Wavelengths and Regenerators Sharing in GMPLS-controlled WSONs

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Abstract—In Wavelength Switched Optical Networks (WSONs), sharing of protection wavelengths is an attractive strategy to increase survivability against failures. However, to guarantee an acceptable quality of transmission (QoT), both working and protection paths may need to undergo optical-electrical-optical (OEO) regeneration. With this aim, the placement of a limited number of regenerators is a cost-effective solution to guarantee QoT.

In this paper, the concept of sharing the protection resources is extended to regenerators. Moreover, shared regenerators can be exploited for ensuring QoT as well as for providing wavelength conversion. The main objective of this paper is the study of different strategies for the selection of regenerators and wavelengths in WSON with a GMPLS-based distributed control plane.

Simulation results show a trade-off between the strategies achieving a high wavelength sharing and those achieving a high regenerator sharing.

I. INTRODUCTION

In Wavelength Switched Optical Networks (WSON), where optical nodes, i.e., optical cross-connects (OXC), are interconnected by high capacity WDM links, a single link failure can cause the loss of a huge amount of data. To avoid such detrimental consequences, Shared Path Protection (SPP) is widely accepted as the most bandwidth-efficient scheme for protecting lightpaths against single-link failures with acceptable recovery times. When adopting SPP, each connection request is served through a working and a protection Label Switched Path (LSP). Specifically, resources (i.e., wavelengths) along protection LSPs are pre-reserved, but not cross-connected. Therefore, each wavelength can be reserved and shared by several protection LSPs that undergo single-link failure affects at most one of the corresponding working LSPs. In other words, the working LSPs must be routed on links belonging to different Shared Risk Link Groups (SRLGs) [1].

At the same time, in WSON, the quality of the transmitted optical signal is degraded by linear and non-linear physical impairments (e.g., amplified spontaneous emission noise, polarization mode dispersion and cross-phase modulation). To mitigate such adverse effects, the utilization of optical-electrical-optical (OEO) regenerators may be required at intermediate nodes to re-amplify, re-shape, and re-time the optical signal (i.e., 3R regeneration). Therefore, each established LSP can be supported by a single lightpath (i.e., an end-to-end optical path) or by a sequence of lightpaths concatenated by means of 3R regenerators at intermediate nodes. Since regenerators are expensive and energy-hungry, placement strategies and utilization policies are required to reduce the number of regenerators to be provisioned in the network while ensuring the required quality of transmission (QoT) for each established lightpath.

To further lower the installation and maintenance costs, this paper proposes to share the regenerators utilized by protection LSPs. Similarly to wavelength resources, 3R regenerators are handled as resources that can be shared among protection LSPs whose working LSPs are SRLG-disjoint. Although the concept is similar to the sharing of wavelengths and wavelength converters in a WDM network with SPP as proposed in [2], the principle is different. Indeed, 3R regenerators are required for guaranteeing QoT, independently of the wavelength continuity constraint.

Support of either SPP or QoT guarantees in the presence of a limited number of 3R regenerators has been studied in the past typically in a static case [1], [3]. The work in [4] proposed extensions for the Generalized Multi-Protocol Label Switching (GMPLS) control plane [5] for implementing SPP in a dynamic, fully distributed way. On the other hand, the problem of designing the nodes in which regeneration should take place is considered in [6] and the GMPLS extensions for regenerator reservation are proposed. However, a combined approach for managing the sharing of both wavelengths and regenerators has not been considered so far.

This paper jointly considers the sharing of wavelengths and regenerators for ensuring both QoT and 100% survivability against single-link failures, in a WSON network with a GMPLS control plane. The paper presents the procedures for properly managing the sharing of both wavelengths and regenerators in the GMPLS control plane. In particular, the GMPLS extensions proposed in [2], [4] and in [6] are jointly exploited. Moreover, the possibility of performing wavelength conversions by means of the 3R regenerators is considered. Several strategies for selecting the sharable resources are proposed. The proposed strategies are evaluated by simulations in terms of blocking probability experienced by the LSPs requests and resource overbuild.

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II. GMPLS-CONTROLLED WSONS

The data plane of the considered WSON is composed of nodes equipped with an OXC and a limited number of 3R regenerators. The OXC is used to switch wavelength-continuous lightpaths while the regenerators can be used for performing 3R regeneration as well as wavelength conversion. Network nodes are interconnected by means of WDM links.

One GMPLS controller exists for each node of the data plane. GMPLS controllers are interconnected by an IP network with the same topology as the data plane topology. Each GMPLS controller maintains a Local Database (LD) containing the information about the availability of the local resources (i.e., wavelength channels on locally connected links and regenerators). The Resource ReSerVation Protocol with Traffic Engineering (RSVP-TE) [7] is used as signaling protocol for establishing LSPs. The Open Shortest Path First with Traffic Engineering (OSPF-TE) [8] is used as routing protocol for advertising wavelength-availability information by means of Link-State Advertisements (LSAs). Each GMPLS controller stores the received LSAs in the local Traffic Engineering Database (TED).

