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# Distributed Sharing of Functionalities and Resources in Survivable GMPLS-Controlled WSONs

A. Manolova, I. Cerutti, R. Muñoz, S. Ruepp, A. Giorgetti, N. Andriolli, N. Sambo, P. Castoldi, R. Martínez, and R. Casellas

**Abstract**—Sharing of functionalities and sharing of network resources are effective solutions for improving the cost-effectiveness of wavelength-switched optical networks (WSONs). Such cost-effectiveness should be pursued together with the objective of ensuring the requested level of performance at the physical layer (i.e., quality of transmission, QoT) and at the upper layer also in the case of a failure (i.e., survivability). This paper aims to apply the sharing concept to a WSON with QoT and survivability requirements (against single-link failures). QoT is guaranteed by resorting to regeneration of the optical signal in intermediate nodes. Survivability is guaranteed by resorting to path protection. To exploit the sharing benefits, the scarce regenerators are used for both regeneration and wavelength conversion (WC) leading to a sharing of functionalities. Also, the shared path protection mechanism is exploited to ensure survivability against single-link failures and make the sharing of network resources (regenerators and wavelengths) possible. The paper presents a novel distributed scheme (DISTR) for reservation of regenerators and wavelengths in generalized multi-protocol label switching controlled WSONs, in order to ensure the required level of QoT and survivability. Novel objects and selection strategies for the resource reservation protocol with traffic engineering extensions are proposed and evaluated. The DISTR scheme effectively combines regeneration and WC points, leading to a noticeable reduction of the regeneration usage with respect to the existing schemes. Moreover, a significant reduction of the blocking probability is achieved, independently of the wavelength selection strategy used.

**Index Terms**—GMPLS control plane; Network resilience; Physical layer impairments; WDM networks.

## I. INTRODUCTION

The fast increase of the data transmission rate per wavelength channel, rapidly approaching 100 Gb/s, and the introduction of dynamically reconfigurable wavelength-switched optical networks (WSONs) are two of the most evident evolution trends in today's optical networks. In WSONs, end-to-end optical connections (i.e., lightpaths) are switched entirely in the optical domain. However, transparent WSONs

are affected by two major challenges: the degradation of the optical signal quality due to transmission impairments [1], and the wavelength continuity constraint [2] from the source to the destination nodes. To better cope with such issues, the concept of *translucent WSONs* [1] has emerged, where regenerators for re-amplifying, re-shaping and re-timing the optical signal (3R regeneration) are strategically placed. The regenerators can be deployed at the nodes where optical–electrical–optical (OEO) conversion is required for ensuring the quality of transmission (QoT) and where the connection's wavelength must undergo (electronic) wavelength conversion. Therefore, each established connection can be supported by either a single lightpath (i.e., an end-to-end continuous optical path) or a sequence of lightpath segments concatenated by means of regenerators at intermediate nodes.

In translucent WSONs, the requested connections can be dynamically established by a distributed control plane such as the generalized multi-protocol label switching (GMPLS) [3] suite. Such dynamic establishment requires the computation of the paths, the estimation of the QoT, the selection of the node(s) where regeneration should take place, the selection of the wavelength(s) for each lightpath (or label switched path (LSP) under the GMPLS terminology), and the reservation of the resources (i.e., regenerators and wavelength channels). These tasks should be performed jointly in a cost-effective way, i.e., with the objective of minimizing the number of resources used. The dynamic establishment of the connections is further complicated when survivability against failures needs to be guaranteed.

The presented work aims to define and configure an efficient strategy for selecting and reserving resources in GMPLS-controlled translucent WSONs with requirements for QoT and survivability against single-link failures. To this end, the designed strategy must be able to perform designation of *regeneration points* (i.e., the nodes where optical signal regeneration is required) and *WC points* (i.e., the nodes in which wavelength conversion (WC) is needed) with the objective of minimizing the overall use of resources, while ensuring survivability.

To minimize the utilization of the regenerators, the strategy should strive to make the regeneration and WC points coincide. This permits the sharing of both functionalities (i.e., OEO conversion for QoT and WC) within the same device [4,5]. To minimize the additional resources required for survivability, the shared path protection (SPP) mechanism can be selected since it is widely recognized as the most capacity-efficient with an acceptable recovery time [6]. Indeed, the wavelength

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channels are shared among the existing protection (or backup) LSPs. Specifically, resources along a protection LSP are pre-reserved, but not cross-connected. Therefore, in order to ensure 100% survivability of the working LSPs affected by a single-link failure, wavelength channels can be reserved for protecting more than one LSP, provided that these LSPs do not share links belonging to the same shared risk link group (SRLG), i.e., there is no sharing violation [4]. It is important to note that wavelength continuity and QoT must also be ensured for the protection LSPs, by resorting to 3R regeneration [7,8]. Interestingly, in translucent WSONs regenerators can be handled in a way similar to wavelength channels and thus can be shared among protection paths whose working paths are SRLG-disjoint [5].

This paper provides a thorough analysis of the performance of a novel distributed scheme, named the DISTR scheme, for joint selection of regeneration and WC points within a dynamic and distributed GMPLS control plane. The strength of the proposed approach is twofold. First, the DISTR scheme is based on a fully distributed approach which is inline with the working principle of the resource reservation protocol with traffic engineering extensions (RSVP-TE) [9] and avoids extensions to the open-shortest path first with traffic engineering extensions (OSPF-TE) protocol [10]. Moreover, the DISTR scheme is independent of the resource (e.g., wavelength) selection strategy, and thus any wavelength selection strategy can be applied. Advanced resource selection strategies specifically designed for improved resource sharing can further enhance the performance of the scheme.

To support the DISTR scheme and the considered wavelength selection strategies, the required extensions of the RSVP-TE signaling protocol are identified. Based on such extensions, the benefits of the DISTR scheme are evaluated for the considered wavelength selection strategies and compared with state-of-the-art schemes for RSVP-TE, through extensive simulations.

