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DICONET: future generation transparent networking with dynamic impairment awareness*

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Abstract. Transparent networks are widely seen as the prime candidates for the core network technology of the future. These networks provide ultra high speed end-to-end connectivity with high quality of service and failure resiliency. A downside of transparency is the accumulation of physical impairments over long distances, which are difficult to mitigate using physical-layer techniques only, and the novel challenges in fault detection/localization. We present here the DICONET project, a set of techniques and algorithms implemented at multiple layers, culminating with the physical implementation of a transparent optical network on a testbed. DICONET consists of a set of impairment-aware network management algorithms, such as routing and wavelength assignment, monitoring, failure localization, rerouting, all integrated within a unified control plane, which extends known solutions to include the impairment-awareness of the underlying layers.

1 Introduction

With ever increasing bandwidth needs, spurred by the emergence of increasingly bandwidth demanding applications such as e-science, e-health, and high-definition video-on-demand and video broadcasting, the future Internet will need

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an ultra high-speed backbone. In addition to the large raw available bandwidth, the future Internet is expected to offer such services as high resiliency to hardware failure, the possibility to request and be granted the utilization of resources with guaranteed quality of service (QoS), for instance, in terms of signal quality, or in terms of guaranteed available bandwidth. The current infrastructure is called "opaque" because signals are regenerated by electronic devices at every node. This makes ultra-high bandwidth and QoS guarantees/management difficult, not scalable, and cost-ineffective. A departure from opaqueness is offered by the possibility to switch signals in the optical domain, rather than in the electrical domain, using so-called "optical crossconnects" (OXCs). In transparent optical networks, where light is switched in the optical domain, data is carried over pre-established circuits called "lightpaths", consisting of a route and a wavelength. The transition from opaque to transparent networking, however, is not possible for all backbone networks. Indeed, transparency implies the transmission of signals over very long distances with no electrical regeneration. Physical impairments accumulate over such distances (potentially thousands of kilometers for very large, continental-sized networks), making error free transmission difficult or impossible to achieve. To overcome this issue, it is possible to regenerate signals at a small number of sites, thereby increasing the total distance that can be spanned by lightpaths. Such networks where regeneration is present at certain nodes only is a compromise between transparent networks and opaque networks are called semi-transparent "managed reach" optical networks.

Transparency (full or partial) in optical networks eliminates the electronic bottleneck, thereby allowing ultra-high datarates in core networks in a cost effective fashion, and the utilization of the circuit-switched technology is an enabling component for many traffic engineering techniques aiming at providing end-to-end QoS and high resiliency. The evolution of networks from opaqueness to transparency requires new hardware, such as the transition from electrical switches to OXCs, but also novel higher layer techniques and protocols to operate and manage the network in order to guarantee that the benefits of transparency for the end-users (QoS, resilience) are actually attained despite the adverse effects of the physical layer. In addition to impairment accumulation, transparent networks make failure localization difficult: indeed, it is not possible to know which equipment on a path is responsible for a fault that is detected by standard electronic hardware in an end-to-end fashion. Electrical regeneration at all nodes permits to isolate faults to the link/node where the fault occurred. Such fault isolation, and, in some sense, mitigation, inherent to opaque networks, is removed in transparent netwoks. Efficient fault detection and mitigation is needed to achieve high resilience purposes and meet Service Level Agreements (SLAs).

The two aforementioned issues inherent to transparency — enhanced physical impairments and change of paradigm needed in failure localization — have prevented operators to deploy transparent networks, despite the benefits in both CAPEX and OPEX. The DICONET project (Dynamic Impairment Constraint networking for transparent mesh Optical NETworks) project brings answers to these open issues [1].