III. DISTRIBUTED SHARED PATH PROTECTION (SPP)

In the considered distributed SPP scheme, for each LSP request, the source node computes a pair of SRLG-disjoint paths, for the working and the protection LSPs. Computation is carried out based on the information available in the TED.

In order to properly implement the distributed SPP scheme, the LD stores the following state for each wavelength channel on locally connected links and regenerators. The Resource ReSerVation Protocol with Traffic Engineering (RSVP-TE) [7] is used as signaling protocol for establishing LSPs. The Open Shortest Path First with Traffic Engineering (OSPF-TE) [8] is used as routing protocol for advertising wavelength-availability information by means of Link-State Advertisements (LSAs). Each GMPLS controller stores the received LSAs in the local Traffic Engineering Database (TED).

A. Reservation of Working LSPs

RSVP-TE is used to reserve the wavelength channels and regenerators for the working LSPs, while ensuring wavelength continuity and QoT for each lightpath. Nodes in which the LSP must undergo regeneration are selected by the destination node using the destination designation procedure [6].

Upon receiving the RSVP-TE Path message, the destination node computes the set of intermediate nodes where regeneration has to be performed based on the regenerator availability information collected by the Path message in the Regeneration Availability Object (RAO) [6] with the objective of guaranteeing an acceptable QoT for each lightpath.

After the designation of the regeneration nodes, the destination node sends back to the source node a Resv message containing the list of designated regeneration nodes using the Regenerator Object (RO) [6]. By receiving this message, each node knows whether it should actually reserve a local regenerator. In particular, if the node is designated for regeneration, an idle regenerator is reserved and set as in-service.

Finally, an idle regenerator can also be reserved when wavelength conversion is required.

B. Reservation of Protection LSPs

Likewise for the working LSP, an RSVP-TE session is triggered by the source node, to establish the protection LSP, along the previously computed SRLG-disjoint path.

During the RSVP-TE signaling, it is necessary to verify whether the resources (i.e., wavelengths and regenerators) in shared-reserved state are sharable, i.e., there is no sharing violation between SRLGs of the working LSP and SRLGs protected by the shared-reserved resource.

For the implementation of the proposed SPP, the following standard objects are required in the Path message: the Label Set, the Explicit Route Object (ERO) and the Primary Path Route Object (PPRO) [7], [10]. Moreover the RAO and following non-standard objects are required:

- Shared Wavelength Vector (S-WV) proposed in [4] 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;
- Shared Regenerator Vector (S-RV) proposed in [2] includes an element for each wavelength contained in the Label Set. Each element indicates the number of sharable regenerators that are required for establishing the LSP on the corresponding wavelengths.

An example of RSVP-TE reservation for the protection LSP and the corresponding update of the objects in the Path messages is shown in Fig. 1 assuming that regenerators can be used for QoT and wavelength conversion.

Each node stores a copy of each received Path message and updates it as follows, before forwarding it. If neither idle nor sharable regenerators are locally available or regenerators are not usable for wavelength conversion purpose, the outgoing Label Set is computed by intersecting the incoming Label Set with the set of wavelengths that are idle or sharable in the outgoing link. Otherwise, if an idle or a sharable regenerator is locally available and regenerators are usable for wavelength conversion purpose, the outgoing Label Set includes all the wavelengths that are idle or sharable in the outgoing link.

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

- Shared Wavelength Vector (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 sharable in the outgoing link, respectively. If the wavelength is contained in the received
Label Set, the corresponding S-WV entry is incremented by 0 (1) if the wavelength is idle (sharable) in the outgoing link, respectively.

- Shared Regenerator Vector (S-RV): if a wavelength conversion is locally required for a wavelength, the corresponding S-RV entry is the maximum weight in the received S-RV incremented by 1 if there is a local sharable regenerator. If wavelength conversion is not required, the corresponding S-RV entry is left unchanged.

The destination node receiving a Path message performs the wavelength selection according to one of the strategies described in Sec. IV-B.

In the backward phase, each node designated for regeneration (i.e., its node-identifier is in the RO included in the received \\textit{Resv} message) reserves an idle or sharable regenerator according to the strategy described in Sec. IV-B. The SRLGs of the working LSP are appended to the list of SRLGs protected by the regenerator, in the LD. If neither idle nor sharable regenerator is available, the reservation is blocked.