## II. STATE OF THE ART IN THE GMPLS CONTROL PLANE

Before presenting the proposed scheme, the most relevant strategies for resource handling in GMPLS networks are surveyed. In WSONs with a distributed GMPLS control plane, the OSPF-TE routing protocol floods any change occurring in the network state. This information dissemination permits the nodes to locally store the current network topology and the resource availability in a traffic engineering database (TED). Detailed information on wavelength availability is available only locally at the nodes. A signaling protocol, namely, RSVP-TE, is required to collect the wavelength availability information along a pre-computed path (forward phase) and to reserve the selected wavelength (backward phase).

To overcome the limitations of the wavelength continuity constraint, the work in [11] considers a WSON provisioned with a limited number of WCs and proposes an RSVP-TE enhancement for maintaining the wavelength continuity as far as possible, thus minimizing the use of WCs. For this purpose, a new RSVP-TE object, called suggested vector (SV), is proposed, along with a strategy for its utilization. An alternative approach for networks with sparse wavelength converters is

presented in [12]. Wavelength reservation is carried out by parallel sessions of RSVP-TE between each pair of nodes equipped with wavelength converters along the pre-computed path.

To ensure QoT, an impairment-aware control plane is necessary [13–15]. Based on the physical impairment information, the optical signal quality can be estimated or measured. One way to provide QoT is to bound the LSP length to the maximum transparent distance (referred to as “QoT distance” hereafter) [16,17]. An alternative is to estimate or analytically compute the optical signal quality using a single or a set of physical performance indicators (such as the optical signal-to-noise ratio (OSNR), the estimated bit error rate, the Q factor) [5,18]. Furthermore, physical impairment parameters can be either disseminated by the OSPF routing protocol (i.e., routing approach) [13,14] or gathered by the RSVP-TE signaling protocol (i.e., signaling approach) extended for QoT support [19].

In addition to the physical impairment information, information about regenerator availability also needs to be either disseminated by OSPF-TE or collected by RSVP-TE. The works in [20] and [21] introduce a novel TLV (type/length/value) for regenerator information dissemination (e.g., availability, tunability range [21]) along with QoT-related information (i.e., node and link OSNR). In [22], the authors propose a novel object for the OSPF-TE protocol to advertise the number of available regenerators at each node, whereas in [23] the authors introduce a regenerator availability object (RAO) for RSVP-TE. In [24], an extension to the explicit route object (ERO), named Regenerator ERO sub-object, is proposed to specify the node(s) in which a regenerator should be reserved. Alternatively, in [25] a regenerator bit is appended in the Label ERO sub-object [25], whereas a new regenerator object (RO) is introduced for RSVP-TE in [22,26]. Designation of the regenerator node can be performed either at the destination [22,26], at the source [22] or during the forward signaling phase [22]. Initial findings related to the sharing of functionalities under the failure-free scenario have been presented in [27].

To ensure survivability based on the SPP mechanism, it is necessary to either disseminate [28] or gather [29–32] the information about the resources reserved for protection purposes, which are referred to as *shared-reserved resources*. The former approach is based on enhancing the OSPF-TE routing protocol with specific SPP extensions to disseminate the required information. In [28], the authors propose a new extension for disseminating shareable resource information on a per-wavelength channel basis. This information includes the status (i.e., idle, in-service or shared) of each wavelength channel on every network link, and the list of the physical links (i.e., SRLGs) protected by each shared wavelength channel. In the latter approach, RSVP-TE is extended to gather the shareable resources during the forward phase of the RSVP-TE signaling process. In [32], the authors extend the Label Set to the so-called Shared Label Set. The performance of the signaling and routing approaches is experimentally assessed in [33].

Such works on SPP neglect the QoT constraint. QoT-guaranteed survivability based on SPP was evaluated for the first time in [34]. In the work, regenerators are selected at the destination and can be used also for WC purposes.

TABLE I  
PROPOSED RSVP-TE ENHANCEMENTS FOR SUPPORTING THE SHARING OF FUNCTIONALITIES AND RESOURCES

RSVP-TE functions	Wavelength selection	WC selection	Regenerator selection	Sharing of functionalities	QoT	Survivability
WC reservation: [11]	distributed	distributed	N.A.	No	No	No
Regenerator reservation: [26]	at destination	N.A.	at destination	No	Yes	No
[22]	at destination	N.A.	at source, at destination, or distributed in forward phase	No	Yes	No
WC and regenerator reservation: [25,27]	at source	at source	at source	Yes	Yes	No
Protection resource reservation: [32,33]	at destination	N.A.	N.A.	No	No	SPP
[35]	distributed	distributed	N.A.	No	No	SPP
[34]	distributed	distributed	at destination	Yes	Yes	SPP

The most relevant works related to RSVP-TE extensions in support of translucent WSONs with SPP and QoT requirements are summarized in Table I. The contribution of this paper to the field is twofold. First, to the best of our knowledge the paper provides the most thorough and up-to-date overview of the state of the art in the field. Second, our work presents an in-depth analysis of the performance of a combined strategy for jointly designating the regeneration and WC points and for selecting the wavelengths [27] in a translucent WSON both under the failure-free scenario and under the SPP mechanism. The combined strategy is compared to the destination designation strategy from [22], referred to as the DEST scheme hereafter. Next, the proposed distributed scheme (DISTR) is presented assuming the absence of SPP support. Then, DISTR is extended to enable the sharing of resources under the SPP mechanism.