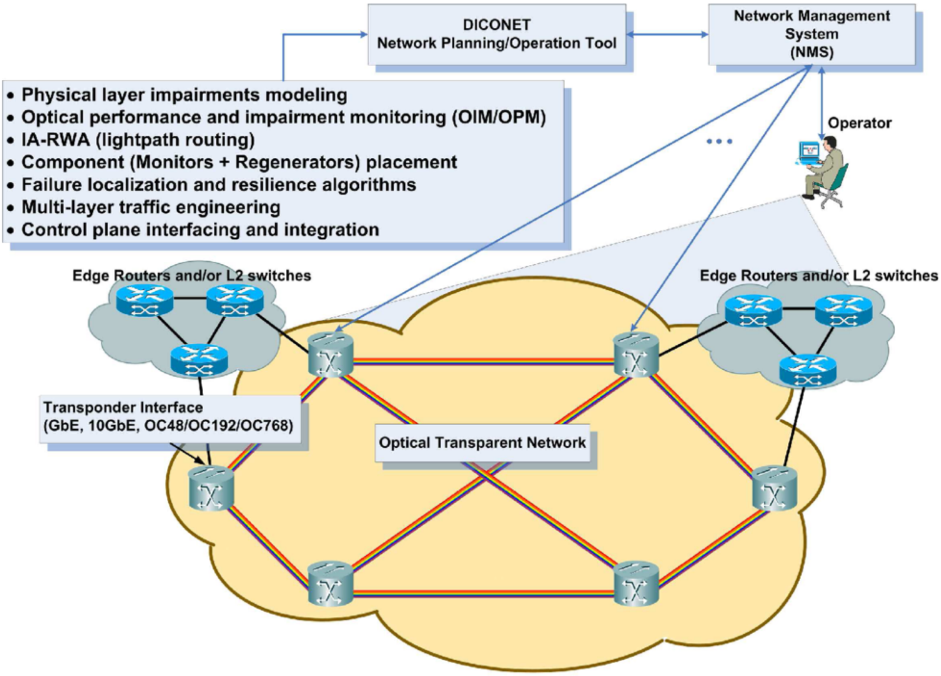

Fig. 1. DICONET vision.

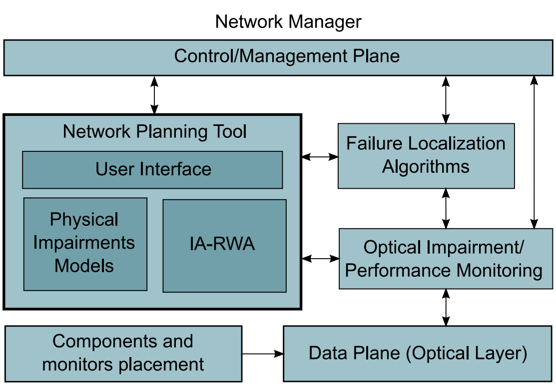

Fig. 2. DICONET components.

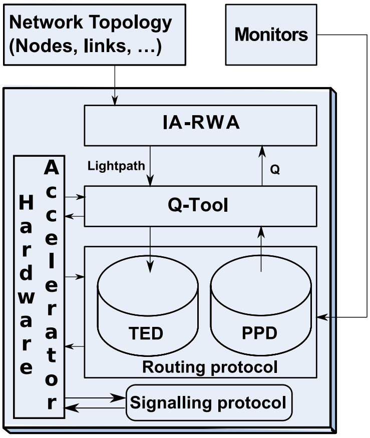

Fig. 3. Control plane architecture: overview.

As depicted in Fig. 1, we propose to extend the core optical networks intelligence to the data plane on the optical layer using a crosslayer approach. To achieve this, a network planning tool is responsible for integrating all the information needed for the control plane to make decisions as is shown in Fig. 2. For instance, the network planning tool gathers the topology and monitoring data to compute Q-factors (a measure of signals Quality of Transmission, QoT) on which control plane routing and wavelength assignment (RWA is the process of finding a lightpath for a network utilization demand) decisions are based. The network planning tool also deals with complex situations where monitoring information is missing and must be estimated from past or other measurements.

The techniques and algorithms developed within the DICONET project are validated using simulations and experiments — mainly using a small-scale testbed mixing real and emulated all-optical nodes. In particular, simulations are carried on over two realistic topologies for which all necessary physical parameters are known: the “Deutsche Telekom” topology, a country-sized (diameter: 800 km) network of 14 nodes and 23 bidirectional links, and the “GEANT-2” topology, a continental-sized (diameter: 7000 km) network of 34 nodes and 52 bidirectional links. Although the Deutsche Telekom topology can be used to simulate fully transparent networks, the GEANT-2 topology is too large to be fully transparent, and hence is used to validate algorithms specific to semi-transparent scenarios such as regenerator placement.

In the remainder of this article, the elements revolving around the network planning tool are described: physical layer-related techniques and tools in Section 2, Impairment-Aware RWA in Section 3, the fault management techniques 4, and the control plane 5. Future work that goes beyond DICONET is outlined in the concluding section.

