

Dynamic Impairment Aware Networking for Transparent Mesh Optical Networks: Activities of EU project DICONET

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Abstract

In order to realize the core networks of the future utilizing the translucent or transparent optical networks the DICONET¹ vision is presented in this article. Providing ultra high-speed end-to-end connectivity with quality of service and high reliability through the exploitation of optimized protocols and lightpath routing algorithms that will complement a flexible control and management plane is integrated in the proposed solution. Physical layer impairments and optical performance are monitored and incorporated in impairment aware lightpath routing algorithms. These algorithms will be integrated into a novel dynamic network planning tool that would consider dynamic traffic characteristics, a reconfigurable optical layer, varying physical impairment and component characteristics. The network planning tool along with extended control planes will make possible to realize the vision of optical transparency possible. This article presents the DICONET framework, which address dynamic cross-layer network planning and optimization while considering the development of a future transport network infrastructure.

Introduction

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

The evolution of optical network architectures can be summarized as opaque, manages reach and transparent (all-optical) networks (see Fig. 1). In opaque architecture the optical signal carrying traffic undergoes an optical-electronic-optical (OEO) conversion at every node in the network. The OEO conversion enables the optical signal to reach long distances; however it is quite expensive due to the number of regenerators required in the network and the dependency of conversion process to the connection bit-rate, and modulation formats. Furthermore commercial regenerators operate on a per wavelength basis, which is directly translated to higher cost in WDM (and even more in dense WDM) systems. Transparent (or all-optical) network architecture was proposed to reduce the associated cost of opaque networks. In transparent networks the signals are transported end-to-end optically, without any OEO conversions along their path. Physical signal impairments limit the transparent reach distance and in order to regenerate signal in optical domain, all-optical regenerators are required, which are not commercially available. Managed reach (semi-transparent or translucent) approach has been proposed as a compromise between opaque and transparent networks [1]. In this approach, selective regeneration is used at specific network locations in order to maintain the acceptable signal quality from source to its

1 - The DICONET project is funded by the Information and Communication Technology program, European Commission, and contributes to the strategic objective "The Network of the Future" by supporting innovative networking solutions and technologies for intelligent and transparent optical networks. The partners of DICONET are acknowledged.

destination. Comparing to the opaque networks, this approach reduces the number of required regenerators, but introduce requirements for optimal regenerator placement during planning phase, complex management, and monitoring of the signal quality in the operational phase.

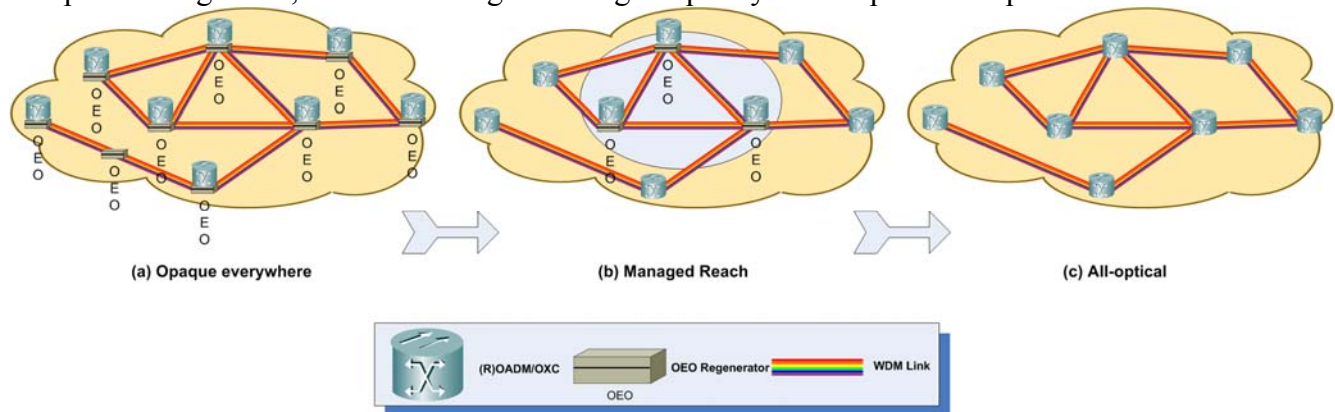


Figure 1: Optical networks evolution [1]