### III. SHARING OF FUNCTIONALITIES

During the RSVP-TE signaling session for establishing an LSP, the following standard objects are used in the Path message: the Label Set, the ERO, and the record route object (RRO). Furthermore, two novel objects for regeneration designation support are used according to [23]: the regeneration availability object (RAO) (in the Path message) and the RO (in the Resv message). The Label Set elements indicate the wavelength availability. ERO contains the sequence of nodes forming the path. RRO contains the actual set of node IDs comprising the full path. RAO contains the information of the available regenerators along the path, whereas RO contains the set of node IDs designated to be regeneration points.

Without loss of generality, it is assumed that QoT is guaranteed by limiting the maximum all-optical reach, i.e., the QoT distance. The computation of the QoT distance (e.g., from the physical layer parameters) is beyond the scope of the paper.

In the DEST scheme [22], the designation of regeneration nodes is performed only at the destination, based on the RAO object (see [23] for detailed operation description), and cannot be modified by the intermediate nodes. The chosen regeneration points are indicated in the RO and put in the Resv message. Then, wavelength selection is performed. Note that a regeneration point may also become a WC point, when WC is required. Under this scheme, the regenerator node designation and the wavelength selection are performed independently and, thus, any sharing of regeneration functionalities is not deliberate.

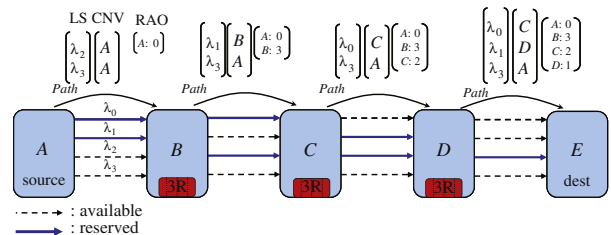


Fig. 1. (Color online) Example of CNV usage.

A joint selection of the WC and regeneration points requires additional information to account for the nodes where WC is required. Next, the novel object for collecting such information is presented and the DISTR scheme based on the novel object is described.

#### A. Novel Object for Sharing Regenerator Functionalities

The novel object for supporting sharing of regenerator functionalities is named the *conversion node vector (CNV)* [27]. It includes an element for each wavelength contained in the Label Set, indicating the ID of the closest upstream node where WC must take place for the corresponding wavelength (see Fig. 1). At the source node, each element of the CNV is initialized with the source node ID for each wavelength included in the outgoing Label Set. In the intermediate nodes, for each wavelength included in the outgoing Label Set, the corresponding entry in the CNV is updated as follows. If a wavelength must undergo WC at the node, the corresponding CNV entry is set to the node ID. Otherwise, the entry is left unchanged.

An example, illustrating the advantage of the CNV vector, is given in Fig. 1. The Label Set, the RAO and the CNV included in each Path message are as shown. Assume that the optical signal must undergo regeneration at least every three hops and that the regenerator availability is as indicated in the RAO. If the regeneration points are selected at the destination according to the DEST scheme, based solely on the RAO object, then the regeneration is designated to take place at node B. If a first fit selection of the wavelength is applied (i.e.,  $\lambda_0$ ), this results in a WC at node C. Similarly, selection of  $\lambda_1$  forces a WC at node D. Thus, two regenerators are needed in both cases (one for QoT provisioning and one for WC).

With the help of the CNV object though, just one regenerator is sufficient for any wavelength in the Label Set. If the destination selects  $\lambda_0$  or  $\lambda_1$ , the regeneration is designated to take place together with the WC in the node indicated in the

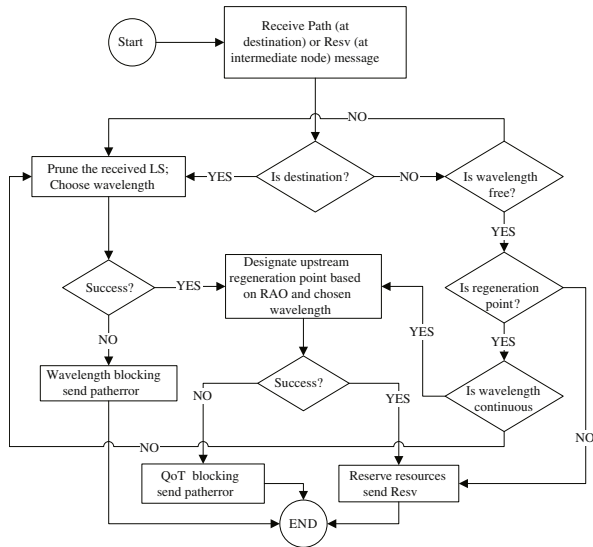


Fig. 2. Flow-chart for the DISTR scheme.

CNV (albeit closer than required). If  $\lambda_3$  is selected, no WC is needed and only one regeneration is required at the maximum QoT distance (i.e., at node B).

### B. Distributed Scheme for Regenerator Designation (DISTR)

The novel distributed joint selection strategy (DISTR) is implemented as follows. The destination node receiving a Path message checks the regenerator availability indicated in the RAO jointly with the required conversion nodes indicated in the CNV. Based on such information, the destination can select at best the upstream regeneration point and/or WC point along with the wavelength to be used.

The joint selection of a regeneration/WC point is performed at the destination node as well as at any intermediate node in which WC or regeneration is required. It consists of three functions: pruning the Label Set, choosing a wavelength and designating the upstream regeneration point (see Fig. 2).

The pruning is performed on the received Label Set as follows. First, a candidate regeneration point is selected as the most distant node in the upstream direction (based on the RRO) within the QoT distance and having at least one available regenerator (i.e., no null entry in RAO). Then, the node identifies the wavelengths in the Label Set which are not continuous to the source and which require WC at a node different from the candidate regeneration point. Such wavelengths are temporarily pruned from the Label Set. If all the wavelengths are pruned, then the pruning is performed by removing all wavelengths which require conversion in the nodes downstream from the candidate regeneration point. If the pruned Label Set is still empty, then the Label Set is left unchanged (i.e., no pruning).

