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ABSTRACT

Future optical networks are moving from static point-to-point connections towards dynamic wavelength-routed networks using all-optical, reconfigurable switching nodes. By doing so, lightpaths are dynamically routed/switched entirely over the optical layer, eliminating current expensive electronic regenerators. However, the lack of OEO transponders (i.e., transparency) makes it necessary to consider the degrading effects of the physical transmission of optical signals accumulated along the path. An efficient strategy to face up this problem and to provide quality-enabled services is to take into account physical impairments during the path computation process (ICBR algorithm). In the work we present a feasible solution which combines ICBR algorithms and the intelligence of a distributed GMPLS-based control plane to set up optical connections with the required QoS in the optical signal. In addition, analytical discussions are given for the assessment and validation of the solution.

Keywords: Transparent networks, physical impairments, RWA, GMPLS.

1. INTRODUCTION

The accelerating growth of data traffic is motivating the research for more efficient, flexible and intelligent optical network architectures. In this direction, IP over Wavelength Division Multiplexing (WDM) technology is becoming accepted as one of the most promising candidates to fulfill these ever-increasing bandwidth demands. On the other hand, there is a global industry consensus to consider the Generalized Multi-Protocol Label Switching (GMPLS) protocol suit [1] to be an integral part of next-generation transport networks, especially as enabler for the Automatic Switched Optical Networks (ASON) [2] control plane, because it renders optical networks intelligent. However, the huge transport capacity of WDM technology is accepted to not be fully used by current optical networks [3]. Such inefficiency on the bandwidth usage is due to the use of expensive optical-electrical-optical (OEO) transponders (i.e., *opaque* networks) causing the electronic bottleneck. These networks have important benefits such as electronic signal regeneration and intrinsic wavelength conversion capability at any hop. However, opaque networks also present remarkable drawbacks: complex layered structure, sensitive to signal format and data rate, elevated *capex* and *opex*, and suboptimal use of WDM's capacity. Thus, future optical networks are moving toward overcoming these limitations and taking full advantage of the WDM technology. This will be achieved using all-optical switches (e.g., reconfigurable optical add drop multiplexers, ROADMs, and/or optical cross-connects, OXCs) that switch/route connections (lightpaths) entirely within the optical domain (i.e., *transparent* networks). Therefore, the introduction of these switches allows to eliminate the need for OEO transponders, favoring the overall network's cost-effectiveness. However, this also results in losing the electrical regeneration of signals, which in turn makes the optical signal not oblivious to the accumulation of the *impairments* due to *fiber transmission* (attenuation, dispersion, non-linearities, etc.), *optical amplification* (amplified spontaneous emission –ASE– noise), and *insertion losses* and *cross-talk* introduced by optical elements such as switches, filters or d/mux in ROADMs and OXCs.

On the other hand, future optical service provisioning is expected to be very rapid, automatic and quality-enabled (QoS). A feasible solution to deal with these necessities is the utilization of accurate in-service performance monitoring to guarantee Service Level Agreement (SLA). Indeed, this strategy allows to design intelligent mechanisms that consider optical-layer monitoring information when provisioning connection with QoS. Performance monitoring in optical networks has traditionally referred to the SONET/SDH layer, that is, bit/block error rates (BER) and other SDH QoS measures. The primary application of performance monitoring is, then, to certify accorded SLAs between network operators and their clients. SLAs are usually "electrical", that is, the set of judging elements used for verifying whether the SLA is satisfied are electrical performance parameters such as BER. However, BER computation is not as fast as desired (minutes) in the context of dynamic, transparent optical networks, wherein changes may occur in msec-sec order. Other parameters such as optical signal noise ration (OSNR), Q-factor or polarization mode dispersion (PMD) penalty are thus being investigated to be employed for guaranteeing with on-line QoS with lower opex and delays. In this article we focus on the utilization of intelligent routing algorithms taking into account monitored physical layer attributes as input parameters (i.e., constraints) for the path computation, with the aim to achieve quality-enabled services. These routing algorithms are know in the literature as Impairment Constraint Based Routing (ICBR). The ICBR's objective is to deal with a dynamic path computation process that entails not only efficient usage of the optical resources (e.g., wavelengths) but also stringent requirements (SLAs) of adequate end-to-end signal quality (QoS) within transparent networks [4].