The network infrastructure of existing core networks is currently undergoing a transformation. All-optical core WDM networks using reconfigurable optical add/drop multiplexers (ROADMs) and tunable lasers appear to be on the road toward widespread deployment and could evolve to all-optical mesh networks based on optical cross connects (OXCs) in the future. In order to realize the vision of transparency, while offering efficient resource utilization and strict quality of service guarantees based on certain service level agreements the core network should efficiently provide high capacity, fast and flexible provisioning of links, high-reliability, and intelligent control and management functionalities. To accommodate all the above requirements in a cost effective manner, an optical core network must be planned in a way that can be easily managed and upgraded in terms of transparency and reconfigurability.

The issues of core optical network planning and operation have been recognized within the FP7 DICONET project as the key enabler for the realization of transparent dynamic optical networks. In this article the existing static network planning procedures are extended toward equivalent ones for a flexible and dynamic networking paradigm. After introducing the main challenges involved in transparent optical networks, the DICONET vision and objectives, including physical layer modeling, optical performance and impairment monitoring schemes, impairment aware path computation, failure localization and control plane extensions is presented.

Transparent Optical Network Challenges

Introducing optical transparency reduces the ability of the digital electronics layer to interact with the optical layer. In practical cases, many end-to-end traffic demands may have a granularity lower than the optical channel capacity. An all-optical lightpath lacks granularity since it corresponds to the whole capacity of an optical channel. The only way to ensure a better use of transparent optical channels is to proceed to electrical traffic grooming of individual connections into all-optical lightpaths. This operation is carried out by means of multi-layer switching nodes made of an electrical cross-connects coupled to optical cross-connects.

Optical transparency has an impact on network design, either by adapting the size of WDM transparent domains in order to neglect physical impact on quality of transmission, or by introducing physical considerations in the network planning process (e.g. extra rules for WDM systems, or performance monitoring). Thus, measurement databases and physical impairments aware algorithms are required. Similarly, new management and control plane functionalities must be defined for dynamic connection management and fault monitoring.

The realization of fully automated and dynamic transparent core optical networks is a difficult task although highly desirable due to the expected cost & performance benefits. This goal has not been yet achieved in commercial exploitation due to: a) limited system reach and overall transparent optical network performance and b) difficulties related to the fault localization and isolation in transparent optical networks.

In transparent optical networks as the signal propagates through a transparent network it experiences the impact of a variety of quality degrading phenomena that are introduced by different types of signal distortions. These impairments accumulate along the path and limit the system reach and the overall network performance. There are distortions of almost “deterministic” type related only to the pulse stream of a single channel, such as Group Velocity Distortion (GVD) or the optical filtering introduced by the multiplexer/demultiplexer elements at the OXCs. The other category includes degradations with disruptive nature such as Amplified Spontaneous Emission (ASE) noise, WDM nonlinearities (four-wave-mixing and cross-phase-modulation) and finally crosstalk.

In a transparent optical network, failures also propagate transparently and therefore cannot be easily localized and isolated. The huge amount of information transported in optical networks, makes rapid fault localization and isolation a crucial requirement for providing guaranteed quality of service and bounded unavailability times. The identification and location of failures in transparent optical networks is complex due to three factors: a) fault propagation, b) lack of digital information and c) large processing time. A single failure may trigger a large number of alarms, which results in redundancy and/or false alarms for some failures. Supervisory information located in the overhead and/or payload of the data transported can only be processed at the source or destination of an optical connection, where the O/E conversions could take place. Transparency also limits the amount of performance parameters available in the core nodes, which are fully analog. The selection of performance parameters to cover the maximum range of faults while assuring cost effectiveness and maintaining transparency, the placement of monitoring equipment to reduce the number of redundant alarms and to lower the capital expenses, and the design of fast localization algorithms are among challenges of fault localization in transparent optical networks.