Wavelength selection is performed using any existing strategy applied to the pruned Label Set. When the wavelength is selected, the upstream regeneration point is decided as follows:

- if the WC point (as specified by the CNV entry corresponding to the selected wavelength) is within the QoT distance,

the WC point also becomes a regeneration point (i.e., WC and regeneration are effectively combined together at the same node);

- if the WC point is outside the QoT distance, the candidate regeneration point is designated.

Note that under DISTR each node designates only the closest upstream node for regeneration and WC (i.e., a fully distributed model), whereas under DEST the destination node designates all needed nodes for regeneration for the entire path. Furthermore, under the DEST scheme the WC points are selected in the backward phase independently of the regeneration points and without the possibility of modifying the destination designation. This lack of flexibility, leading to waste of regeneration resources, is efficiently averted by the DISTR scheme which performs joint selection of regeneration and WC points.

## IV. SHARING OF NETWORK RESOURCES

In this section, the DISTR scheme is extended to support the SPP mechanism. In SPP, network resources (i.e., wavelengths and regenerators) can be shared between protection LSPs that are SRLG-disjoint. To ensure SRLG-disjointness, the following states must be recorded in the local database for each wavelength channel on the locally connected links and for each local regenerator:

- *idle*: idle resources can be reserved by either working or protection LSPs;
- *in-service*: in-service resources are currently used for working LSPs;
- *shared-reserved*: shared-reserved resources are currently reserved by one or more protection LSPs, provided that the corresponding working LSPs do not share any SRLG, i.e., there is no *sharing violation*.

In addition, the local database indicates the list of SRLGs that each shared-reserved resource is protecting [32].

In this work, it is assumed that OSPF-TE advertises aggregated wavelength availability information, i.e., the number of idle, in-service, and shared-reserved [28] wavelength channels per link. Such aggregated information is stored in the TED at each node. Based on such information the source node computes a pair of SRLG-disjoint paths, for the requested working and protection LSPs, using the information available in the TED.

### A. Objects for Sharing Regenerators and Wavelengths on the Protection LSPs

To enhance the sharing of network resources, the following non-standard objects are required in the Path message of the RSVP-TE session for the protection LSP:

- Shared wavelength vector (S-WV) proposed in [32] includes an element for each wavelength contained in the Label Set. Each element indicates the number of links on which the corresponding wavelength is in shared-reserved status.

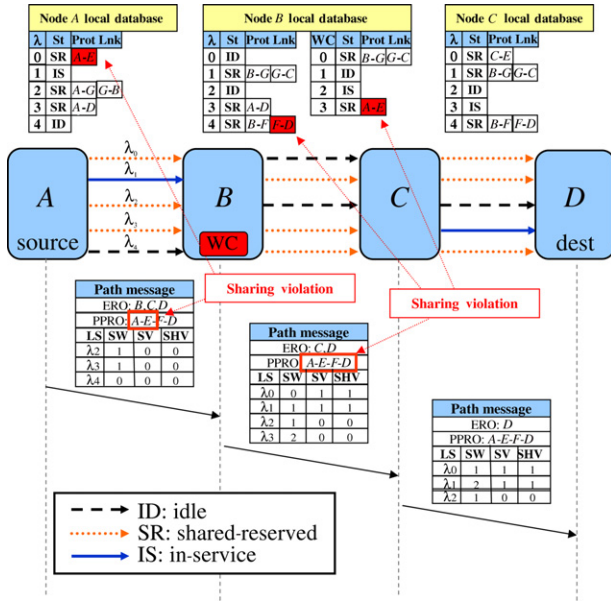


Fig. 3. (Color online) RSVP-TE operations for the protection LSP.

- Shared regenerator vector (S-RV) proposed in [35] includes an element for each wavelength contained in the Label Set. Each element indicates the number of shareable regenerators that are required for establishing the LSP on the corresponding wavelength.

These objects should be included along with the standard objects: Label Set, ERO, RRO and primary path route object (PPRO) [9,36].

### B. Distributed Strategy for Protection Resource Selection

Wavelength channels and regenerators for the working and protection LSPs are reserved by RSVP-TE, while ensuring wavelength continuity and QoT [23]. In particular, after the successful establishment of the working LSP, a second RSVP-TE session is triggered by the source node to establish the protection LSP, along the previously computed SRLG-disjoint path. During this RSVP-TE signaling session, it is necessary to verify whether the resources (i.e., wavelengths and regenerators) in the shared-reserved state are *shareable*, i.e., there is no sharing violation between SRLGs of the working LSP and SRLGs protected by the shared-reserved resource.

Whereas the reservation of resources for the working LSPs takes place as described in Section III, the reservation of resources for the protection LSPs is as sketched in Fig. 3.

Each node stores a copy of each received Path message and, before forwarding it, updates it as follows. If neither idle nor shareable regenerators are locally available, the outgoing Label Set is computed by intersecting the incoming Label Set with the set of wavelengths that are idle or shareable in the outgoing link (see the Path message update at node C in Fig. 3). Otherwise, if an idle or a shareable regenerator is locally available, the outgoing Label Set includes all the wavelengths that are idle or shareable in the outgoing link (see the Path message update at node B in Fig. 3).

For each wavelength included in the outgoing Label Set, the corresponding S-WV and S-RV elements are updated as follows:

- S-WV: if the wavelength is not contained in the received Label Set, the corresponding S-WV entry is set to 0 or 1 depending on whether the wavelength is idle or shareable in the outgoing link, respectively. If the wavelength is contained in the received Label Set, the corresponding S-WV entry is incremented by 0 or 1 if the wavelength is idle or shareable in the outgoing link, respectively.
- S-RV: if a WC is locally required for a wavelength, the corresponding S-RV entry is the maximum value in the received S-RV incremented by 1 if there is a local shareable regenerator. If WC is not required, the corresponding S-RV entry is left unchanged.