2 Physical Layer modeling, monitoring, estimation

In current backbone networks, where signals are regenerated by optical-electrical-optical converters at every node, achieving error-free transmission (e.g., Bit-Error Rate: BER$< 10^{-5}$ before Forward Error Correction) is done by proper link engineering. In future generation transparent core optical networks, lightpaths traverse several links without regeneration and physical impairments accumulate over potentially very long propagation distances. Thus, real-time or near real-time monitoring of the physical impairments that have an impact on signals' BER is needed, in order to provide the control plane the adequate information to *detect failures or equipment quality degradation/aging*, ensure that *Service Level Agreements* in terms of signals' quality of transmission are met, and to make appropriate *RWA or rerouting* decisions to mitigate physical layer impairments.

Relevant physical impairments for 10Gbps transparent optical networks with standard fiber, dispersion map and grid spacing were shown to be the interplay between chromatic dispersion and self-phase modulation, amplifier noise, and multichannel nonlinear effects (crossphase modulation, XPM, and four wave mixing, FWM). Multichannel impairments (XPM and FWM) cause the QoT of different lightpaths to be interdependent, since establishing a new lightpath may increase the impairments seen by other already established lightpaths to increase. As will be seen shortly in Section 3, this interdependence renders physical-layer only network design cost-ineffective and paves the way for more advanced, cross-layer techniques, to mitigate physical layer impairments. Although relevant for different architectures (for instance, with tighter grids or higher bitrates), node crosstalk resulting from optical single leaks at nodes can be ignored with the standard 50 GHz ITU grid spacing for 10Gbps NRZ-modulated signals. At 40Gbps, polarization mode dispersion (PMD) has to be accounted for.

We combine two complementary approaches to know the quality of the transmission seen by lightpaths — which can be lightpaths already established in the network, or candidate lightpaths selected by a RWA algorithm. Hardware monitors, placed at strategic locations, inform the control plane about the current state of the network. We classify monitors into the following two types: Optical Impairment Monitors (OIM) are deployed at the *link level* and allow for efficient failure localization and lightpaths transmission quality *estimation*, while Optical Performance Monitors (OPM) give *measurements* of *end-to-end* lightpaths transmission quality. To achieve efficient and useful monitoring, it is necessary to deploy the following OIM equipment: optical power, optical signal to noise ratio (OSNR), chromatic dispersion and PMD monitors. While optical power monitors are typically implemented by default at all optical nodes, the other OIMs are expensive equipment which can only be deployed at a few locations. In the case of OSNR, however, it was shown recently that, by adding power monitors at non-standard locations (e.g., inline amplification sites) and by using appropriate estimation method, the information gained with the additional power monitors is sufficient to accurately estimate OSNR. End-to-end lightpaths' quality of transmission will be monitored through Q-factor monitors — the so-called "Q-factor", defined as the ratio $(\mu_1 - \mu_0)/(\sigma_0 + \sigma_1)$ between the mean difference $(\mu_1 - \mu_0)$ over the sum of the standard deviations $(\sigma_0 + \sigma_1)$ of sampled "0" and "1" symbols after photodetection. Q-factor monitoring is generally expensive, especially because the clock recovery step needed to perform synchronous sampling to obtain the relevant quantities $\mu_0, \mu_1, \sigma_0, \sigma_1$ at the optimal sampling time. We have proposed novel asynchronous Q-factor monitoring techniques that bypass the need for clock recovery [1].

In some cases, no OPM information is available but the BER of a lightpath needs to be known. This can be due to the lack of OPM hardware at a specific location, or because the BER of a lightpath that is not yet established (hence does not physically exist). In such cases, *monitoring* is not possible and *estimation techniques* have to be employed. In particular, we use a "QTool" to estimate Q-factors for lightpaths not monitored or established. "QTool" relies on well-known physical layer models [2] and is fed with the OIM information. If OIM data needed by QTool is missing, it is interpolated from available data and analytical models. The QTool is an important part of a transparent network architecture as the lightpath establishment module relies on it to estimate a priori the Q factor of candidate lightpaths. Underestimation of Q may lead to rejection of lightpaths which Q factor is actually acceptable, while overestimation may lead to acceptance of lightpaths which Q factor is actually too low to guarantee error-free transmission. In addition, overdesigning is needed to counter adversarial effects of physical parameters measurement/estimation errors. We have shown that an uncertainty in powers (which are in turn needed to compute Q factors) above 0.5 dB leads an explosion in the amount of the resulting needed overdesigning (e.g., in terms of regenerators) by network designers [3].