DICONET Vision

The most commonly adopted approach to overcome the mentioned issues of optically layer transparency is the utilization of optoelectronic regenerators on per channel basis on all (opaque architecture) or selected (managed reach) optical nodes. The other approach is the exploitation of impairment management techniques that may be implemented in-line (i.e. optical means of impairment compensation) or at the optical transponder interfaces (i.e. electronic impairment mitigation). However in addition to physical layer impairment management techniques, a third approach could be considered, in which special Routing and Wavelength Assignment (RWA) algorithms are used for lightpath routing that take into account the physical characteristics of the lightpaths. We categorize this class of algorithms as Impairment Aware RWA (IA-RWA) algorithms. The vision of DICONET project, as depicted in Fig. 2, 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 (optical layer).

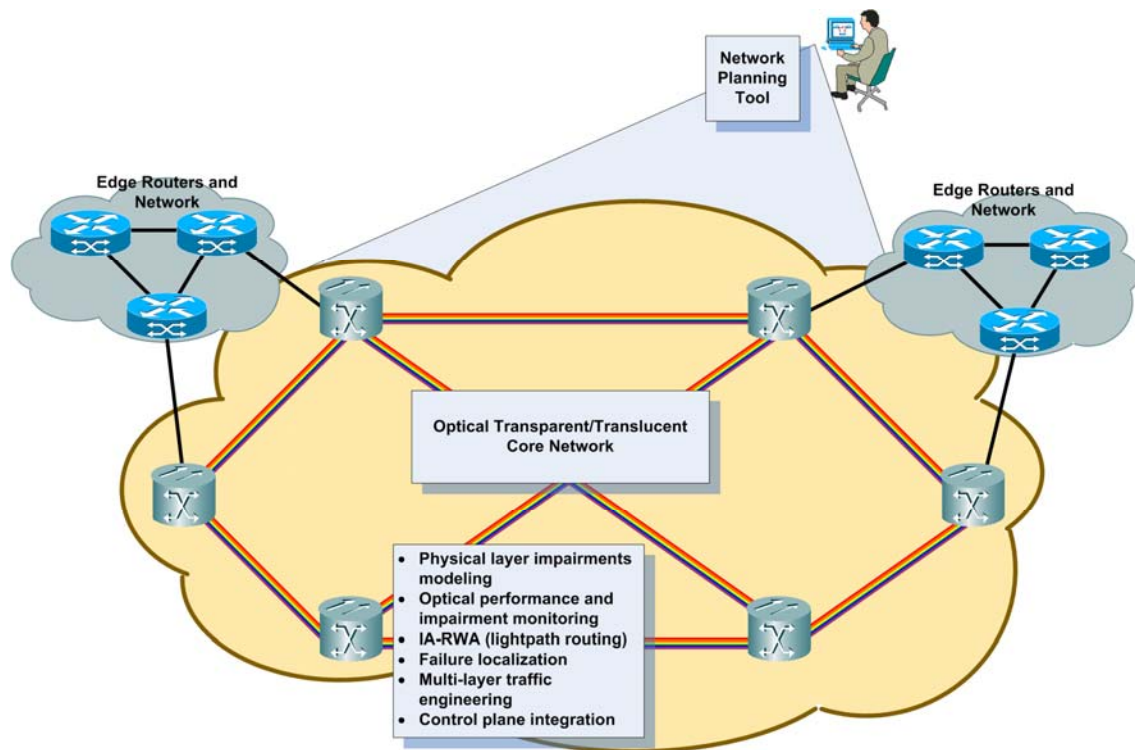


Figure 2: The DICONET Vision

The key innovation of DICONET is the development of a dynamic network planning tool residing in the core network nodes that incorporates real-time assessments of optical layer performance into IA-RWA algorithms and is integrated into a unified control plane. The proposed solution serves as the key enabler for automated network reconfiguration capability, which also provides network resiliency and QoS-guaranteed connectivity. In order to realize the DICONET vision, several building blocks should be considered in an orchestrated fashion. In the following sections we briefly present these building blocks.