The destination node receiving a Path message performs wavelength selection according to one of the strategies described in Section V. In the backward phase, each node designated as a regeneration point (regardless of the applied regeneration designation method) reserves an idle or shareable regenerator according to one of the strategies described in Section V.

After reserving the regenerator, a wavelength is reserved. The node checks whether the Label Set of the stored Path message (i.e., the Path message of the same RSVP-TE session) contains the wavelength selected for reservation and performs the following operations:

- If the wavelength is included in the stored Label Set and is available on the incoming link, this wavelength is reserved for the protection LSP.
- If the wavelength is not included in the stored Label Set and an idle or shareable regenerator is available (or has been already reserved for QoT), then the regenerator is reserved and another wavelength is selected on the incoming link for the protection LSPs, according to one of the strategies described in Section V.
- If the wavelength is not included in the stored Label Set and no idle nor shareable regenerator is available, the reservation is blocked.

The SRLGs of the corresponding working LSP are appended to the list of SRLGs protected by the selected wavelength and regenerator in the local database.

## V. RESOURCE SELECTION STRATEGIES

For both working and protection LSPs, resource selection is performed at the destination node and at any intermediate nodes in which a regenerator is required. The following strategies for selecting an available resource are considered.

### A. Regenerator Selection Strategy

Each node acting as WC or regeneration point selects a regenerator locally as follows. For the working LSPs the required regenerator is randomly selected among all idle regenerators. For the protection LSPs (under SPP), the required regenerator is randomly selected among all shareable regenerators. In the absence of a shareable regenerator, a regenerator is randomly selected among all idle regenerators.

## B. Wavelength Selection Strategy

Wavelength selection (WS) is applied to the Label Set (either the original one under DEST or the pruned one under DISTR). For the performance evaluation under the failure-free scenario two WS strategies are considered: first fit (FF) and random (RA). Under SPP, the working LSPs use a standard FF selection strategy. For the protection LSPs the wavelength is selected according to one of the following traditional WS strategies:

- random (RA): random selection;
- first fit (FF): selects the lowest-indexed available wavelength;
- last fit (LF): selects the highest-indexed available wavelength;

or according to one of the following advanced WS strategies proposed in [32,35]:

- maximum wavelength sharing (SW): selects the wavelength with the highest S-WV value; ties are broken by using the LF strategy;
- maximum regenerator sharing (SR): first, the S-RV is checked to see whether any wavelength has a value of 0 (i.e., no conversion is required using that wavelength); if present, LF is used as a tie breaking policy among null value wavelengths; if absent, the wavelength with the highest S-RV value (i.e., highest regenerator sharing) is selected; ties are broken using the LF strategy.

## VI. PERFORMANCE EVALUATION

In this section, the performance of the DISTR scheme under different WS strategies (for the protection LSPs) is evaluated by means of simulations, performed with the event-driven simulator OPNET [37]. DEST scheme performance [22] is also shown for comparison.

A pan-European network topology [38] with  $N = 28$  nodes and  $L = 61$  bi-directional links, each carrying  $W = 40$  wavelength channels, is considered. Each link belongs to a different SRLG. Requests for (protected) LSPs are dynamically generated following a Poisson process and uniformly distributed among all source–destination pairs. The inter-arrival and holding times of the LSP requests are exponentially distributed with averages of  $1/\lambda$  and  $1/\mu$ , respectively, where  $1/\mu$  is fixed to 30 min. All results are plotted against the total input network load defined as  $N \cdot \lambda/\mu$ .

The processing time of the packets is considered negligible compared to the optical propagation and transmission time. Working LSPs are routed along the shortest paths on the links having idle wavelengths. FF wavelength selection is applied for working LSPs. Each protection LSP is routed along the shortest path on the links that are not used by the corresponding working LSP and that have available (i.e., idle and/or shareable) wavelengths. To select the wavelength of the protection LSP, one of the WS strategies presented in Section V is used.

Following the results in [39], the number of regenerators installed at each node is proportional to the nodal degree and

the available wavelengths per link according to

$$\#3R_i = \left\lceil \text{NodalDegree}_i \cdot \frac{W}{5} \right\rceil \quad \text{for } i \in \{1 \div N\}.$$

For simplicity, the chosen QoT distance is expressed as the number of hops (i.e., links of equal length are assumed). In particular, a QoT distance of two hops is chosen. A longer QoT distance will provide similar relative performance among the evaluated strategies and schemes since they are independent of the QoT model and the same path is used under both DISTR and DEST for the same source/destination pair. Simulation results are collected on  $3 \cdot 10^6$  LSP requests and presented for the cases of absence of SPP and presence of the SPP mechanism in Subsections VI.A and VI.B, respectively.

### A. Benefits of Functionality Sharing

The ability of the DISTR scheme to combine WC and regeneration points is first assessed in the failure-free scenario. The simulation results are shown in Fig. 4 with the confidence interval bars at 95% confidence level. In the figure, four performance metrics are quantified:

- blocking probability: the ratio between blocked and requested LSPs (Fig. 4(a));
- average regenerator usage (Fig. 4(b));
- average path length (Fig. 4(c));
- average number of WCs performed outside of regeneration points, i.e., average number of WC points that are not regenerator points (Fig. 4(d)).

