Experimental Demonstration of an Impairment Aware Network Planning and Operation Tool for Transparent/Translucent Optical Networks

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***Abstract*—Core optical networks using reconfigurable optical switches and tunable lasers appear to be on the road towards widespread deployment and could evolve to all-optical mesh networks in the coming future. Considering the impact of physical layer impairments in the planning and operation of all-optical (and translucent) networks is the main focus of the DICONET project. The impairment aware network planning and operation tool (NPOT) is the main outcome of DICONET project, which is explained in detail in this paper. The key building blocks of the NPOT, consisting of network description repositories, the physical layer performance evaluator, the impairment aware routing and wavelength assignment engines, the component placement modules, failure handling and the integration of NPOT in the control plane are the main contributions of this work. Besides, the experimental result of DICONET proposal for centralized and distributed control plane integration schemes and the performance of the failure handling in terms of restoration time is presented in this work.**

***Index Terms*—Optical Network Planning, Optical Network Operation, Physical Layer Impairments, Impairment Aware Control Plane, Transparent Optical Networks.**

I. Introduction

The evolution trend of optical networks is a transformation towards high-capacity and cost-effective core optical networks. In opaque networks, the optical signal undergoes an expensive optical-electronic-optical (OEO) conversion at every switching node. One approach to decrease the cost is the use of sparsely placed electrical or optical regenerators. The lack of practical all-optical regeneration, gives rise to the intermediate optical network architecture, which are defined as translucent networks [1]. In translucent networks, a set of sparsely but strategically placed regenerators (i.e., OEO conversion) is used to maintain the acceptable level of signal quality from the source to its destination. Conversely, in transparent optical networks the signal remains in optical domain as it propagates through a lightpath from source to destination. The promise of future optical networks is the elimination of a significant amount of electronic equipment (lower CAPEX and OPEX), as well as added capabilities, such as the ability to transport any type of data format (modulation and bit rate independence) through the network and support for dynamic demands [2]. As one of recent efforts toward this goal, the key outcome of the DICONET project [3] is the design and development of an intelligent Network Planning and Operation Tool (NPOT), which considers the impact of physical layer impairments (PLIs) in planning and operation phase of optical networking.

Network planning is more focused on the details of how to accommodate the traffic that will be carried by the network. In this phase, which typically occurs before a network is deployed, there is generally a large set of demands to be processed at one time. Therefore the main emphasis of network planning is on finding the optimal strategy for accommodating the whole demand set (traffic matrix) [4], [5]. In network operation phase, the demands are generally processed upon their arrival and one at a time. It is assumed that the traffic must be accommodated using whatever equipment already deployed in the network. Therefore the operation process must take into account any constraint posed by the current state of the deployed equipment, which, for instance, may force a demand to be routed over a sub-optimal path [6], [7].

Considering the impact of PLIs on transparent [8] and highly dynamic optical networks [9] has received much attention recently [10], [11]. The work in [8] reported the result of a centralized integration scheme for transparent networks considering various PLIs, while [12] only investigated a distributed Generalized Multi-Protocol Label Switching (GMPLS) integration for translucent networks.

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In our previous work we demonstrated and compared the distributed and centralized impairment-aware control plane integration schemes for transparent optical networks with dynamic traffic [13]. In this work we present the DICONET NPOT and its key building blocks along with control plane integration schemes. The performance of centralized and distributed impairment-aware control plane approaches over a realistic 14-node experimental test-bed under dynamic traffic conditions are also presented. The experimental test-bed integrates the developed NPOT engine, the extended GMPLS control plane protocols required for supporting the innovative DICONET solutions and the various communication protocols to allow all DICONET building blocks to run in an orchestrated fashion. To the best of our knowledge, for the first time, impairment-aware control plane schemes with integrated real-time Quality of Transmission (QoT) estimator are demonstrated.

This paper is organized as follows. In Section II we present the architecture and key building blocks of the DICONET NPOT. The control plane integration schemes, in which the NPOT is integrated into an impairment aware control plane is explained in Section III. The experimental setup and obtained results are presented in Section IV and Section V respectively. Section VI draws the conclusions of this work.