Physical Layer modeling and monitoring

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

The important linear impairments that should be modeled and monitored are Amplified Spontaneous Emission Noise (ASE), Chromatic Dispersion (CD), Crosstalk, Filter Concatenation, and Polarization Mode Dispersion (PMD). ASE noise is the principal source of noise in doped fiber amplifiers. In these amplifiers the initial spontaneous emission is amplified in the same manner as the signals, which degrade the optical to signal noise ratio (OSNR). This noise limits the reach and capacity of WDM all-optical networks. Chromatic dispersion is the impairment due to which different spectral components of a pulse (frequencies of light) travel at different velocities. Chromatic dispersion arises for two reasons. The first is that the dependency of refractive index of the fiber to the optical wavelength (material dispersion) and the other is due to the waveguide dispersion. Waveguide dispersion occurs when the speed of a wave in a waveguide (such as an optical fiber) depends on its frequency for geometric reasons, independent of any frequency dependence of the materials from which it is constructed. Chromatic dispersion also limits the maximum transmission reach. The effect of chromatic dispersion can be minimized using Dispersion Compensation Fibers (DCF) or Dispersion

Shifted Fibers (DSF). Crosstalk (inter-channel and intra-channel crosstalk) is the general term given to the phenomenon by which signals from neighboring wavelengths leak and interfere with the signal in the actual wavelength channel. Almost every component (e.g. Multiplexer and Demultiplexers, and switches) in a WDM system introduces crosstalk impairment. Filter concatenation impairment is produced by signal passage through multiple WDM filters between the source and the destination and originates mainly due to the narrowing of the overall filter pass-band. Finally, PMD is the most important polarization effect for high capacity, high bit rate long haul systems. PMD gives rise to the differential group delay between the two principle states of polarization.

The effects of nonlinearities are more severe at higher bit rates and at higher transmitted powers. There are two categories of nonlinear effects. The first arises due to the interaction of light waves with photons (molecular vibrations) in the silica medium. The two main effects in this category are Stimulated Brillouin Scattering (SBS) and stimulated Raman scattering (SRS). The second set of nonlinear effects arises due to the dependence of the refractive index on the intensity of the applied electric field, which in turn is proportional to the square of the field amplitude. The most important nonlinear effects in this category are self-phase modulation (SPM) and four-wave mixing (FWM). References [2-3] provide good overall starting points.

In addition to analytical and simulation techniques for modeling the physical impairment, optical impairment and performance monitoring techniques are required to realize the impairment aware lightpath routing (i.e. IA-RWA) mechanism. The monitoring could be implemented at the impairment level (Optical Impairment Monitoring - OIM) or at the aggregate level where the overall performance is monitored (Optical Performance Monitoring – OPM) [4]. In the former approach, every tunable network element should report its status in terms of e.g. input/output power, noise figure, and dispersion. Then the effect of physical degradation is identified using appropriate analytical models. In the latter approach, optical monitoring systems are located at each node for assessing the overall impact of each degradation. An effective OIM/OPM strategy, which evaluate the status of the link, would support the network Control Plane in performing lightpath establishment or rerouting functions. The most important link performance parameters can be summarized as: a) Residual dispersion, b) Total EDFA input/output powers, c) Channel optical power & wavelength, d) OSNR (Optical Signal-to-Noise Ratio) and e) Q-factor – as an estimator of the overall system performance.

The development of a physical layer modeling and monitoring scheme will provide the intelligence to the DICONET platform to: a) implement failure localization methods of single and multiple failures in transparent optical networks b) implement novel impairment aware lightpath routing (i.e. IA-RWA) schemes that will consider all key physical impairments and their interplay and c) construct and control complex network topologies while efficiently maintaining a high QoS and the fulfillment of service level agreements.

Impairment aware lightpath routing

In communication networks, routing generally involves the identification of a path for each connection request between a source and destination node in the network. In optical networks, the wavelength of the path should be also determined. The resulting problem is considered as RWA problem in literature. If wavelength conversion is allowed in the network, a lightpath can exit an intermediate node on a different wavelength. If no wavelength conversion is allowed then the wavelength continuity constraint is imposed to the generic RWA problem. This constraint implies that a lightpath should occupy only a specific single wavelength, throughout its path from the source to the destination node. A good survey of routing and wavelength assignment algorithms can be found in [5].