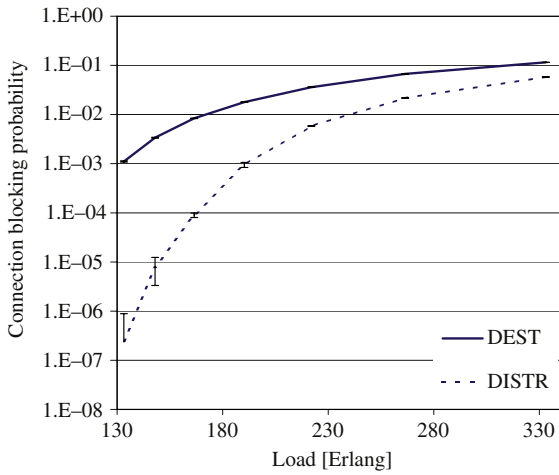
The last metric indicates the effectiveness of the functionality sharing. The fewer WC points out of regeneration points there are, the more efficient the regenerator usage is and the better the functionality sharing is.

The results indicate three main advantages: i) improved LSP blocking (Fig. 4(a)); ii) decreased overall regenerator usage (Fig. 4(b)); and iii) increased average LSP path length (Fig. 4(c)). All these benefits are due to the higher number of occasions on which functionality sharing is performed. Indeed, as shown in Fig. 4(d), DISTR uses fewer regenerators for WC alone (note that short LSPs which do not require regeneration might still need WC). This leads to higher regenerator availability and lower blocking (i.e., more LSPs will have a chance to be established). Furthermore, with respect to the DEST scheme performance, the longer LSPs in the DISTR scheme have an increased chance of being established, leading to an increased average LSP path length (Fig. 4(c)).

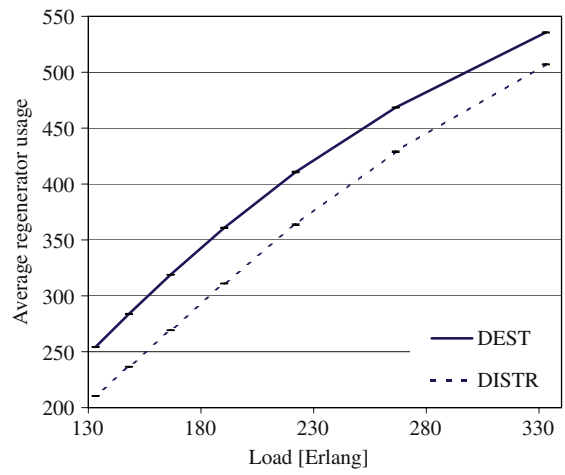
### B. Benefits of the Sharing of Functionalities and Network Resources

Here, the effects of applying the DISTR scheme under the SPP mechanism are evaluated. The goal is to observe the effects of combining both sharing of functionalities and sharing of network resources. The DISTR scheme is compared with the DEST scheme when combined with the WS strategies outlined in Section V.

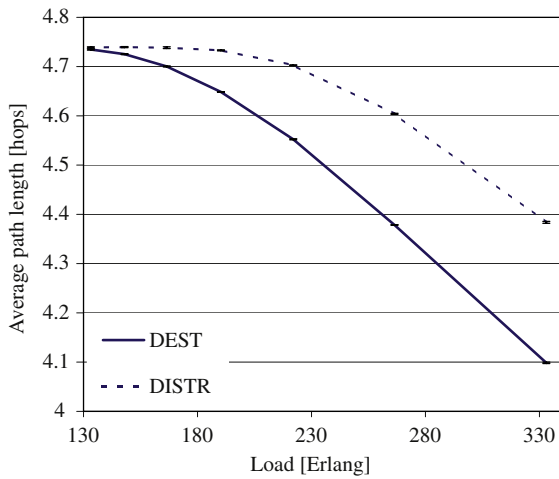
The simulation results in Figs. 5–9 assess the performance in terms of the following:



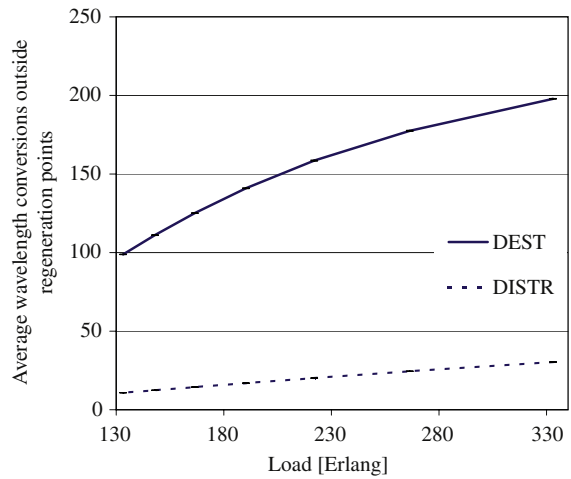
(a) LSP blocking probability.



(b) Regenerator usage.



(c) Average path length.



(d) Average wavelength conversions outside of regeneration points.

Fig. 4. DISTR and DEST performance in the absence of SPP versus load.

- blocking probability: the ratio between blocked and requested LSPs; it is the probability that the working or the protection LSP for a given connection request fails due to a lack of either available wavelengths or regenerators (Fig. 5);
- average regenerator usage (Fig. 6);
- average number of WCs performed outside of regeneration points (Fig. 7);
- wavelength overbuild: the ratio between the average number of wavelengths reserved for protection LSPs and the average number of wavelengths reserved for working LSPs (Fig. 8);
- regenerator overbuild: the ratio between the average number of regenerators reserved for protection LSPs and the average number of regenerators reserved for working LSPs (Fig. 9).