The rest of this work is organized as follows. In section 2, we address the motivations for using ICBR algorithms as well as a brief discussion and comparison of the most representative ICBR approaches in the literature. The architecture of an impairment-aware optical control plane to achieve a distributed and intelligent ICBR is presented in section 3 besides the implemented in-service monitoring system in the ADRENALINE testbed. Finally, in section 5, we draw our conclusions.

2. IMPAIRMENT CONSTRAINT-BASED ROUTING (ICBR)

Routing in wavelength-routed network usually assumes that all the paths have adequate end-to-end signal quality [4]. This assumption is suitable for opaque networks, since OEO conversions regenerate the signal at every node along the route. Indeed, every data link between the optical switches (e.g., add-drop multiplexers) is isolated by OEO transponders. Thus, the objective of routing within opaque networks is to achieve an efficient utilization of the network resources (e.g., bandwidth) through the selection of both an spatial route (nodes, links) and an spectral route (wavelength) which minimizes the blocking of subsequent connection requests. This problem has been largely studied using Routing and Wavelength Assignment (RWA) algorithms [5].

Nevertheless, the introduction of transparency imposes a new challenge on the lightpath provisioning, since the optical connections must remain entirely in the optical domain from the source to the destination nodes. As a result, transmission impairments accumulate while the signal travels, which causes that at the receiver the optical signal may not fulfill the stringent QoS required by the client, affecting the revenues of the network operator. One solution to face up this problem is to employ RWA algorithms that consider physical-layer effects besides network-layer issues in order to guarantee adequate end-to-end quality of the optical signal. These RWA algorithms are known as ICBR or impairment-aware RWA (IRWA) [6, 7].

2.1 Constraints models for ICBR algorithms

In the literature we may find constraint models for some performance parameters that aim at being included in ICBR (or IRWA) algorithms to be employed in transparent optical networks. The common approach is to consider different performance parameters for the proposed RWA algorithms, as illustrated in table 1. For example, Ramamurthy *et al*. [8] proposed to use ASE noise and cross-talk effects for estimating the BER in the receiving end of the lightpath. In [7], Huang *et al*. modeled their IRWA algorithm taking into account the PMD and the OSNR performance parameters separately. In [9], Cardillo *et al*. enhanced OSNR Huang's model. Finally, in [10] Kulkarni *et al*. utilized an ICBR approach using the Q-factor as a performance parameter, integrating the effects of the interplay of linear impairments (chromatic dispersion, PMD, ASE noise, cross-talk and filter concatenation).

Table 1. Summary of the most relevant IRWA algorithms.

	Constraint model/s	Impairment/s considered	RWA algorithm	Network Scope
Huang *et al.* [7]	PMD and OSNR (separately)	ASE (linear transmission effects) and PMD penalty (δ_{PMD})	Two Steps: 1) Network-layer solution 2) Physical-layer route evaluation (thresholds).	*Complete* Network Scope, *Centralized* Routing decisions and *Static* Parameters
Ramamurthy *et al.* [8]	BER estimation (thresholds)	ASE (linear transmission effects) and cross-talk		
Cardillo *et al.* [9]	OSNR	ASE (linear and non-linear transmission effects)		
Kulkarni *et al.* [10]	Q-factor	Chromatic dispersion, PMD, ASE noise, cross-talk and filter concatenation	Three Steps: 1) link cost computation, 2) shortest path, 3) validation of signal quality	

