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On-line ICBR in a transparent GMPLS network: a reality check

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Abstract— Future optical transport networks are moving from static point-to-point connections towards dynamic wavelength-routed networks using all-optical, reconfigurable switching nodes. As a result, 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 this paper 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. Furthermore, experimental and analytical discussions are given for the assessment and validation of the proposed solution.

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) 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 suite [1] to be an integral part of next-generation transport networks, especially as enabler for the Automatic Switched Optical Network (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 utilization is due to the use of expensive optical-electrical-optical (OEO) transponders, which originates the well-known electronic bottleneck. These *opaque* networks have important advantages such as electronic signal regeneration as well as the capability of intrinsic wavelength conversion on every hop of the connection. However, *opaque* networks also present important drawbacks: a complex layered structure, sensitive to signal format and data rate, elevated capital and operational costs (*CAPEX* and *OPEX*), and suboptimal use of WDM's capacity. As a consequence, future optical networks are expected to overcome these limitations and take 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) which allow to switch/route entirely an optical connection (lightpath) over the optical domain (i.e., transparent networks). Thus, the introduction of transparency in optical networks eliminates the need for expensive OEO transponders (reducing capex) during the switching of a lightpath. 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, nonlinearities, 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 requirements is the utilization of accurate in-service performance monitoring to guarantee Service Level Agreements (SLA). Indeed, this strategy allows to design intelligent mechanisms that consider optical-layer monitoring information when provisioning connections with QoS. Performance monitoring in optical networks has traditionally referred to the SONET/SDH layer, that is, bit/block error rates (e.g., 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 a dynamic, transparent optical network, in which changes may take place in msec-sec order. Other parameters such as optical signal noise ratio (OSNR), Q-factor or polarization mode dispersion (PMD) penalty are thus being investigated to be used for guaranteeing on-line QoS with lower opex and delays. In this paper we focus on the utilization of intelligent routing algorithms which take into account monitored physical layer attributes as input parameters (i.e., constraints) for the path computation, with the aim to achieve quality-enabled services. Such routing algorithms are known in the literature as Impairment Constraint Based Routing (ICBR). The objective of the ICBR algorithms is to deal with a dynamic path computation process that entails not only efficient usage of optical resources (e.g., bandwidth) but also stringent necessities of adequate signal quality (SLA) in transparent optical networks [4].

The remainder of this paper 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 algorithm is presented in section 3, whereby some required GMPLS protocol extensions are also presented. In section 4, experimental and analytical evaluations are used to discuss the feasibility of our approach. Finally, section 5 concludes this paper.

2. IMPAIRMENT CONSTRAINT BASED ROUTING

Routing in wavelength-routed networks usually assumes that all the paths have adequate end-to-end signal quality [4]. This assumption is suitable for opaque

networks, wherein OEO conversions are always used at each intermediate hop of the optical connection. Hence, each data link between the optical switches (e.g., add-drop multiplexers) is isolated by OEO transponders. Therefore, the aim of routing within opaque networks is to achieve an efficient utilization of network resources (i.e., bandwidth and wavelengths) by means of selecting both a spatial (node and links) and a spectral (wavelength) route which minimizes the connection blocking probability of subsequent connection requests. This problem has been largely studied and resolved by means of Routing and Wavelength Assignment (RWA) algorithms [5].

However, the introduction of transparency imposes a new challenge on the lightpath provisioning, since optical connections must remain in the optical layer along the whole route from source to destination. Hence, transmission impairments accumulate while the signal travels. As a consequence, the received signal at the destination may not fulfill the stringent QoS required by the end client, affecting the revenues of the optical network operator. One solution to address this problem is to employ RWA algorithms that not only consider network-layer issues, such as bandwidth or end-to-end delay, but also physical-layer effects with the objective of guaranteeing adequate quality of the optical signal at the receiver node. These RWA algorithms are known as ICBR or impairment-aware RWA (IRWA) [6, 7].

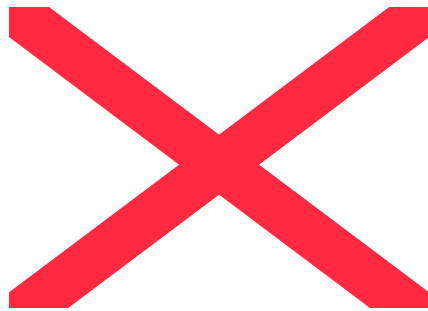
2.1. CONSTRAINT MODELS FOR IMPAIRMENT-AWARE RWA

In the literature we may find constraint models for some performance parameters that aim at being included in 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 impairment-aware RWA algorithm taking into account the PMD and 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, which integrates the effects of the interplay of linear impairments (chromatic dispersion, PMD, ASE noise, cross-talk and filter concatenation).