II. Network Planning and Operation Tool

The main novelty of the DICONET project [3] is the design and development of a physical layer impairments 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. 1. Network description repositories, QoT estimator, IA-RWA engines, component placement modules and failure handling module are the key building blocks of the NPOT. The planning mode specific modules are accessible through a command line interface (CLI). In order to realize the communication of the NPOT with the other entities in the DICONET control plane integration schemes (operation mode), a messaging protocol layer is designed and implemented on top of the standard TCP/IP socket interface. The modular design of the 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 the existing ones. In the sequel we present each of these building blocks of the NPOT.

A. Network Description Repositories

The network description (both at physical layer level and topology level) is included in two main repositories that are kept as external databases to the NPOT. The Physical Parameters Database (PPD) is the master repository, which 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 kept in the PPD (expressed in XML format). The Traffic Engineering Database (TED) includes the nodes and detailed network topology in XML format. The connectivity of the nodes in the network and the definitions of network nodes (e.g. node ID, node IP address, node names) are kept in this repository. The NPOT XML parser is responsible to parse the XML repositories and transform the network description (physical specification and network topology) into the internal data structures, which are stored inside the NPOT memory. The NPOT PPD and TED manager is responsible to manage the PPD and TED data structures, while they are residing inside NPOT memory.

B. QoT Estimator

In the framework of transparent optical networks, physical layer impairments can be categorized into "static" and "dynamic" impairments. Static impairments are topology-dependent: they do not depend on the dynamic state of the network (i.e., 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) [10].

To assess the QoT of a lightpath in NPOT, we have developed a "Q-Tool" which is able to compute the so-called "Q-factor" for a lightpath given the network topology, physical characteristics, and network state (i.e., active lightpaths in the network). The NPOT Q-Tool offers fast assessment of the QoT of a lightpath given a specific set of lightpaths, and physical topology; based on analytical and numerical simulations. The building blocks of the NPOT Q-Tool are presented in Fig. 2. 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) and then computes the Q-factor of those lightpaths and return them back to the calling module. The Q-Tool is developed in MATLAB and interfaced to NPOT through a shared library. 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:

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

where the Q factor is defined as [14]:

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

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.