These models consider that the parameters needed to compute PMD, OSNR or Q-factor bounds are static. As an example, in Huang's model the PMD is represented by its penalty (δ_{PMD}), whilst the potential OSNR level in the channels of the lightpaths to be set up is estimated by considering a launch power level at the transmitter and the gains and losses of the elements along the route using an iterative method as described in [8]. It is worth noting that, in order to decide whether a route has a valid signal quality, Huang's approach compares the estimated PMD penalty and the computed OSNR level at the end of the computed route with two thresholds concerning each of the performance parameters. These threshold serve to satisfy the service class requested in the SLA mapping the OSNR level to the target BER and a maximum tolerable PMD penalty for each class over a given data rate (e.g., 10 Gb/s). In [9] Cardillo *et al*. proposed to use the OSNR model described in [7] with some enhancements to consider non-linear penalties (Kerr Effect) besides the linear effects that occur along lightpath transmission. Finally, in Kulkarni's model [10] the link Q penalty is selected as the performance parameter to determining whether the quality of the signal is adequate at the receiver. Note that this Q-factor, which is used as an intermediate parameter for BER and OSNR, can be based on measured signal quality (using a monitoring system) or on static parameters (e.g., PMD and ASE [10]). With this information, ICBR algorithms are capable of computing the lightpath Q penalty by decrementing the budget by each link penalty (minimization affects traffic engineering) or by choosing link with too high Q penalty.

2.2 Considerations of constraints models for on-line use of ICBR algorithm

The constraints models described above make use of a centralized entity that is aware of detailed optical physical information within the transparent network. This centralized entity is, thus, the responsible for executing the IRWA algorithm for each received connection request. The output of such path computation is a path that satisfies a particular set of performance parameters (e.g., OSNR, Q-factor, etc.), needed to fulfil the targeted SLA. Indeed, these IRWA or ICBR algorithms typically use a *two-step approach*: the first step deal with computing a feasible route in which only the network-layer attributes and performance objective (e.g., shortest path, optimal resource utilization) are reached. Once a feasible spatial and spectral route is found, it becomes a candidate lightpath. The second step, then, concerns checking whether such a candidate lightpath is compliant with the optical performance parameter/s, that is physical-layer objective/s, required by the connection (i.e., SLA). This check is done either analytically or numerically during the IRWA process.

It is important to remark that since this two-step approach is aware of both complete network and detailed physical-layer information, the ICBR route decisions results the most exact. However, due to the large amount of information (e.g., granularity on per wavelength basis) that need to be managed and since all the routing decisions are performed by a single entity, the degree of complexity and scalability may result prohibitive in dynamic traffic environments. Therefore, the constraints models described in section 2 are adequate for static scenarios where the physical-layer parameters rarely change and can be stored in a centralized database. If we wanted to use these model in a dynamic scenario, the amount of monitoring points needed to update the values of the required parameters would result in increased capex and opex. For this reason, in the literature the variables needed to compute the performance parameters (e.g., attenuation, insertion losses, etc.) are assumed to be static, and are used as such in the ICBR models of previous section. But in dynamic environment this might not be the case, for instance for cross-talk introduced in the nodes, the behaviour of the amplifiers or eventual failures in fiber links, such as fiber cut. Therefore, it is interesting that a monitoring system update changing values. Indeed, amplifier gain, as well as noise figure, are slowly changing parameters, which should be taken into account when launching the IRWA algorithm. It is clear that placing monitoring points at each node to capture the above-mentioned variations comes at an extra cost, but many optical devices have embedded monitoring capabilities (e.g., gain monitoring in amplifiers), and not all the elements need to be monitored. Therefore, OSNR monitoring seems to be the only extra capability needed for engineering optical-layer monitoring.

Taking the above into account, it seems reasonable to derive static, centralized ICBR models to a more distributed, on-line context to fulfil two goals: practical feasibility and scalability. The former is achieved because in the distributed ICBR models the amount of physical-layer information needed for the routing computation is less than in the centralized case, thus lesser monitoring points are required, that is, the scheme is more cost-efficient. Concerning the scalability, the essence of distribution is to handle in a more efficient way the performance variations that may occur a changing physical layer; with granularities at wavelength level, centralized IRWA models are only suitable for static scenarios, in which no dissemination is done.