The DISTR scheme improves the blocking by up to two orders of magnitude (Fig. 5) and decreases the amount of regenerators used in the network (up to 35% at low loads) due to the efficient functionality sharing (Fig. 6). In contrast to DEST, in DISTR the difference between the various WS strategies is negligible, due to the pruning of wavelengths in the Label Set, which limits and randomizes the set. This leads to spreading out of

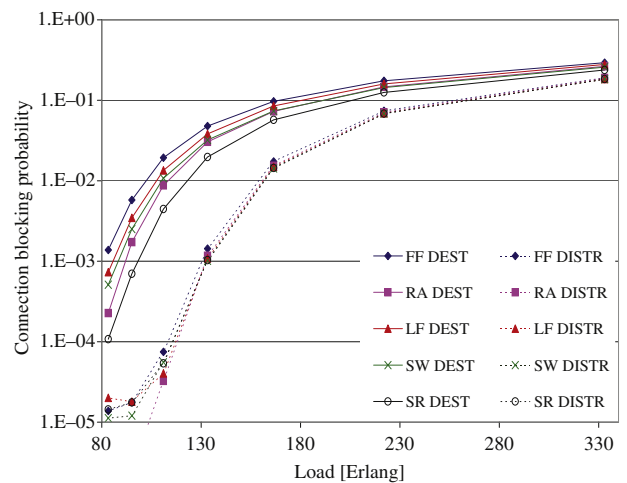


Fig. 5. (Color online) Total LSP blocking probability versus load.

the load among all wavelengths. As a result, any advantage due to using an advanced WS strategy (e.g., SR or SW) is nullified. In fact, the performance of all WS strategies becomes



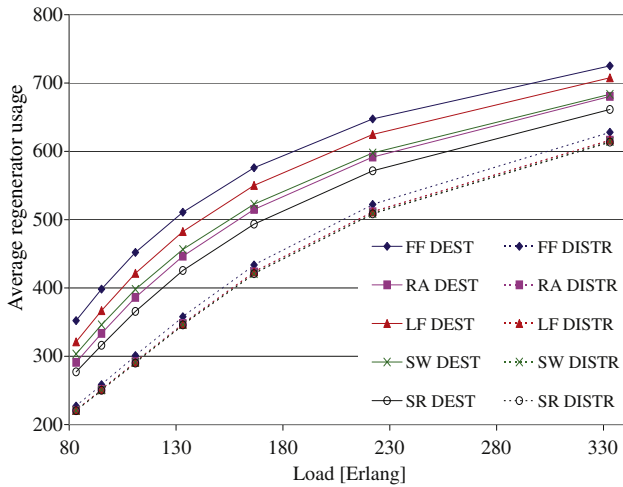
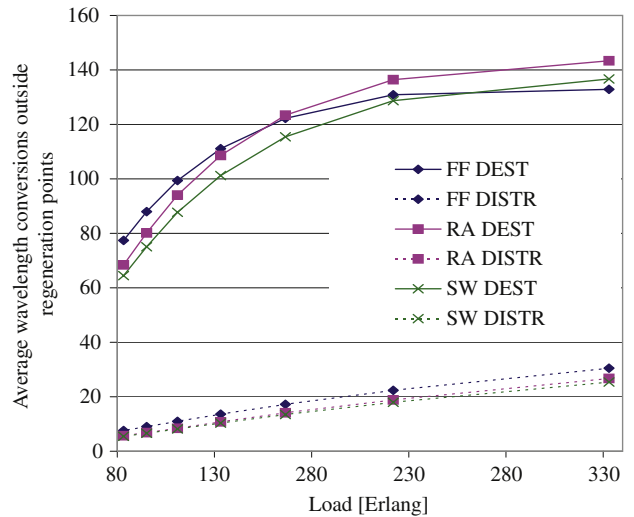


Fig. 6. (Color online) Average regenerator usage versus load.

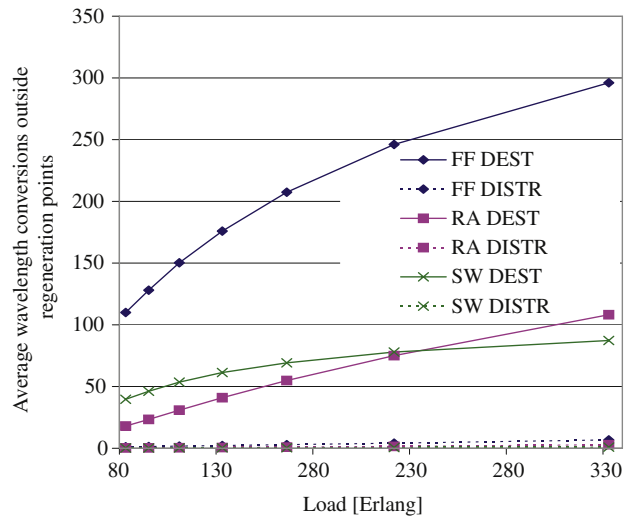
undistinguishable since after pruning they all use an already optimized Label Set with unpredictable size and composition.

Figure 7 illustrates the average number of WCs performed outside of regeneration points for three of the wavelength selection strategies. DISTR clearly outperforms the DEST scheme by more than 82% for the working LSPs and more than 97% for the protection LSPs. The joint selection of WC and regeneration points performed by the DISTR scheme not only saves the scarce regenerators (see Fig. 6), but also utilizes them more efficiently for WC.

A side effect of the DISTR scheme is the increase of the resource overbuild for both wavelengths and regenerators (see Figs. 8 and 9). This implies that the introduction of functionality sharing worsens the shareability of resources. One reason for the lower resource overbuild in DEST with respect to DISTR is the higher regenerator usage under DEST (Fig. 6). Combined with the high LSP blocking probability this entails that on average there are more regenerators used per light-path. Moreover, there is an increase of the occasions where WC is performed outside of regeneration points (see Fig. 7). As a result, the chances for sharing the wavelength and regenerator resources increase, thus improving the overbuild under DEST. Another reason for the worse resource overbuild is the Label Set pruning procedure under DISTR, which changes the Label Set in a random manner from the resource sharing standpoint; i.e., the Label Set used for the final wavelength selection typically comprises a subset of the wavelengths smaller than the original one. Since the resource sharing objective is met by specifically designing the Label Set and adding extensions to it, breaking its structure and content diminishes the expected effect of improved resource sharing. Indeed, in DISTR the performances of the FF, LF, SW and SR approach the performance of the RA strategy (the worst performing under both designation schemes). RA spreads out the load among all wavelength resources, effectively minimizing the chances of resource sharing. The only WS strategy that improves the wavelength overbuild under DISTR is the RA strategy itself, which is again due to the pruning function. The pruning of the Label Set limits the number of wavelengths for the protection LSPs and this improves the chances of resource sharing.