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

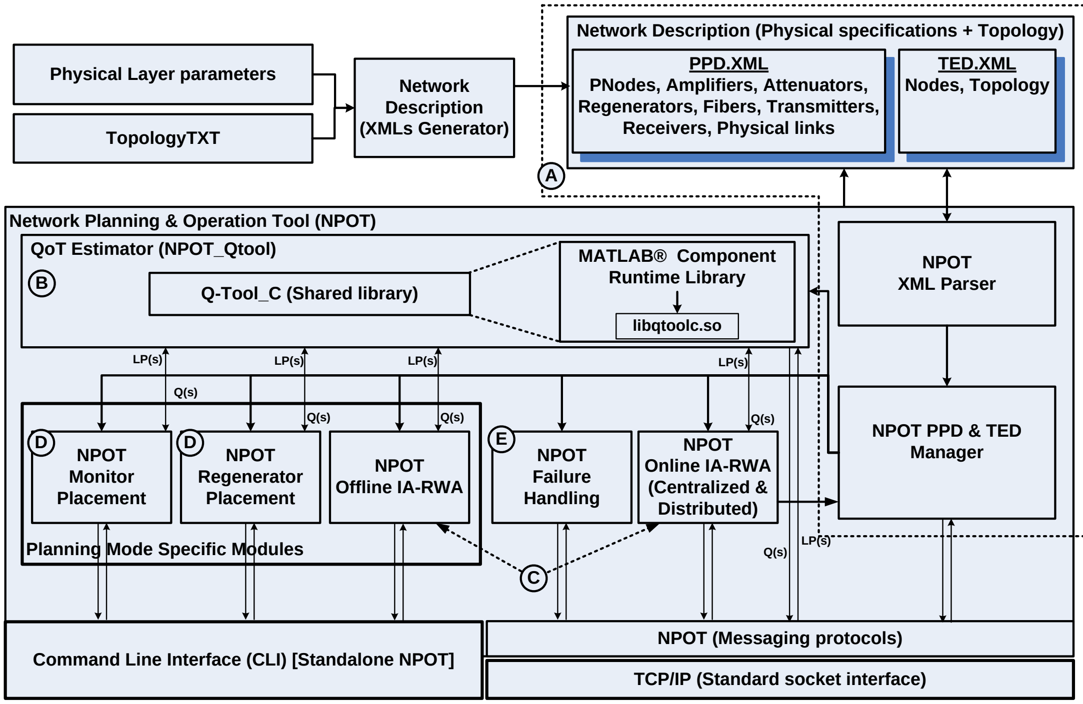

Fig. 1. Anatomy of DICONET Network Planning and Operation Tool: A) Network description repositories, B) QoT estimator, C) IA-RWA engines, D) Component placement modules, and E) Failure handling module.

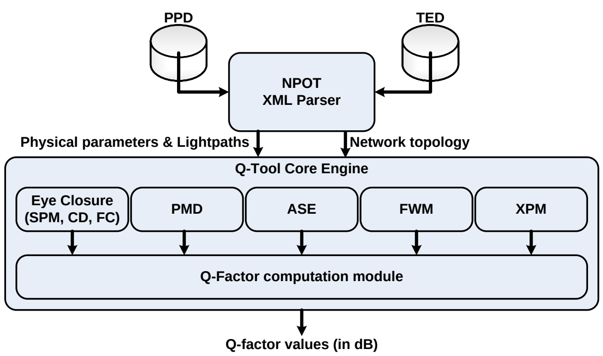

Fig. 2. Building blocks of the NPOT Q-Tool module.

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

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

The numerator of (3) refers to the difference of the minimum detected current at the level of “1” and the maximum at the “0” level which defines the distortion induced by SPM, CD and FC on the signal (Eye diagram closure effect). The summand in the denominator of (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 (0s) and marks (1s) 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 has to be subtracted from the total estimated Q-factor.

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 in the process. Thus, contrary to various similar works ([15], [16], and [17]) that rely solely on analytical or semi-analytical models to estimate the QoT, the proposed Q-Tool introduces a balance between speed and accuracy by numerically simulating the single-channel signal propagation.

The analytical model utilized in the NPOT Q-Tool to estimate the power of the ASE noise of a cascade of inline (EDFA) amplifiers is similar to the models in [18], [19] to assess 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 [20], which is properly modified to match the specific link architecture. The analytical expression of σ^2_{XPM} is derived using the approach reported in [15].

The NPOT Q-Tool treats XPM and FWM as random noise that affects the QoT identically as ASE noise, imposing fluctuations that typically occur at the mark level. As shown in [21] 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 [21] 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 ([20] "Cartaxo model"), as in the Q-Tool. It was shown in [21] that FWM is well approximated with a Gaussian distribution. Assuming a random behavior is particularly applicable in FWM due to the fact that many independent channels contribute to the total FWM power. The work in [21] utilizes the model reported in [22] and is extended for a multi-span system, which is implemented in the NPOT Q-Tool.

To estimate the PMD induced penalty on Q-factor values the approach used in [23] is utilized in the NPOT Q-Tool. To calculate the PMD-induced penalty two different methods have been generally followed [24]. 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 a comparison for a 10Gb/s NRZ signal in [24] 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 rendering the choice for the analytical approach valid for the framework of DICONET NPOT. However, in a higher-bit-rate system, in which robust modulation formats to PMD are utilized (e.g. RZ), the mentioned approach could not be applied.