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 α_{PMD} , which can be computed as defined by Cantrell in [12], whilst the potential OSNR level in the channels of the lightpaths to be established is estimated by considering a launch power level at the transmitter and the gains and losses of the elements along the route. It is worth nothing that, in order to decide whether a route has a valid signal quality, Huang's approach compares the estimated PMD penalty along the calculated route and the computed OSNR level at the end of the route against two thresholds concerning each of the performance parameters. These thresholds serve to satisfy the service class requested in the SLA by 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) [11]. OSNR is estimated using an iterative method to calculate the signal and noise powers (principally resulting from ASE, cross-talk and Raman amplification) propagating through a lightpath [7], as defined by Ramamurthy *et al.* in [8]. In [9] Cardillo *et al.* proposed to use the OSNR model

considered 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 for 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, ASE [10]). With this information, ICBR algorithms are capable of computing the lightpath Q penalty, defined by Cantrell in [12], by decrementing the budget by each link penalty (minimization affects traffic engineering) or by not choosing links with too high a Q penalty.

Table 1. Summary of the most relevant Impairment-aware RWA algorithms



2.2. CONSIDERATIONS OF CONSTRAINT MODELS FOR ON-LINE USE OF RWA ALGORITHMS

The constraint 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 launching the IRWA algorithm for each connection request received. The output of this routing computation process is a path which satisfies a particular set of performance parameters (e.g., OSNR, Q factor, BER estimation), needed to accomplish the targeted SLA. Indeed, these IRWA or ICBR algorithms typically use *two-step approach* the first step deals 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 route (spatial and spectral path) is found, it becomes a candidate lightpath. The second step, then, concerns checking whether this computed (candidate) lightpath is compliant with the optical performance parameter/s (i.e., physical-layer objective/s) required by the connection, as indicated in the SLA. This check is done either analytically or numerically during the IRWA process.

It is important to highlight that since this two-step approach is aware of both complete network layer and detailed physical layer information, the utilized ICBR algorithm is the most exact when performing routing decisions. However, due to the large amount of information (e.g., granularity on per wavelength basis) that needs to be managed and since all the routing decisions have to be made by this single entity, the degree of complexity and scalability may result prohibitive in dynamic traffic environments. Therefore, the constraint models described in section 2.1 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. In fact, almost each network element along the path should report on its performance status. In particular, measuring the Q penalty at each link, which is related to the eye and noise penalties [12], would result in higher opex due to the increased optical-layer performance management needed for obtaining the eye diagram (the noise penalty is obtained from measurements of signal power, and knowing the noise figure of the amplifier chain). For this reason, in the literature the variables needed to compute performance parameters (e.g., attenuation, insertion losses, etc.) are assumed to be static, and are used as such in the IRWA models of section 2.1. But in a dynamic environment this might not be the case, for instance for cross-talk introduced in the nodes, the behavior of the amplifiers or eventual failures in fiber links, such as a fiber cut.

Therefore, it is interesting that a monitoring system update changing values. For example, optical power values in the ingress and egress of a link capture the values of attenuation and amplifiers' gains which, combined with information about the amplification gain value, usually provided by management agents embedded in optical amplifiers, result in up-to-date knowledge of the fiber attenuation and gain of amplifiers. Indeed, amplifier gain, as well as noise figure, are slowly changing parameters, which should be taken into account when performing the RWA decisions. 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, such as gain monitoring in amplifiers or power measures at input and output ports of OADMs and OXCs, and not all the elements need to be monitored. Therefore, OSNR monitoring seems the only extra capability needed for engineering optical-layer monitoring. On the other hand, apart from information tied to OSNR and Q factor, RWA algorithms can make use of packet delay. Latency is a very important SLA parameter, especially for real-time or latency-sensitive applications, which require delay-bounded communication.

Taking the above into account, it seems reasonable to derive static, centralized IRWA models to a more distributed, on-line context to fulfill two goals: practical feasibility and scalability. The former is achieved because in the distributed IRWA the amount of physical-layer attributes needed for the routing process is less than in the centralized case, thus lesser monitoring points are required, that is, the scheme is more cost-efficient. Concerning 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 or port level, the centralized IRWA models described in section 2.1 are only suitable for static scenarios, in which no dissemination is done.