In most RWA proposals the optical layer is considered as a perfect medial and therefore all outcomes of the RWA algorithms are considered valid and possible even though the performance may be unacceptable. The incorporation of physical impairments in transparent optical network planning problems has received more attention from research communities. These proposals can be classified

into two main categories: a) effects of impairments on network performance and network design with impairment consideration. In the former category the RWA algorithm is treated in two steps: first a lightpath computation in a network layer module is provided, and then lightpath verification is performed by the physical layer module. In the other category the physical layer impairments are considered before the network layer module proceeds to the lightpath computation and a validation of the signal quality requirements follows. Our proposed IA-RWA algorithms the cost of a link will be a vector (not a single cost value) with entries corresponding to individual impairments. This conceptual approach allows for handling impairments differently and more efficiently.

The impairment aware RWA proposals can be also classified as static and dynamic depending on whether or not the impairments and overall network conditions are assumed to be time dependent. Physical impairments may vary during time (i.e. dynamic network conditions) and thus change the actual physical topology characteristics. We refer to this situation as the “dynamic network condition”. Network traffic (i.e. request for lightpath establishment) can also be static or dynamic. The great majority of the proposed RWA algorithms in the literature only consider static traffic (permanent lightpaths demands) and network conditions (time invariant impairments). IA-RWA algorithms in DICONET proposal try to address other possible scenarios as indicated in Table 1. In Case 3, we consider the more realistic situation, in which dynamic traffic demands may induce a different behavior from certain devices like amplifiers or OXCs.

Table 1: Network and traffic conditions captured by IA-RWA algorithms in DICONET

	Static traffic conditions	Dynamic traffic conditions
Static network conditions	N/A	Case 2
Dynamic network conditions	Case 1	Case 3

Failure localization

The peculiar behavior of all-optical components and architectures bring forth a new set of challenges for network reliability and resilience. Failure management is one of the crucial functions and a prerequisite for protection and restoration schemes. An important implication of using all-optical components in communication systems is that available methods used to manage and monitor the health of the network may no longer be appropriate. All-optical components are not by design able to comprehend signal modulation and coding, therefore intermediate switching nodes are unable to regenerate data, making segment-by-segment testing of communication links more challenging. As a direct consequence, failure detection and localization using existing integrity test methods is made very difficult.

In the DICONET framework an algorithm that solves the multiple failure location problem in transparent optical networks is proposed where the failures are more deleterious and affect longer distances. The proposed solution also covers the non-ideal scenario, where lost and/or false alarms may exist. Although the problem of locating multiple faults has been shown to be NP-complete, even in the ideal scenario where no lost or false alarms exist, the proposed algorithm keeps most of its complexity in a pre-computational phase. Hence, the algorithm only deals with traversing a binary tree when alarms are issued. This algorithm locates the failures based on received alarms and the failure propagation properties, which differ with the type of failure and the kind of device that are in the network. Another algorithm has been proposed to correlate multiple security failures locally at any node and to discover their tracks through the network. The algorithm is distributed and relies on a reliable management system since its overall success depends upon correct message passing and processing at the local nodes. To identify the source and nature of 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 generic localization procedure, which will be initiated at the downstream node that first detects serious

performance degradation at an arbitrary lightpath on its output side. Once the origins of the detected failures have been localized, the network management system can then make accurate decisions to achieve finer grained recovery switching actions. In this scope DICONET aims at developing efficient and innovative failure localization algorithms based on the information received by the network management system to enable physical layer aware protection/restoration schemes. In addition novel attack detection and localization methods will be investigated and deployed by the control plane to provide advance security and reliability in future optical networks

Network Planning Tool

The key innovation of DICONET is the development of a dynamic network planning tool residing in the core network nodes that incorporates real-time measurements of optical layer performance into IA-RWA algorithms and is integrated into a unified control plane. As depicted in Fig. 3, this tool will integrate advanced physical layer models with novel impairment aware lightpath routing algorithms. It will serve as an integrated framework that considers both physical layer parameters and networking aspects and will optimize automated connection provisioning in transparent optical networks.