C. 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 under the form of lightpaths (i.e., the combination of a route between two nodes, and a wavelength), the problem of pre-planned resource allocation in such networks is called static or offline RWA problem [10]. The offline IA-RWA algorithm, which is utilized in the NPOT is named offline "Rahyab"[1] and is adopted from [4]. There are two IA-RWA engines for the operation (online) mode of the NPOT. In the distributed integration scheme, which will be defined in more detail in Section III, the NPOT IA-RWA module receives a demand, computes k shortest routes from source to destination without PLIs consideration. In case of demand with (1+1) protection requirement, this module computes k diverse pairs of primary and backup paths. The caller module (i.e., Optical Connection Controller "OCC") tries to establish the lightpath from source to destination using the extended 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 Section III) the NPOT IA-RWA engine [6] computes the lightpath from source to destination and assigns a wavelength for it and returns it back to the caller (i.e., OCC). The OCC tries to establish the lightpath using the signaling protocol and returns the result of the lightpath establishment process back to the NPOT. If the establishment is successful, the NPOT updates the list of active lightpaths in the network and also updates the topology data structure. If the lightpath establishment is not successful, the source OCC notifies the NPOT accordingly.

[1]Rahyab means "path finder" in the Persian language.

The IA-RWA engines in general can be used for transparent or translucent optical networks. In the case of translucent networks, the information regarding the regeneration sites (decided by the COR2P algorithm of the NPOT) are available through the PPD repository. Particularly in the distributed scheme, the utilized IA-RWA engine is not constrained by the regeneration sites, whereas the IA-RWA algorithm of the centralized case is able to exploit them. However, the experimental setup represents a transparent optical network and both centralized and distributed schemes are evaluated under similar conditions.

D. Component Placement Modules

Regenerator and monitor placement modules are two component placement modules of the NPOT, which are mainly designed for planning mode. The main assumption in all-optical network 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 8000 km, clearly some regeneration is still required. The NPOT regenerator placement module is responsible for optimizing the number of regeneration sites and modules 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 [25], [26]. This module receives a demand set (traffic matrix) along with the network description and minimizes the number of required regeneration sites and regeneration ports in the network. The COR2P algorithm utilizes the NPOT Q-Tool in order to evaluate the performance of the physical layer. In addition to the regenerator placement, the NPOT exploits a special purpose monitor placement algorithm, which 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 [7], or failure localization.

E. Failure handling

When a failure occurs, the optical transparency leads to a propagation of Loss-of-Light (LoL) alarms, which are detected in the incoming port of all downstream nodes from the failure point. This makes additional failure localization functionalities necessary in networks where transport plane devices operate in transparent mode. Such functionalities are provided in GMPLS by the LMP protocol [27].

Assuming that LoL alarms for one or multiple input wavelengths are received, the goal of LMP is to determine whether

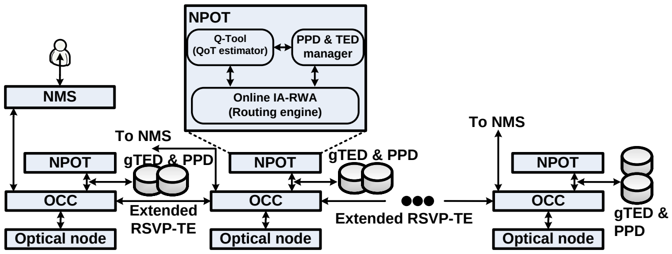

Fig. 3. Distributed control plane integration scheme.

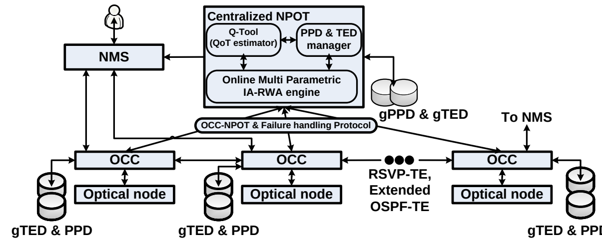

Fig. 4. Centralized control plane integration scheme.

the failure has occurred in the local link connected to the upstream node of the affected lightpaths or in any of the further upstream links. For these purposes, the node, which detects the LoL sends a *ChannelStatus* message [27] to the adjacent node containing the list of individual failed wavelengths (if no individual wavelength is specified, this indicates that the whole link is failed). Upon receiving this message, the adjacent node correlates the failure alarms, checking whether it is also detected locally for the affected lightpaths. If the failure is clear on its input wavelengths, the failure is localized on the link connecting both nodes. Otherwise, the failure is located on a further upstream link. Once the failure alarms are correlated, the upstream node sends a *ChannelStatus* message back to the downstream node, indicating whether the link is failed or not.