3 Impairment aware lightpath routing

In transparent networks, data is transmitted over "lightpaths", the combination of a route and a wavelength. Because all-optical wavelength conversion is still experimental, once a signal is launched over a channel, it has to remain on the same channel (wavelength) from end-to-end, or from electrical regenerator to electrical regenerator in the case of semi-transparent networks. Such constraint, unique to all-optical networks, is called "wavelength continuity constraint". RWA refers to the problem of finding a route and a wavelength for each demand in a set; the demands can be static (e.g., known in advance, for long-term capacity allocation) or dynamic (lightpath demands arriving at the network management system potentially randomly, e.g. for e-science, e-health, content delivery networks, and other very high-speed applications). Even if the demand set is known, as in the static case, the RWA problem is known to be NP-complete [4], warranting the search for heuristics. In the case of transparent networks, the situation is made more complicated by the accumulation of physical impairments as signals propagate through the links. Indeed, mechanisms must be devised to ensure that signals' quality remain above a predetermined threshold to guarantee error-free communication even as physical impairments (potentially originating from interaction with other signals as in XPM and FWM) accumulate. When lightpaths are blocked because its QoT would be insufficient, or because establishing it would cause the QoT of other lightpaths to become insufficient, "QoT blocking" occurs. The QoT of a signal depends not only on the signal's path, but also on the existence of other signals in the network through nonlinear effects (XPM/FWM). This further adds to the complexity of the RWA problem in transparent networks. RWA algorithms that take into account physical layer information/impairments to make a decision are called impairment-aware RWA (IA-RWA) algorithms.

Although much research has been devoted to the online routing case where demand arrivals and terminations are dynamic (see the survey [5], where we compared and categorized more than 80 RWA algorithms), static or offline RWA where the lightpaths' demand set is known in advance by the network operator has been far less studied.

In particular, in [6], we solved the offline IA-RWA problem using a linear programming (LP) formulation. Although the RWA problem is originally an integer, not linear, programming problem, we used computationally efficient LP techniques and obtained integer solutions by proper piecewise linearization of the cost function and rounding techniques. Physical layer impairments are accounted for directly within the programming formulation by adding two sets of constraints, one seeking to minimize lightpaths' lengths and the other to minimize interference between copropagating lightpaths. In another approach, all physical constraints were integrated in a single set of constraints by converting the impact of all effects into a single "noise" parameter. It was shown through simulations that considering physical impairments within the LP formulation decreases sharply demand blocking rate compared with the case where physical impairments are evaluated as a final check. The single-parameter formulation decreases blocking rate even further.

Although LP is a valuable tool to compute (near-)optimal solutions to the IA-RWA problem, it is computationally expensive to run and faster heuristics should be considered too. In [7], we developed such heuristics, based on a preprocessing step where demands are ordered taking into account their expected resource consumption: demands using more capacity, which are expected to be more difficult to accommodate, are allocated first. Since the algorithm relies on simple heuristics, it is computationally efficient and we showed through simulations that blocking rate was decreased when using this pre-ordering heuristic. The algorithm was also adapted to the case where some lightpaths needed protection.

4 Failure localization

By design, transparent nodes (OXCs) do not decode signals that traverse them and component failure can only be detected in an end-to-end, as opposed to local, fashion. This makes failure localization difficult in transparent networks. At the same time, failure recovery and localization is very important in networks where a single link can carry dozens of wavelengths modulated at 10-40Gbps each. It was shown in a recent study that CAPEX gains of shared (e.g. 1:1) protection over dedicated (e.g. 1+1) path protection are negligible in transparent optical networks [8]; however, it should be kept in mind that shared protection incurs higher OPEX than dedicated protection.

Single failure detection and recovery is a well-known topic in transparent optical networks, but the multiple failure case was far less studied. This problem was shown to be NP-complete and heuristics are needed. We will propose a cross-layer failure detection algorithm that is able to account for the differences at the physical layer of the various network components and effects of potential effects (e.g., in terms of failure propagation) to effectively determine the origins of detected failures. Another algorithm has been proposed to correlate multiple failures locally at any node and to 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 grain recovery switching actions. Failure detection relies on the knowledge of the network's physical layer state, which is addressed in the following section through control plane mechanisms.

5 Control Plane

Monitors, nodes, network management system communicate through a so-called "control plane", a set of protocols which makes interactions between all elements in the network possible. The control plane is ultimately responsible for lightpath establishment, tearing down, rerouting, failure detection, dissemination of hardware monitoring information, and traffic engineering in general. Several protocols well-adapted to circuit-switching architectures at the wavelength granularity already exist; however, none incorporates physical layer characteristics. For this reason, we propose to extend well-known protocols to include optical layer characteristics in control planes. DICONET will evaluate and implement two distinct GMPLS-based control planes: a centralized control plane and a distributed control plane, both relying on the building blocks depicted in Fig. 3.