3. ICBR ALGORITHMS IN DISTRIBUTED GMPLS-BASED OPTICAL CONTROL PLANE

The optical control plane [2] is seen by the industry as the most promising solution for introducing intelligence in future optical networks. This control plane represents a common set of distributed functions and interconnection mechanisms (signalling and routing) that set up lightpaths dynamically with a required level of QoS. Indeed, the control plane achieves this QoS in terms of network-layer requirements such as on-demand bandwidth and connection reliability. Thus, the used RWA algorithms are focused on providing paths dealing with these requirements as well as optimising the overall network realization. Distribution is widely considered as the best choice for handling dynamic connection requests [3], that is, every network node is governed by a common control plane. In such an scenario, path computation is driven by the source node of each connection request, which enhances the network scalability if one compares it with a centralized RWA model under the same dynamic traffic conditions. Figure 1 depicts the architecture of an optical control plane considering physical impairments. The optical control plane is made up of three main controller, as described in ITU-T ASON recommendation [2]: the *Link Resource Manager* (LRM), to maintain an updated view of the local transport plane resources, the *Routing Controller* (RC), for computing routes (RWA algorithm) and for disseminating resource and network topology information using a distributed routing protocol such as Open Shortest Path First Traffic Engineering

(OSPF-TE) [11], and the *Connection Controller* (CC) , which sets up, modifies and tears down lightpaths using a distributed signalling protocol as Resource Reservation Protocol (RSVP-TE [12]).

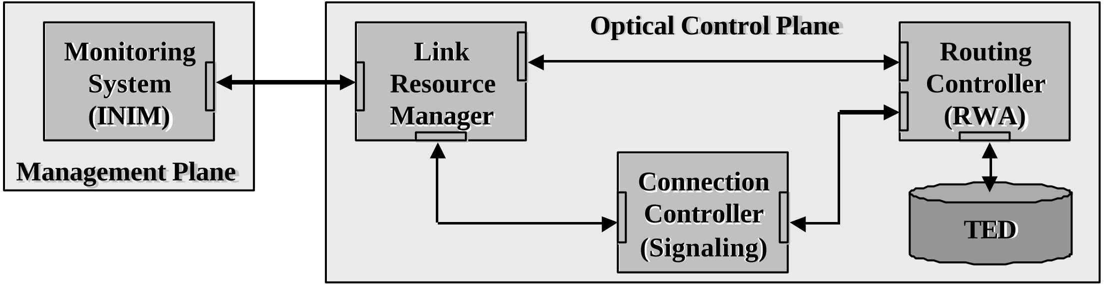

Figure 1. Architecture of a distributed GMPLS-based control plane for transparent optical network.

Any change occurred within a node, that is (local) link attributes, such as bandwidth de/allocation or variations in performance parameters, is reflected in the LRM. Thus, the LRM keeps track of any change over any attached local data link and informs the RC in order to flood (update) the network with such new information. This updated information will be used by the corresponding RWA algorithm on any node within the network. For this aim the updating/flooding procedure concerns the dissemination/broadcast of any variation suing a particular routing protocol (e.g., OSPF-TE). This information is then collected on each node in a repository referred to as *Traffic Engineering Database* (TED) which is used to maintain an updated picture of not only its local network resources (i.e., adjacent data links) but also information related to remote links. Network-wide information stored in every RED serves as the input information for the RWA algorithms in order to compute optimal routes by using up-to-dated network-layer attributes.

The use of ICBR algorithms in a distributed control plane requires that every node's TED be updated with physical-layer information within the network. For this aim, two main challenges needs to be addressed within the considered distributed scenario: an on-line monitoring system and physical-layer extensions to existing routing protocol. The former focus on monitoring the transport plane in order to notify the control plane about any change concerning physical-layer variations (e.g., channel OSNR) as shown in Fig. 1. This information is then passed to the corresponding LRM, which in turn is responsible to decide whether the variation is required to be populated (threshold policies) to the whole network using a distributed routing protocol. For this purpose existing GMPLS-based routing protocols need to be extended to flood optical performance parameters such as power and noise levers, as TE parameters (e.g., bandwidth) are disseminated.