Based on these GMPLS failure management features, the failure handling module in the NPOT is responsible for reacting upon data plane failure situations. This module collects the failure location information from the control plane, sent as an asynchronous trap message from the upstream OCC node. Furthermore, it updates the gTED and gPPD (global PPD and global TED) databases accordingly, so that failed network components are not used in subsequent lightpath computations. Once the upstream OCC node has notified the failure to the NPOT, it can also continue with the recovery of those affected lightpaths. To this end, an RSVP-TE *Notify* message is sent to the source node OCC of each affected lightpath that, in turn, will request the backup lightpath to the NPOT in order to restore the end-to-end connectivity.

III. Control Plane Integration Schemes

Two control plane integration schemes have been investigated and assessed within the DICONET project, namely, distributed and centralized. The remainder of this section presents their details, together with the centralized lightpath restoration procedures that are currently deployed in the test-bed. As will be shown, the NPOT modules described above plays a key role in both integration schemes and failure restoration scenarios.

A. Distributed approach

In the distributed approach (Fig. 3), both RSVP-TE [28] and OSPF-TE [29] protocols were extended to consider PLIs, providing a compromise 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 distributed approach, each node in the network runs an instance of the NPOT, which is connected to an OCC via the NPOT-OCC communication protocol that is specifically developed for NPOT integration schemes. Upon receiving a new connection request, the source OCC node requests the online IA-RWA module of the NPOT to compute k-shortest routes from source to destination without the PLIs knowledge. However, the wavelength availability information stored in the gTED is used in route computations. 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 receiving the PATH message, the destination node requests its NPOT for QoT estimation. 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 that share at least one optical section with the candidate one) are notified to request for a QoT estimation from their respective NPOTs. This verification step makes sure that the Q-factor of the affected active lightpaths remains above the required threshold in spite of 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. If the re-computed Q-factor values of all affected active lightpaths are above the threshold, 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 to the source node, which then tries lightpath establishment on next candidate route. If none of the k-candidate routes meets the required QoT the request is finally blocked. In the distributed mechanism the contention resolution is handled using standard RSVP-TE. During the RESV phase of RSVP-TE, if the wavelength is already reserved for some other concurrent connection, the intermediate node sends a RESV-ERR message to the source node which tries on the next candidate path. The current LSP setup might also result in wrong evaluation of impairment affects and is handled using a distributed resource locking mechanism.

B. Centralized approach

In the centralized approach (Fig. 4), the NPOT carries out the impairment-aware routing and wavelength assignment and failure handling functionalities, while the OCCs execute the extended GMPLS protocols and interface to the actual optical nodes in the test-bed. A TCP-based messaging protocol has been developed to facilitate the communication between 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 for 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), which describe the network topology and the physical layer characteristics completely. In particular, Q-Tool is the module within NPOT that quantifies the impact of the PLIs on the lightpaths' QoT. Note that the same QoT estimator is also used in the distributed scheme.

When the NPOT finds a lightpath with guaranteed QoT (Q-factor value above a pre-defined threshold), the lightpath is returned back to the source OCC which triggers the *standard* RSVP-TE signaling protocol. Upon successful establishment of a lightpath, the global PPD and TED in 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 lack of resources/wavelengths or unacceptable QoT, the demand is blocked and the source OCC informs the NMS accordingly.

When a link failure occurs, the NPOT failure handling module collects the failure location information from the control plane and updates the gTED and gPPD databases accordingly. So the failed network components are not used in subsequent lightpath computations. Once the upstream OCC node has notified the failure to the NPOT, it can also continue with the recovery of those affected lightpaths. The source node OCC of each affected lightpath will be notified and will request the NPOT for the backup lightpath computation to restore the end-to-end connectivity. Then, the source OCCs trigger the signaling protocol for the actual lightpath establishment as explained earlier (Section II-E).