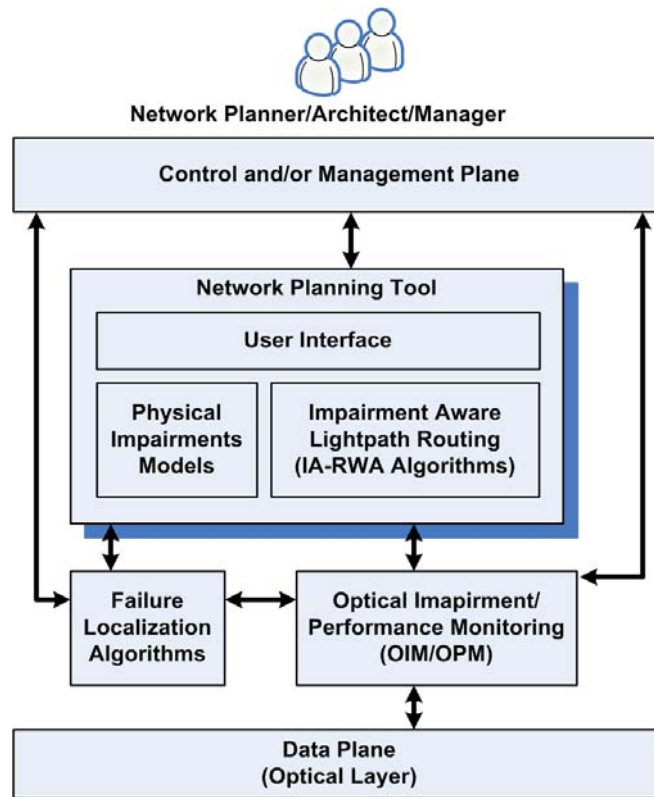


Figure 3: DICONET Network Planning tool

The network planning tool has two operational modes: a) off-line mode and b) on-line (or real-time) mode. In off-line mode a full map of network traffic and network conditions will be fed to the tool in order to produce the planning outcomes. These results can be disseminated to the network management system, controlled by an operator. For on-line use of the network planning tool an online traffic engineering solution is required utilizing an interface between the control plane and the management plane so that network situation could be evaluated in real time and its results could be periodically disseminated into the network. In on-line mode, this dynamic network planning tool can be used to support optimum network operation and engineering under dynamically changing traffic and physical network conditions.

Control Plane Extensions

In order to realize an impairment aware control plane (impairment aware light path routing, topology and resource discovery, path computation, and signaling), existing protocols should be properly extended. The extended control plane will in turn address traffic engineering, resiliency, and QoS issues and will support automated and rapid optical layer reconfiguration. The GMPLS protocol suite [6] has gained significant momentum as a candidate for unified control plane [7]. There are some proposals to address the integration of physical layer impairments into the GMPLS control plane.

