF) ps/nm/km
Attenuation	0.23 (SSMF), 0.4 (DCF) dB/km
PMD	0.1 ps/(km)$^{1/2}$
Channel spacing	50 GHz
Amplifier noise figure	6 dB
Mean under compensated dispersion	80 ps/nm per span
Q-factor threshold	15.5 dB (BER = 10^{-9} without FEC)
Line rate	10 Gbps
Number of channels per fiber	16

5 Discussions and Results

In this section we report the performance result obtained for the planning and operation modes of DICONET NPOT. In particular, the IA-RWA engines are the main focus of performance evaluation.

5.1 Planning Mode

The IA-RWA module of NPOT for planning (i.e., Rahyab algorithm) served all demands without any blocking for all load values (i.e., 0.3, 0.6 and 0.8). The Rahyab module of NPOT intensively invokes the Q-Tool to evaluate the performance of each candidate lightpath in order to guarantee the minimum QoT impact of the new

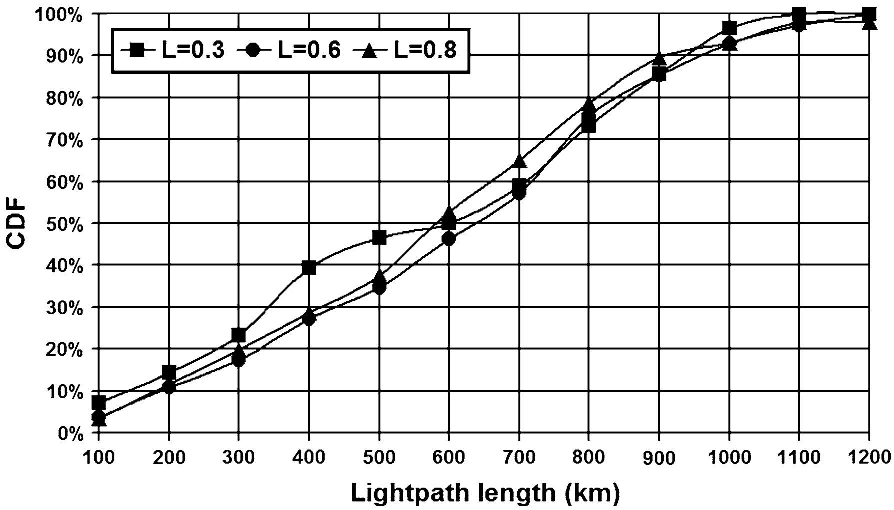

Fig. 7 CDF of lightpath length for different loads

lightpath on the currently established ones. As a result, the computation time of NPOT is quite high.

The cumulative distribution function of the lightpath length for different loads is depicted in Fig. 7. The distribution of the lightpath lengths is presented in Fig. 8 for all 3 demand sets combined. We can observe from these two figures that the routing engine of NPOT could find long feasible lightpaths, with an average length equal to 572 km. NPOT only considers the active (i.e., already established) lightpaths in order to admit or reject a demand. Rahyab utilizes an adaptive wavelength assignment approach, in which the wavelength of the candidate lightpath is selected so as to introduce the minimum impact on the currently established lightpaths. The Rahyab wavelength usage pattern is adaptive along the available channels per link depending on the network state, while some channels are not assigned to any lightpath. We also observed that for the given demand sets, on average, the first 10 channels on the links were sufficient for the NPOT planning tool to serve 80% of the demands.

5.2 Operation Mode

Figure 9 shows the ratio of successfully established connections as a function of the number of available channels *W* per fiber, for various network loads. The load in the network affects the success ratio since when more connections request service, the ratio of successfully served connections decreases, even if there are many available channels. Figure 10 illustrates the average execution time (in seconds) per connection request of the IA-RWA engine for the operation mode (the MP algorithm), for different numbers of available channels and traffic demands. A large number of available channels increases MP algorithm’s execution time, since in this case more candidate lightpaths are calculated by the MP algorithm. In addition,