3.1 Physical link extensions to the GMPLS OSPF-TE routing protocol

Transmission impairments are monitored in-service so that suitable performance parameters can be provided to the optical control plane (Fig. 3). Unlike centralized ICBR models (section 2.1), we group parameters using data link granularity instead of on a per wavelength basis. This results in a trade-off between scalability and accuracy: whilst the routing protocol scalability is improved since the amount of information to be disseminated is lower than in the centralized approach, the ICBR algorithm must work with aggregated link information, which results in losing accuracy on the routing decisions. Physical-layer parameters are carried within the TE Link State Advertisements (TE-LSA) [11]. In particular, information is encapsulated within the top-level Link Type/Length/Value /TLV) as a common sub-TLV, which is depicted in Fig. 2 as *Impairment sub-TLV*. The contents of this new sub-TLV are: *Type*, used to identify uniquely this sub-TLV, *Length*, contains the total length in (bytes) of the sub-TLV, and *Value*, which contains the physical link parameters such as OSNR, PMD, etc. As a result of the flooding process each node's TED will be aware of the new impairment parameter value even if the affected link is not adjacent.

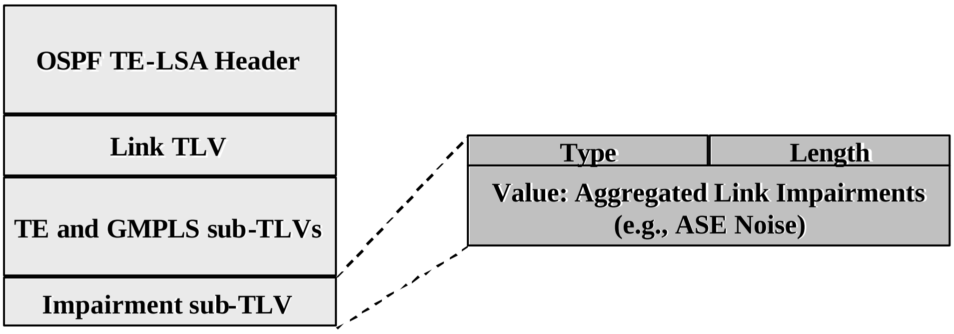

Figure 2. Proposed Impairment sub-TLV information in GMPLS OSPF-TE routing protocol.

4. Experimental Implementation and Discussion of Distributed ICBR Algorithm

4.1 The ADRENALINE testbed: general features

The ADRENALINE testbed is a hybrid platform composed of real emulated optical nodes and links whose topology can be dynamically configured to enable a wide range of experiments. The ADRENALINE testbed is composed of a transport plane, a control plane and a management plane. The transport plane is formed by three real all-optical ROADMs and two real OXCs, connected by bidirectional link using two unidirectional fiber of 35 km each. Every fiber carries up to eight wavelengths using dense WDM technology. Furthermore, ADRENALINE comprises nine optical connection controller (OCC) with the architecture depicted in Fig. 1, which are used to emulate the implemented distributed GMPLS control plane. The management plane is formed by three distributed optical managers, an in-service monitoring system and embedded agents in OCCs and active elements. The communication among the control and management elements is done through the Data Communication Network (DCN), which is based on fast Ethernet, point-to-point links carried over both emulated and real links. For further details about ADRENALINE the interested reader is referred to [13].

4.2 The INIM system

The ADRENALINE testbed integrates an experimental In-Service, Non-intrusive Monitoring system (INIM), which combines distributed elements and non-intrusive monitoring to guarantee SLAs based on optical and IP parameters, and provides information no a per link basis to perform on-line ICBR computation [14]. The INIM system uses the IP control channel of the DCN to transfer management information, including performance monitoring. The main processes of the INIM system (Fig. 3) are the filtering, correlation and aggregation of events (*Gatherer*), the verification of the SLA of each connection established, and the monitoring of the status concerning optical resources on a link-state basis (*Event Manager*). These last two processes correlate data from network topology, events and SLA/link-state parameters, and decide if any SLA fails, as well as the status of the optical links. INIM provides two outputs: in normal operation, it log performance information, including SLA and link-state validation. Otherwise, the system raises an alarm to the service management system or the LRM of the affected link (Fig. 3). As for physical-layer performance information relevant to ICBR, the gatherer process receives messages from optical monitoring points that contain information related to physical-layer events (channel OSNR, power and wavelength drift), IP-layer events (packer delay or loss of each lightpath), links where events occur (link index) and lambda services affected by the events (channel index).