3. ICBR IN GMPLS-BASED CONTROL PLANES

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 (e.g., signaling and routing) that can establish lightpaths dynamically with a required level of QoS. In fact, the control plane achieves this QoS basically in terms of network-layer requirements (e.g., bandwidth demands

and connection reliability). The RWA algorithms utilized are thus focused on providing routes which guarantee these connection demands by optimizing 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 this scenario, path computation for a particular connection request is driven by the source node of the connection, which enables to enhance network scalability when comparing with a centralized RWA model in a similar dynamic scenario. Figure 1 shows the main architecture of an optical control plane considering physical impairments [2]. This control plane is formed by three main controllers, as described in the ASON recommendation [2]: the Link Resource Manager (LRM), which maintains an updated view of the local data plane resources (e.g., link information), the Routing Controller (RC), which is the responsible for both computing the routes (RWA algorithm) and disseminating resource and network topology information (e.g., with OSPF-TE [13]), and the Connection Controller (CC), which sets up, modifies and tears down optical connections using a signaling protocol (e.g., RSVP-TE [14]).

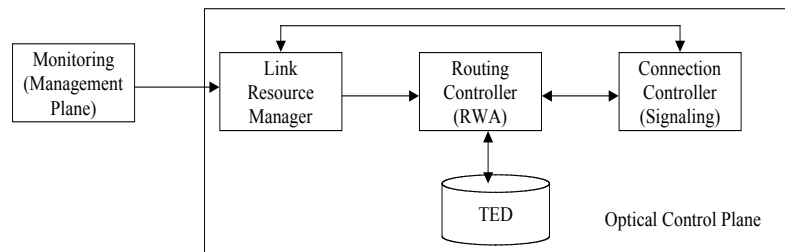


Figure 1: Architecture of a distributed GMPLS-based control plane for a transparent optical network

Any change produced within a node, that is (local) link attributes, such as bandwidth de/allocation or variations in performance parameters, is reflected in the LRM. Then, the LRM keeps track of any change occurred on any attached local link and informs the RC in order to flood (update) the network with such new information. This updated information will be used for subsequent route computation processes (RWA). The updating/flooding mechanism concerns the dissemination/broadcast within the network of any modification (e.g., link failure, bandwidth change) using the routing protocol. This information is then collected on each node in the Traffic Engineering Database (TED). By doing so, the TED becomes a repository located in each node with an updated picture of not only its local network resources (e.g., adjacent links) but also information related to remote links. Network-wide information stored in every TED serves as the input information for the RWA algorithms in order to compute optimal routes by using updated network-layer attributes.

The use of ICBR algorithms in a distributed control plane requires that the TED placed on each node be updated with physical-layer information regarding any link within the network. Therefore, the existent GMPLS-based routing protocols need to be extended to flood optical performance parameters such as power and noise levels or PMD, as traffic engineering (TE) attributes are disseminated [11]. With this information stored in the TED, the source node of a connection request can launch the corresponding ICBR algorithm to satisfy both the network demands (e.g., bandwidth, delay) and end-to-end quality of the optical signal (e.g., OSNR, estimated BER).

3.1. EXTENSIONS TO THE GMPLS OSPF-TE ROUTING PROTOCOL WITH INFORMATION ABOUT IMPAIRMENTS

In this section we address the extensions to the GMPLS OSPF-TE routing protocol needed to disseminate physical-layer information (Table 1) besides TE attributes. Transmission impairments are monitored in-service so that suitable performance parameters can be provided to the GMPLS control plane (Figure 3). Unlike in 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: while the routing scalability is improved because the amount of information to be disseminated on a per link basis is lower than on a per wavelength basis, the ICBR algorithm must work with aggregated link information, which results in losing accuracy on the routing decisions. Impairment-related parameters are carried on the TE Link State Advertisements (TE-LSA) [13]. In particular, information is encapsulated within the top-level Link Type/Length/Value (TLV) as a common sub-TLV, which is referred in Figure 2 as impairment sub-TLV. The contents of the impairment sub-TLV are: *Type*, which is used to identify uniquely this sub-TLV, *Length*, which contains the total length (in bytes) including the header of the sub-TLV, and *Value*, which contains the link parameters considered (e.g., OSNR, PMD). The construction of the proposed Impairment sub-TLV is similar as standardized TE information (link metric, unreserved bandwidth, etc.)

Therefore, an on-line monitoring system can inform the LRM about changes in physical parameters such as ASE noise or PMD penalties in adjacent links (Figure 1). Note that the monitoring system only provides this information to the LRM that “owns” the affected link. After that, the LRM informs the RC in order to flood the new physical value to the entire network by using the appropriate extensions to OSPF-TE. As a result of the flooding mechanism every node’s TED will be aware of the new impairment parameter value even if the link is not adjacent. This global information will be used by the ICBR algorithm during the path computation.