(a) Working LSPs.



(b) Protection LSPs.

Fig. 7. (Color online) Average number of WCs performed outside of regeneration points.

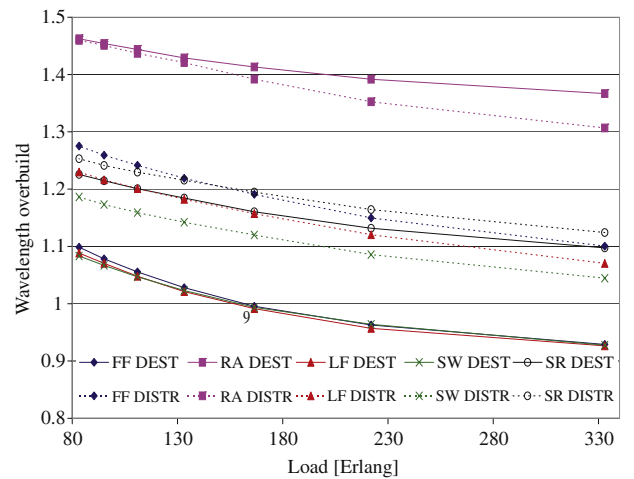


Fig. 8. (Color online) Wavelength overbuild versus load.

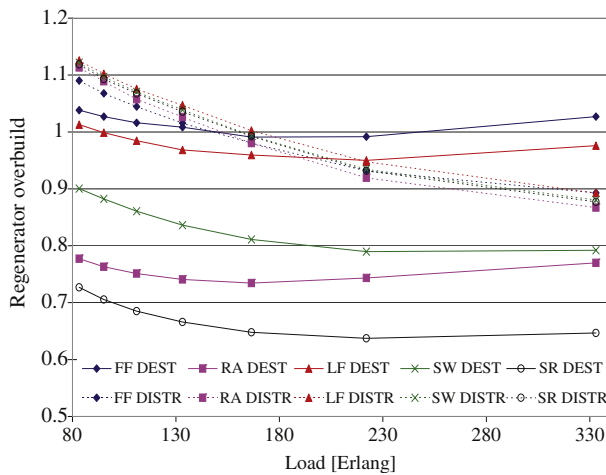


Fig. 9. (Color online) Regenerator overbuild versus load.

Regarding the regenerator overbuild (Fig. 9), all WS strategies under the DISTR scheme have very similar behavior, and are generally less efficient than under the DEST scheme in sharing regenerator resources among protection paths. When the load increases, however, the DISTR scheme succeeds in reducing the regenerator overbuild thanks to a wiser regeneration point choice. On the other hand, the regenerator overbuild under DEST, which is not aimed at optimizing regeneration and WC point locations, tends to a constant value, or even to grow for high loads. As expected, the SR wavelength selection strategy achieves the lowest regenerator overbuild at all loads, since it fosters the regenerator sharing among protection paths.

Note that the wavelength and regenerator overbuilds are ratios between the used working and protection resources. The measures do not indicate the absolute resource usage. Regardless of the observed degradation of the wavelength and regenerator overbuilds, the DISTR scheme achieves a lower regenerator usage (Fig. 6) and blocking probability (Fig. 5). In other words, although more resources are used for the protection LSPs, the overall resources used in DISTR are significantly less than in DEST.

Considering the results obtained for the resource overbuild, the LSP blocking and the average number of WC points that are not regeneration points, a clear trade-off between functionality and resource sharing is observed. When using DEST, the main focus is merely on the sharing of resources between protection LSPs, which is performed by applying intelligence within the resource selection process. Under DISTR, on the other hand, the primary focus is on sharing regenerator functionalities within one single LSP, i.e., the intelligence of the scheme is in optimizing the node-resource usage. By doing so, the resource sharing becomes a secondary objective. Since DISTR shrinks the Label Set in its attempt to optimize functionality sharing, this leads to a decrease in the benefits the specifically designed resource sharing strategies (i.e., the WS strategies) can bring. However this is significantly balanced by the lower blocking and overall regenerator usage.

The WS strategies presented have conflicting optimization objectives (i.e., maximization of regenerator sharing versus maximization of wavelength sharing) that give rise to a trade-off with respect to the resource sharing [34] (e.g., the SW

strategy has lower wavelength overbuild than SR but higher regenerator overbuild). In DISTR, this trade-off is reduced and becomes negligible in the considered scenarios.

## VII. CONCLUSION

This paper evaluates the performance a scheme, named DISTR, for joint and distributed selection of regeneration and WC points in GMPLS-controlled WSONs with QoT and survivability requirements. Extensions of DISTR to support the SPP mechanism are presented.

The performance of DISTR is assessed for different wavelength selection strategies, both traditional and advanced, and compared to the destination designation scheme (DEST). The simulation results show that DISTR is able to significantly improve the blocking probability (by more than an order of magnitude), decrease the regenerator usage and increase the average LSP path length. Such improvements hold also in the presence of the SPP mechanism, even if the percentage of resources allocated for protection (i.e., the resource overbuild) is increased. Interestingly, these improvements are almost independent of the wavelength selection strategy. The presented simulation results indicate that under the investigated network scenario the regeneration designation scheme is more important than any intelligent wavelength selection strategy. Finally, the presented DISTR scheme fits well with the distributed nature of the RSVP-TE protocol, requires only one additional object and does not involve extensions to the routing protocol in the network.

## ACKNOWLEDGMENT

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