IV. Evaluation Scenario

The experimental evaluation of the proposed approaches has been conducted on the DICONET test-bed located at the UPC premises in Barcelona (Fig. 5). The physical characteristics of the network are depicted in Fig. 6. The test-bed consists of a configurable signaling communications network (SCN) running over Wavelength Selective Switch (WSS)-based OXC emulators. In this configurable SCN, optical connection controllers (OCCs) are interconnected by 100 Mbps full-duplex point-to-point Ethernet links, describing the same physical topology of the emulated optical transport plane.

Each OCC is interconnected with the respective OXC through the Connection Controller Interface (CCI). Moreover, the OCC-NPOT interface interconnects each OCC with the respective NPOT or the centralized NPOT depending on whether the distributed or the centralized approach is evaluated, respectively. Running on top of the architecture, the

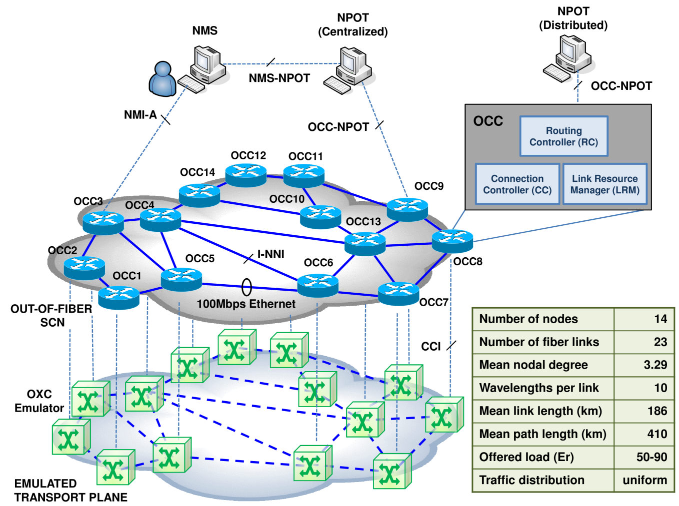

Fig. 5. DICONET testbed set-up. Specific data plane topological parameters and offered traffic characteristics are depicted in the table beside.

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

Fig. 6. Physical layer characteristics of the test-bed, which are stored in XML description of the PPD and used by the NPOT Q-Tool.

developed NMS allows the request of soft-permanent lightpaths via the Network Management Interface (NMI-A), which are served by the GMPLS-enabled control plane automatically. In this way, long and tedious manual interventions related to the traditional static permanent transport services are here avoided. Furthermore, the NMS allows a global supervision of the network active lightpaths state, as well as the current configurations in each network node. In the test bed, OCCs are deployed using Linux-based routers (Pentium IV operating at 2 GHz). Each OCC implements the full GMPLS protocol stack: RSVP-TE for signaling, OSPF-TE for routing and information advertisement, and LMP for failure management. Both RSVP-TE and OSPF-TE protocols have been extended for carrying PLI information, as detailed in Section III.

In this work, a 14-node meshed network configuration describing the same topology as the generic Deutsche Telekom (DT) has been configured. The topology of this network and the link lengths are depicted in Fig. 7. Moreover, 10 bidirectional wavelengths per link have been assumed. Given the physical characteristics of DT network, lightpaths can be transparently established between any two nodes in the network. However, the heterogeneous characteristics of the fiber links and nodes, and considering the impact of neighboring lightpaths on each other, introduce cases in which the QoT of the lightpaths fall below the acceptable threshold. Regarding the

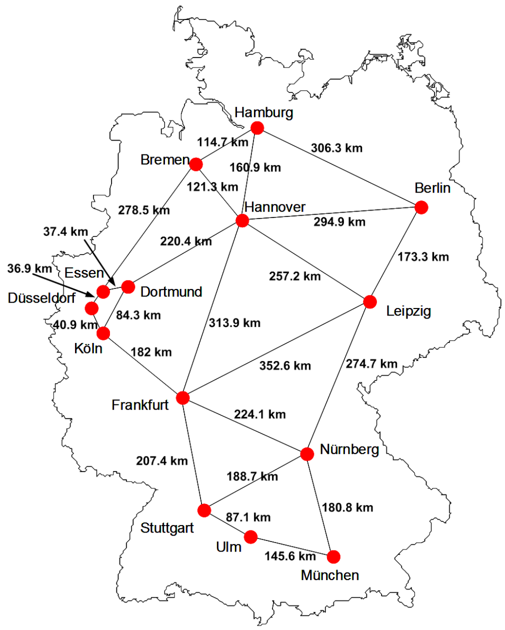

Fig. 7. The topology and link lengths of the Generic Deutsche Telekom (DT) network.