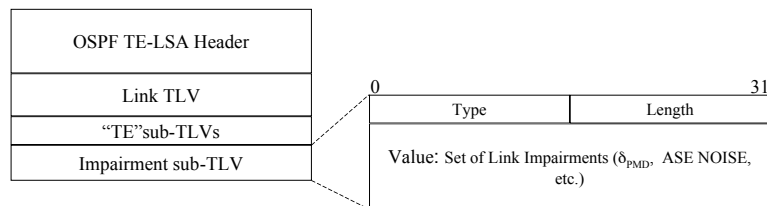


Figure 2. Proposed impairment sub-TLV information in OSPF-TE

4. EXPERIMENTAL PERFORMANCE AND DISCUSSION OF DYNAMIC AND DISTRIBUTED ICBR

4.1. THE ADRENALINE TESTBED

The ADRENALINE testbed is a hybrid platform composed of real and 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 links using two unidirectional fibers of 35 km each. Every fiber carries up to 8 wavelengths using dense WDM technology. The control plane Furthermore, ADRENALINE comprises 9 Optical Connection Controllers (OCC) with the architecture depicted in Figure 1, which are used to emulate the implemented distributed GMPLS control plane. The management plane is formed by 3 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 [15].

4.1.1. 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 on a per link basis to perform ICBR [16]. 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 (Figure 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 logs 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. The INIM system can be installed in Windows and Linux OS, and is based on several programming languages depending of the component criticism (delay-bound). Critical processes are developed in Java, medium processes in Java/FESI and non-critical in Shell Script. 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 (packet delay and loss of each lightpath), links where events occur (link index) and lambda services affected by the events (channel index).

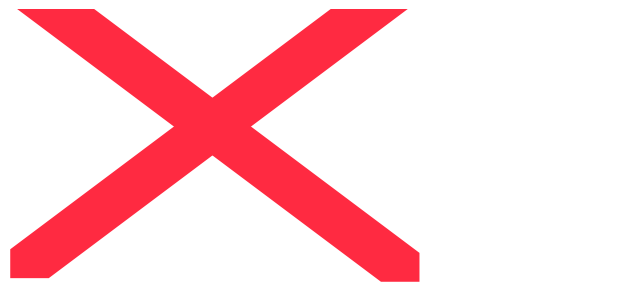


Figure 3: Architecture of the INIM system

4.1.2. GMPLS-BASED ROUTING CONTROLLER IMPLEMENTATION

The routing controller located in the OCCs of the ADRENALINE testbed is meant to be used in a multi-domain, single autonomous system environment (e.g., carrier). It was designed to manage two independent routing instances, each one related to a different plane [17]: OSPFv2 [18] within the control plane or DCN, and GMPLS OSPF-TE within the transport (data) plane [13]. The motivation of such a separation is that in a GMPLS network the control and transport plane topologies may be neither identical nor congruent. This means that a failure over the control topology (e.g., control link ~~can~~*must* not affect the connections over the data plane, and vice versa. Routing within the control plane is performed by classical IP routing in order to route control and management IP packets through the DCN. As an example, RSVP-TE signaling messages are exchanged within the DCN to establish and release optical connections within the transport plane. On the other hand, routing concerning the data plane involves path computation (links, nodes and wavelength) for every lightpath request received. This is realized executing ICBR algorithms that take into account the updated information maintained in the TED repository, as described in section 3. Therefore, OCCs' RCs in the ADRENALINE testbed were designed and implemented according to the architecture shown in Figure 1. More detailed information about the implemented RC can be found in [17].

4.2. DELAY STUDY

The primary application of performance monitoring is to certify SLAs between network operators and their clients. The study of the verification periodicity of the INIM system is crucial to ensure the certification of SLAs in the ADRENALINE testbed in a periodic manner. Furthermore, the study of monitoring delays is also applied when the INIM system must inform/update the control plane about any significant degradation in the optical links. Obviously, this study results primordial when considering ICBR routing algorithms for two reasons: check the efficiency of the distributed model in front of any physical parameter change, and validate the overall performance (e.g., routing algorithm delay, routing flooding) as a way to evaluate the feasibility of distributed ICBR based on real-time monitoring information.