The IA-RWA module makes RWA decisions based on QTool computations. The QTool computes Q factors based on information contained in two databases: the "traffic engineering database" (TED), which contains resource availability information while the "physical parameters database" (PPD) contains impairment-related information.

In the centralized approach, all computations are done by a dedicated process called "Path Computing Element" (PCE) on a dedicated server. In Fig. 3, the PCE groups the IA-RWA and QTool blocks as well as the hardware acceleration module, which is presented in detail further in this section. The control plane learns monitoring information via extensions of the routing protocol (OSPF-TE) or with SNMP queries. Standard RSVP-TE is used for the signaling.

In the distributed approach, an instance of the control plane runs on every node. A link-state routing protocol, OSPF-TE, can be used to disseminate the monitor information to all nodes. By design, information in the TED or PPD can be outdated as OSPF-TE takes a positive time to converge. Signaling is done by a modified version of RSVP-TE that is able to account for impairments in real time, as a lightpath is being established [9]. This is done to counter any stalled or outdated information in the local TED/PPD.

These two solutions are investigated in depth to determine which is best suited to transparent core optical network. The centralized approach suffers from the lack of scalability and the single point of failure issues, but is able to compute optimal paths as all relevant and current data is known by the control plane. The distributed approach is more scalable but may make sub-optimal choices especially if the data it bases its decisions on is outdated.

Signaling and routing protocols of the GMPLS control plane stack are complex with many messages, parameters and procedures. Frequent updates are needed to account for the dynamic network state. Thus, current implementations of GMPLS control plane protocols (signaling and routing) are purely software-based. The software-based implementation can handle a complex control plane and in a flexible fashion. However, the performance of the software implementation can degrade dramatically when the network size, connectivity and number of calls or connection requests increase. GMPLS implementations in software are rarely capable to handle large number of requests in a few milliseconds. Considering that the connection setup time per optical switch is in the order of milliseconds, this bottleneck of control plane can have adverse effect on the network performance. The DICONET control plane uses extended GMPLS to facilitate IA-RWA and fault localization which makes the software stack even more complex and computationally intensive compared to standard GMPLS implementations. Example of these functions include impairment-aware forwarding and path selection and fault localization/detection, and in particular online physical layer impairment processing like the QTool. Therefore, to improve performance of the control plane, a hardware implementation of some of computationally intensive control protocol procedures can be envisioned. The main objective is to overcome the complexity of the control plane stack by implementing only time critical procedures of the DICONET control protocols in Field Programmable Gate Arrays (FPGAs) with embedded network processor in the form of a control protocol hardware accelerator. The hardware can potentially perform control protocol procedures up to 1000 times faster than the equivalent software based approach. Some of the protocols mentioned in the three architectures needs extensions to standard protocols (e.g., RSVP-TE, OSPF-TE) and standardization efforts for an impairment-aware control plane has already started [9, 10].

6 Future work

DICONET is a broad project which aims at making concrete many requirements of the core optical network of the future, focusing on the interplay between the physical layer, which effects cannot be ignored at the core networks scale, and the upper layers, by using an adapted network planning tool and control plane. The project has started in January 2008 and will end in June 2010. By that time, a working implementation of the techniques developed will be running over a testbed mixing real and emulated OXCs. The so-called network planning tool will integrate all developed techniques and a cross-layer control plane will be implemented and running. Key functions will be implemented into FPGA, a demonstration will take place, control plane extensions will be standardized and the economic viability of the DICONET approach to future generation optical networks will be proved with a techno-economic study. Because we can leverage the strong complementarity between academic and industrial partners, it is expected that the prototype can be used as a starting point for industry-grade development and deployment of future generation optical networks.

Although the DICONET project addresses challenging issues, such as creating a control plane for a new kind of network and developing failure localization algorithm, it is only a first step towards even more complex architectures. Indeed, even when transparency is achieved and the issues addressed by DICONET are solved through cross-layer design for core networks, the segmentation between access and core networks, and the isolation between core networks operated by different managing entities, means that QoS from end-user to end-user is currently impossible to achieve. Therefore, the research presented here in the context of core networks should be extended to provide true end-to-end connectivity and transparency or partial transparency, through appropriate technical and standardization efforts.

7 Acknowledgments

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