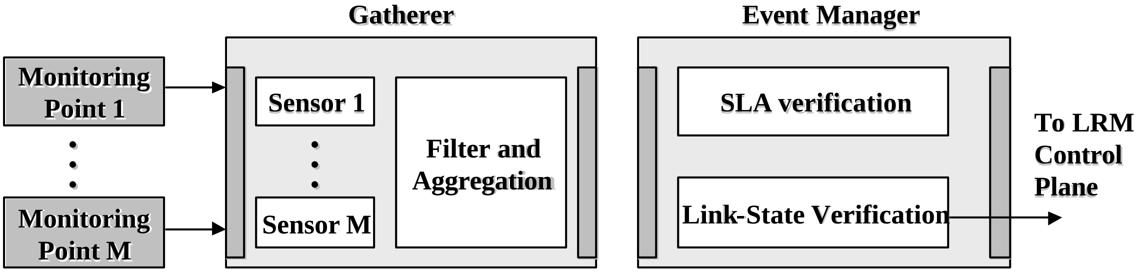

Figure 3. Architecture of the INIM system.

4.3 Distributed ICBR: analysis of drawbacks and penalties.

The utilization of ICBR algorithms within distributed GMPLS-based control plane represents an improvement for guaranteeing adequate end-to-end quality of the optical signal of the lightpaths, besides traditional network-layer demands. This model conveys some benefits and advantages with respect centralized models [6-10]: suitability in dynamic traffic environments, awareness to optical-layer variations, higher scalability and flexibility, higher cost-effectiveness and less routing computational load. However, this models also introduces some restrictions which are closely related to the essence of distributed routing models. These limitations are reduced to: TED inconsistency at each node's control plane if link information changes are too frequent, and necessity to provide a multi-constrained (network and physical-layer) RWA algorithm. In the former, the variability of physical impairments is not affected significantly if one increases the rate of connection requests. Only small channel power variations may occur due to setup or tear down of adjacent channels (cross-talk). Note that the same statement cannot be made for TE attributes, since bandwidth is highly linked to traffic fluctuations. However, threshold policies may be used for alleviating such updating problem if changes occur frequently.

On the other hand, the need for a multi-constrained RWA algorithm does not imply on increasing the complexity, but in the required time for algorithm execution, as well as in the setup delay for establishing a lightpath. In a distributed model, the main objective of the TE-based RWA o CBR algorithms is to compute the shortest path (e.g., Dijkstra), whereby every link along the path must satisfy the constraints such as bandwidth, protection level, etc., requested by the connection. The algorithm complexity is mainly due to the Dijkstra process rather than the evaluation/validation of every network link. Therefore, using distributed ICBR algorithm does not augment the computational complexity (compared to distributed TE-based RWA algorithms) but the computation time, which is increased because physical-layer constraints are considered besides network-layer restrictions during the path computation. By considering a two-step approach [7-9], IRWA algorithms may perform a signal-quality estimation once a route is computed. In this case the algorithm's complexity is affected because an additional validation process is required for each routing computation. If signal-quality estimation is not realized after the route computation, the destination node of the lightpath needs to validate the adequateness of the received optical signal, thus increasing the setup delay as well as the blocking probability as long as the computed route is refused due to poor physical-layer performance (connection re-attempts are needed).

5. CONCLUSIONS AND FUTURE WORK

The article focuses on addressing the problem of distributed, dynamic setup of lightpaths in reconfigurable transparent optical networks taking into account impairment degradations affecting optical transmission and TE. An efficient solution to this problem in static scenarios is the use of centralized ICBR algorithms which compute end-to-end routes taking into account detailed physical-layer information. However, this solution presents severe drawbacks in dynamic environments, mainly low scalability and expensive implementation. Therefore, we propose the utilization of a distributed ICBR model which involves an on-line monitoring system to provide updated physical-layer information to a distributed GMPLS-based control plane on a per link basis. Then, the routing computation is done by the source node considering not only TE and topology issues but also the physical parameters disseminated by the routing protocol. Implemental and architectural details of the proposed model and scenario are further detailed, besides an analytical assessment of the proposed distributed ICBR algorithm.

Future work is focused on identifying a single aggregated physical link parameter instead of using several performance parameters (e.g., OSNR, PMD, etc.), on a per channel basis. This link parameter will favor scalability in terms of flooded routing protocol information and the computational complexity of the ICBR algorithm.

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