4.2.1. CHANGE IN THE STATUS OF AN OPTICAL RESOURCE

Starting from the monitoring points, which inform of significant variations in the status of resources and services, we analyze the processing delays of all the elements involved in the INIM system and ICBR. Figure 4 illustrates the delays of the implemented INIM system until an alarm is raised to the service management system or to an OCC's LRM module. For any change or sample of the status of a lambda service or optical resource, the gatherers receive an event message after a delay named D_{event} . The processing in the gatherers (filtering and aggregation) will take D_{f-a} time. D_{event} depends on the monitoring point (sampling rate, interworking with the gatherers, etc.), whereas D_{f-a} may vary for each type of performance parameter only in what concerns the sensor process in the gatherer. Once in the event manager, D_{verify} can be either for SLA (depending on number of active connections) or link/channel values. In the latter, an alarm may be raised to the OCC of the/an affected link (D_{adm}). With the aim of computing the end-to-end delay to report on a change in the status of

a link, we add ICBR delays: in the control plane, information will be updated globally through computing a suitable algorithm (D_{alg}) and flooding the aggregated information (D_{flood}). This end-to-end delay ($D_{linkchange}$) is:

$$D_{linkchange} = D_{event} + D_{alarm} + D_{verify} + D_{f-a} + D_{alg} + D_{flood} + D_{event}$$

Figure 4 depicts average values of the delays involved in $D_{linkchange}$ for the physical-layer performance metrics of optical channel power and OSNR, in the scenario where the INIM system reports on any change on a per channel basis. From Figure 4 it can be inferred that $D_{linkchange}$ values obtained in the ADRENALINE testbed are below 400 msec [19], considering worst-case values for D_{event} (sampling of the monitoring point and event with SNMP protocol).

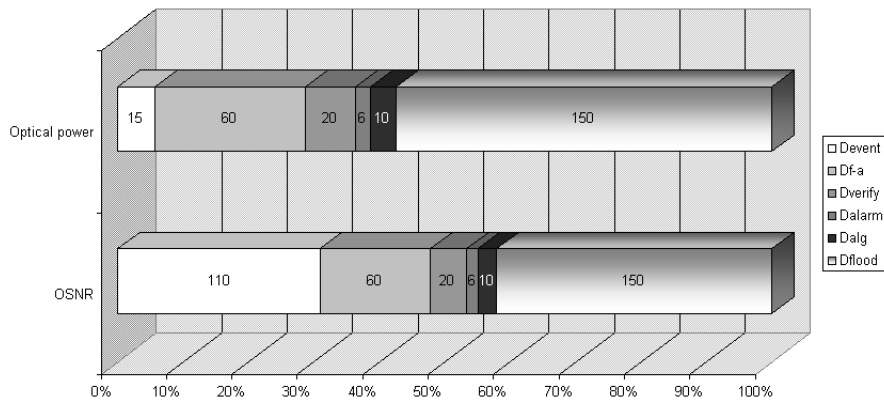


Figure 4: Delay (msec.) to update a status change of physical-layer parameters

4.2.2. DISTRIBUTED ICBR: ANALYSIS OF LIMITATIONS AND PENALTIES

The utilization of ICBR algorithms according to a distributed model as described in section 3 (GMPLS-based control plane) represents an improvement for guaranteeing adequate end-to-end optical signal of the lightpaths, besides traditional network-layer demands. This model conveys some benefits and advantages with respect to the centralized ICBR 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 model also introduces some restrictions which are closely associated to the essence of distributed models. These restrictions are reduced to: TED inconsistency on the OCC 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 variations in channel power 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 the bandwidth is highly dependent on the traffic fluctuations. However, threshold policies may be used for alleviating this updating problem if changes occur frequently.

On the other hand, the need for a multi-constrained RWA algorithm does not imply an increase in the complexity but in the required time for execution, as well as in the setup delay for establishing a connection. In a distributed model,

the main objective of TE-based RWA/CBR algorithms is to deal with the shortest path route (Dijkstra), whereby every link along the path must satisfy the constraints (e.g., bandwidth, protection capabilities, resource class/color [13]) imposed by the lightpath request. The complexity of such routing algorithms is mainly due to the Dijkstra algorithm rather than the evaluation/validation of every network link. Therefore, the utilization of distributed ICBR algorithms does not augment the computational complexity (compared with TE-based RWA algorithms) but the computational time, which is increased because physical-layer constraints are considered besides network-layer restrictions when calculating each route. By adopting 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 must validate the adequateness of the received optical signal, which increases the setup delay (required time for establishing the optical connection) and may increase the blocking probability if the computed route is refused because of poor physical-layer performance (connection re-attempts are needed).

5. CONCLUSIONS AND FUTURE WORK

This paper 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. Thus, we propose the use 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 within the whole network. Experimental delay studies show the feasibility of on-line monitoring for updating physical-layer parameters. Analytical discussions evaluate the suitability of the proposed distributed ICBR approach.

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

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