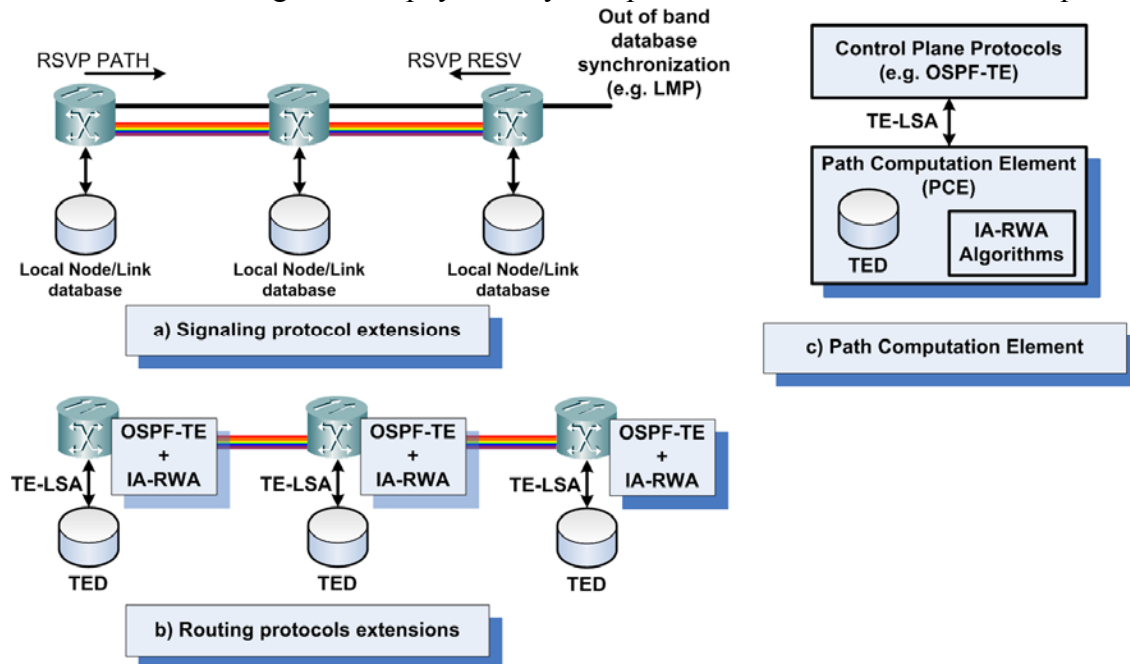


Figure 4: Control Plane extensions

One direction deals with enhancement of GMPLS signaling (e.g. Resource Reservation Protocol with Traffic Engineering extensions ‘RSVP-TE’) and management (e.g. Link Management Protocol ‘LMP’) protocols. In this approach, lightpaths from source to the destination are dynamically computed using current routing protocols (e.g. OSPF-TE), without considering the optical layer impairments. Only upon lightpath establishment, the enhanced reservation protocol computes the amount of impairments and based on the results the lightpath setup request can be either accepted or rejected. Following this approach a local database in each node (e.g. OXCs or ROADMs) is required to store the physical parameters that characterize the node and its connected links. In order to setup a lightpath, the source node generates an extended version of the RSVP PATH message, which includes the physical information of the transmitting interface and corresponding link. Each node along the path updates this message by adding its own local values. Admission control at the intermediate or the destination node compares the accumulated values with thresholds and decide to accept or reject the lightpath setup request.

In the second approach, physical layer information are inserted into the some Interior Gateway Routing Protocol (IGRP) (e.g. OSPF-TE). The source node of the lightpath interacts with the Traffic Engineering Database (TED). Network-wide information, which are stored in TED serves as the input information for IA-RWA algorithms in order to optimal lightpath taking into account the physical layer information. Physical layer information are carried on the TE link state advertisements (TE-LSA), in order to provide an updated and accurate inputs to the IA-RWA algorithms. By using the appropriate extensions to the OSPF-TE, physical layer information are flooded to the entire network. As a result of this flooding mechanism, the local TED database of nodes will be updated accordingly.

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

The main control plane aspects that are addressed by the DICONET relate to: a) Multilayer network control and b) Routing and signaling-related mechanisms and physical network characteristics information dissemination.

Summary

Transparent optical networks are the next evolution step of managed reach (translucent) optical networks. Both of them have been recognized as the evolution of static WDM networks. In order to provide high-speed and QoS guaranteed connectivity, with high reliability, considering the realistic optical layer, the DICONET vision proposed in this article as a disruptive and novel solution for optical networking. Two main challenges of transparent networks, which are: a) limited system reach and overall network performance due to physical impairments and b) challenges related to failure localization and isolation, presented in this article as the main motivations behind the DICONET project. It is the vision of DICONET that intelligence in the core optical networks should not be limited only to certain functionalities of control and management planes, but should also be extended to the physical layer. Following this vision, the main physical impairment and the essential role of optical impairment and performance monitoring discussed and the consequently the impairment aware lightpath routing (IA-RWA) algorithms and failure localization algorithms complemented with an impairment aware control plane presented in this article.

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