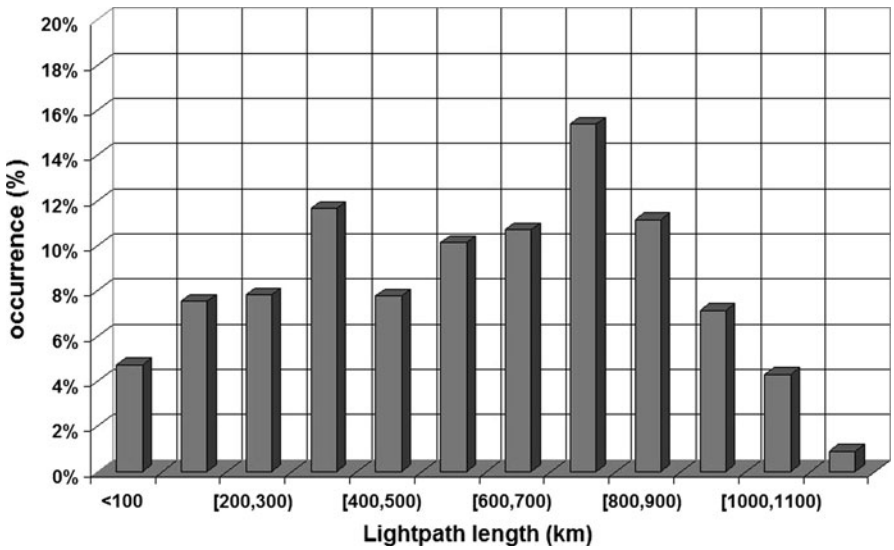

Fig. 8 Distribution of lightpaths length

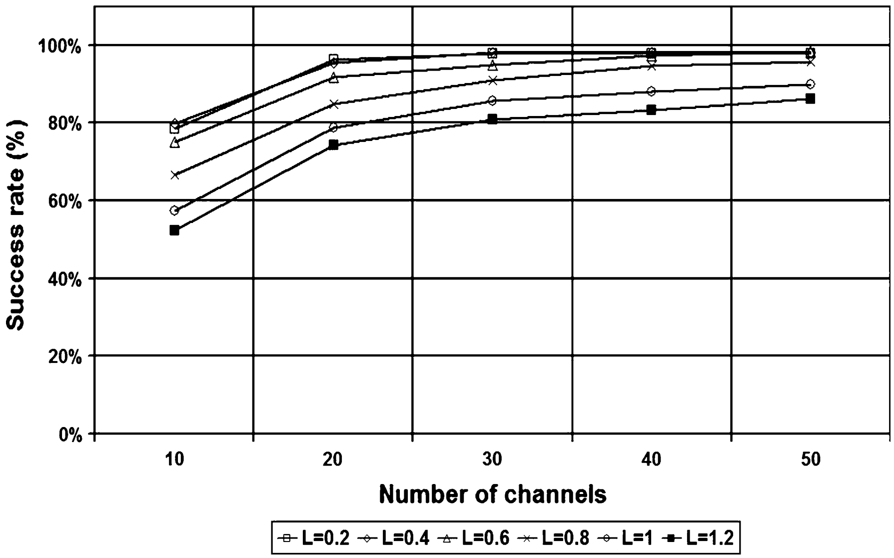

Fig. 9 The success rate versus the number of available channels *W* per fiber

when the number of established lightpaths is large, the Q-factor value of many of these (affected) lightpaths has to be evaluated before a new/candidate lightpath is established, increasing the total execution time. In any case, as illustrated in Fig. 10, the execution time is acceptable and appropriate for the online mode. In our tests,

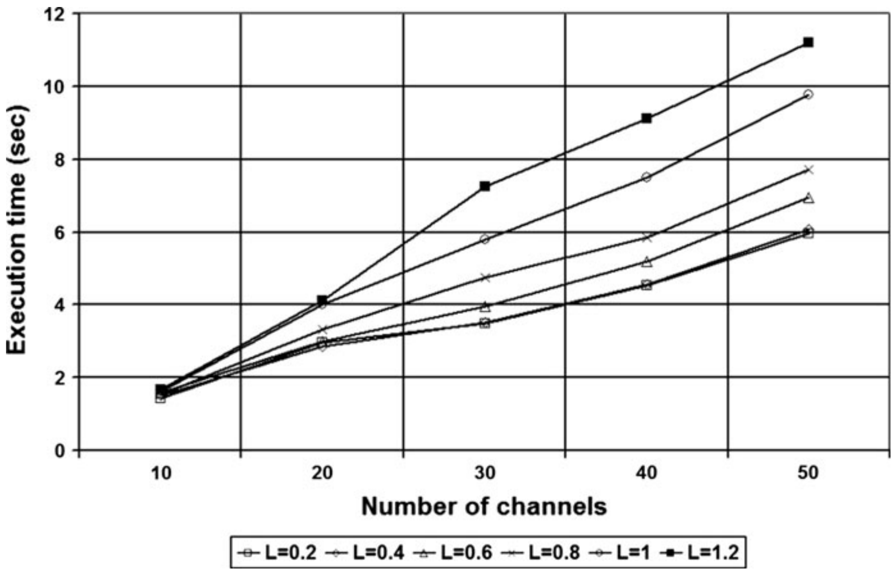

Fig. 10 The average execution time per connection request versus the number of available channels W per fiber

we also observed that the average length of the lightpaths is decreased from 457 to 415 km, when the load L is increased from 0.2 to 1.2. This is because when the offered load to the network is increased, then the impact of physical impairments (and in particular, that of the interference among lightpaths) becomes more severe and, consequently, the IA-RWA algorithm tends towards selecting shorter feasible lightpaths. Figure 11 depicts the distribution of channel usage for traffic load of 0.2 and 1.2. We can observe that the IA-RWA engine uniformly utilizes the available channels per fiber (i.e., $W = 10$). Additionally, in order to quantitatively evaluate the performance of the MP IA-RWA engine, we fed the RWA solutions produced for different values of the load to the NPOT Q-Tool. The distribution of the Q-factor values for 10 available channels per fiber ($W = 10$) and traffic loads 0.2 and 1.2, are shown in Fig. 12. The average Q value of the active lightpaths is 27.2 and 25.7 dB for loads 0.2 and 1.2, respectively. We can also observe that by increasing the traffic volume, the distribution of the Q-factor values is skewed towards a lower quality. However, all the active lightpaths have an acceptable Q value, above the 15.5 dB threshold.