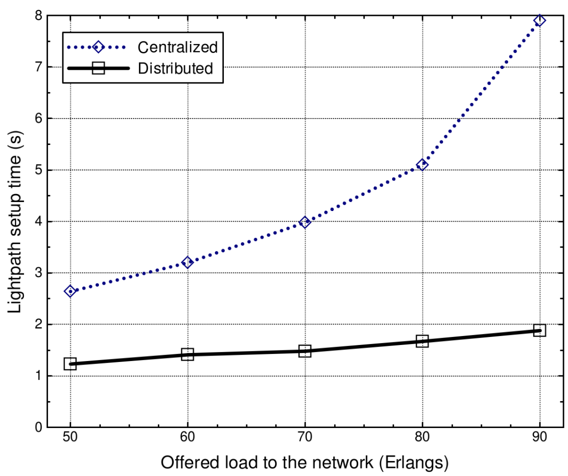

Fig. 8. Performance comparison of centralized and distributed approaches: lightpath setup time as a function of the offered load to the network.

traffic characteristics, uniformly distributed lightpath requests arrive to the network following a Poisson process. Moreover, lightpath holding times (HTs) are exponentially distributed with a mean value of 600 seconds. Different dynamic loads (in Erlangs) are thus generated by modifying the connection inter-arrival times (IATs) accordingly (load = HT/IAT).

V. Experimental results

Figs. 8 and 9 depict the setup delay and the blocking probability (BP) experienced by the incoming lightpath establishment requests, depending on whether the distributed or centralized approach is deployed in the network. In particular, $k = 2$ candidate shortest routes are computed in the distributed case. Each result has been obtained as the average of 10,000 requests.

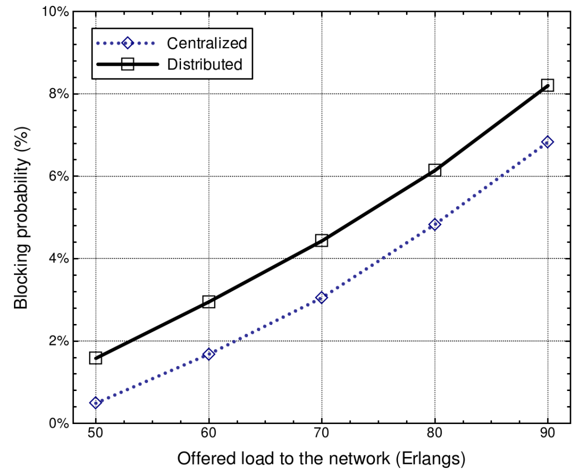

Fig. 9. Performance comparison of centralized and distributed approaches: lightpath blocking probability as a function of the offered load to the network.

Looking at the results in Fig. 8, the distributed approach yields lower setup times, especially as the offered load to the network increases. To explain this, note that in the centralized scheme only one route computation is allowed at the same time. Furthermore, a sufficient amount of time must be left between two consecutive route computations in order to let the centralized NPOT be fed with the new wavelength availability and PLI information. Otherwise, subsequent routes might be computed with inaccurate link state information. Hence, the centralized NPOT scheduler must delay new incoming requests until the signaling and the respective flooding of the previous connection establishment has been completed (around 2 seconds in the test-bed). In contrast, the distributed approach can benefit from parallel lightpath establishments, as the Q-factor values of the new LSP and the involved active ones are computed during the signaling process. This eventually results into very attractive connection setup times, around 1.8 seconds, 1/5th of the setup time reported in [8].

In contrast, Fig. 9 shows that the centralized approach leads to lower BP than the distributed solution. In fact, end-to-end routes in the latter are computed only with wavelength availability information. These routes lead in some occasions to unacceptable Q-factor of candidate or potentially disrupted lightpaths and hence need to be blocked. In contrast, route computation in the centralized approach relies on complete and updated wavelength availability and PLI information, so the computed routes more likely satisfy the requested Q-factor values. Given that the scenarios assume only 10 channels per link, both schemes yield somewhat high blocking probabilities. However the purpose of this result is to underline the relative difference between the two schemes in the presence of high dynamic traffic.

In addition, we have conducted experiments to assess the performance of the proposed centralized lightpath restoration procedures in the network. To this end, we have independently loaded the network with 10, 20, 30, 40 and 50 bidirectional active lighpaths between randomly selected node pairs. The dynamic demands (i.e., requests for a lightpath) can request for either a 1+1 protected or an un-protected restorable lightpath,

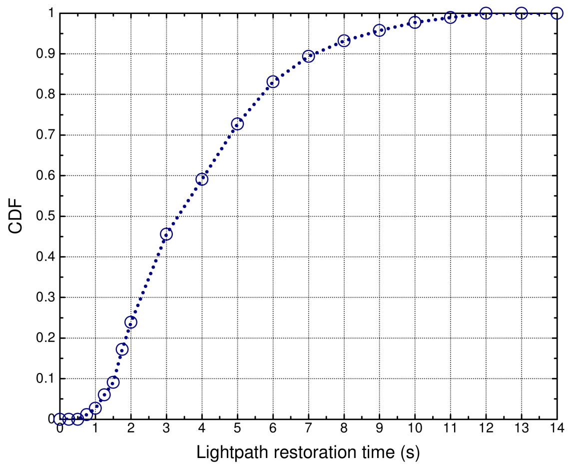

Fig. 10. Cumulative Distribution Function (CDF) of the measured lightpath restoration time in the network.

respectively. For the the unprotected restorable lightpaths, a single QoT-compliant working path is established in the beginning. In case that this path is affected by a failure, a new QoT-compliant backup path computation is requested to the centralized NPOT and the lightpath is dynamically established through the GMPLS-enabled control plane. These connections follow a 70-30% restoreable-protected ratio (i.e., for the 1+1 protected lightpaths, working and backup lightpaths are established at the same time). Then, on each deployed network scenario, 10 independent failures are caused in randomly selected links (only those links carrying restorable traffic are considered), which makes restoration actions for each affected restorable lightpath to be triggered.

This set of 500 experiments enables the measurement of the total restoration time in the network, obtaining 3.6 seconds in average. For better illustration, Fig. 10 also plots the Cumulative Distribution Function (CDF) of these measured lightpath restoration times, that is, the probability that a lightpath restoration does not exceed a certain number of seconds. From the figure, we can see that 72% of the lightpath restorations are performed only within 5 seconds, although the sequential behavior of the NPOT may occasionally lead to increased restoration times when a high number of lightpaths are affected (e.g., 10 s in 2% of the cases). Finally, we have measured the physical distances of the primary and backup lightpaths. From the results, the average physical distance of the primary lightpaths is 452 km, whereas it increases to 630 km for the backup ones. Nonetheless, the NPOT always assures the required QoT for them, which is crucial for the successful restoration.

VI. Conclusions

A key contribution of DICONET project is the design and development of a physical layer impairments aware network planning and operation tool that resides in the core network nodes that incorporates the performance of the physical layer in planning and operation decisions. The architecture and key building blocks (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 presented centralized and distributed control plane integration approaches for impairment-aware transparent optical networks. From the experimental evaluation, the distributed approach provides one fifth of the lightpath setup time than that of previously reported (centralized) alternatives, also outperforming our centralized approach especially for high traffic loads. For low traffic loads, however, our centralized approach results in reduced lightpath blocking ratio and similar setup time delays than the distributed solution, thus being more appropriate in such scenarios. Efforts in DICONET will be devoted to further reduce lightpath setup time to milliseconds' time-scales by means of FPGA hardware acceleration.

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