6 Conclusions

A key contribution of the DICONET project is the design and development of a PLIs aware network planning and operation tool, namely the NPOT. NPOT resides in the core network nodes, incorporating the performance of the physical layer when making planning and operation decisions. The architecture and key building blocks

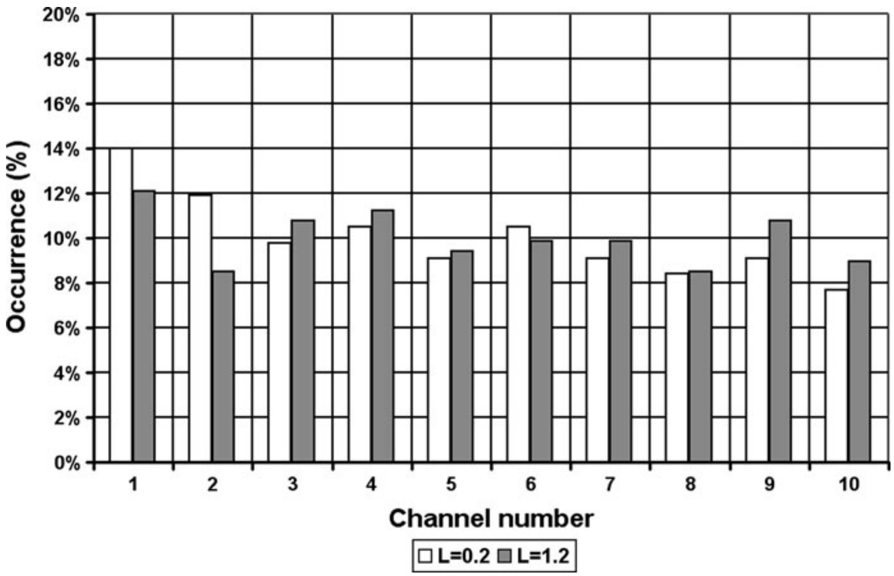

Fig. 11 Distribution of channel usage

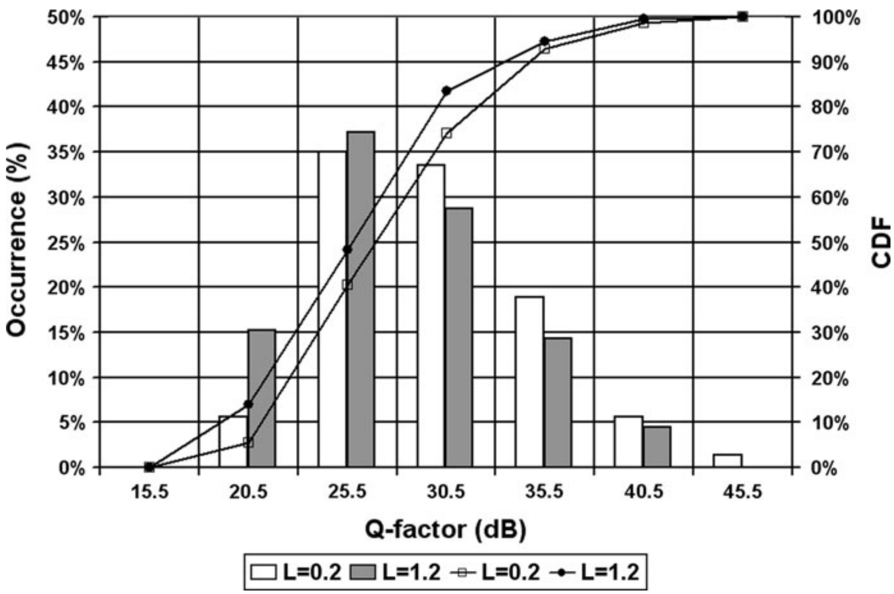

Fig. 12 Distribution of Q-factor ($W = 10$)

(i.e., network description repositories, QoT estimator, IA-RWA engines, component placement algorithms, and failure localization modules) of the DICONET NPOT were presented in this work. This paper also described centralized and distributed control plane integration approaches for impairment-aware transparent optical networks. The performance of the DICONET NPOT for planning and operating a typical nation-wide core network was also presented.

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