Then, the node checks if the Label Set of the stored Path message (i.e., the Path message of the same RSVP-TE instance) 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 both the regenerators can be used for wavelength conversion purpose and an idle or sharable 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 Sec. IV-B.
  - If the wavelength is not included in the stored Label Set and either regenerators cannot be used for wavelength conversion purpose or no idle nor sharable regenerator is available, the LSP is blocked.

If the LSP is not blocked, the SRLGs of the corresponding working LSP are appended to the list of SRLGs protected by the selected wavelength, in the LD.

IV. RESOURCE SELECTION STRATEGIES

For both working and protection LSPs, resource selection is performed at the destination node and at any intermediate node, in which wavelength conversion is performed. For the working LSPs, wavelengths are selected according to a first-fit (FF) strategy, while regenerators required for QoT or wavelength conversion purposes are randomly selected among the idle ones.

For protection LSPs, the following strategies are proposed for selecting the resources.

A. Protection LSP Regenerator Selection

When a regenerator is required for QoT and/or for wavelength conversion purposes, it is locally selected by the node. In particular, the required regenerator is randomly selected among all sharable regenerators. In absence of sharable regenerators, a regenerator is randomly selected among all idle regenerators.

B. Wavelength Selection

One of the wavelengths contained in the received Label Set is selected according to one of the following strategies:

- random (RA): random selection;
- first fit (FF): selects the lowest-indexed wavelength;
- last fit (LF): selects the highest-indexed wavelength;
- maximum wavelength sharing (WS): selects the wavelength with the highest S-WV weight. Ties are broken by using LF strategy;
- maximum regenerator sharing (RS): first, the S-RV is checked if any wavelength has a weight of 0 (i.e., no conversion is required using that wavelength). If present, LF is used as a tie breaking policy among null weight wavelengths. If absent, the wavelength with the highest S-RV weight (i.e., highest regenerator sharing) is selected. Ties are broken using the LF strategy.

V. PERFORMANCE EVALUATION

In this section, the performance of the proposed strategies are evaluated by means of simulations performed with the event-driven simulator OPNET [11].

The European network topology with $N = 28$ nodes and $L = 60$ bi-directional links, each carrying $W = 32$ 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 an average of $1/\lambda$ and $1/\mu$ seconds, respectively, where $1/\mu$ is fixed to 30 minutes. All results are plotted against the network load defined as $\mu/\lambda$.

The processing time of the packets is considered negligible compared to the optical propagation and transmission time. The average inter-arrival time $1/\lambda$ is higher than the set-up time, so that the probability of resource contentions in the backward direction is negligible [12].

Computation of the working and the protection LSPs are carried out by running the Suurballe [13] disjoint path computation algorithm.

The number of 3Rs per node is limited to 8. It is assumed that optical signal must undergo 3R regenerations after 3 hops for ensuring an acceptable QoT.

Wavelength selection strategies are compared in terms of:

- 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 either lack of available wavelengths or regenerators;
- wavelength overbuild (WO): the ratio between the number of wavelengths reserved for protection LSPs and the number of wavelengths reserved for working LSPs;
- regenerator overbuild (RO): the ratio between the number of regenerators reserved for protection LSPs and the number of regenerators reserved for working LSPs.

\section{A. Results and Analysis}

Two different scenarios have been considered. In the first scenario, regenerators are only used for regeneration purpose, while in the second scenario regenerators are also used for performing wavelength conversion.

1) \textit{Regenerators used for QoT only}: Fig. 2 presents the blocking probability for the different wavelength selection strategies. Due to the considered load conditions and the relatively long paths in the network, the dominating blocking is due to the lack of regenerators rather than the lack of wavelength resources. For this reason, the blocking probability is almost unaffected by the wavelength selection strategies.

Fig. 3(a) and Fig. 3(b) show the resource overbuild for wavelengths and regenerators, respectively. The WS strategy clearly achieves the best wavelength sharing. The strategy achieves between 37% and 21% improvement compared to the worst performing strategy (RA), and 10%-7% improvement compared to the second-best performing strategies (LF and RS). As for the blocking, the wavelength selection strategies have no influence on the regenerator overbuild (see Fig. 3(b)).

2) \textit{Regenerators used for QoT and wavelength conversion}: Fig. 4 illustrates the blocking probability when regenerators can be used for QoT as well as for wavelength conversion purposes. It can be seen that the blocking has increased compared to Fig. 2. This is due to the fact that regenerators are used also for wavelength conversion and thus a lower number of regenerators is available for QoT. Since the dominating blocking is due to lack of regenerators rather than lack of wavelength resources, the overall blocking is negatively affected by the utilization of regenerators as wavelength converters.

However, contrary to Fig. 2, the wavelength selection strategies have a significant impact on the blocking performance. This is due to the possibility of performing wavelength conversion.

The best performing strategies are RS and then RA as they minimize the utilization of the regenerators and thus the blocking due to lack of regenerators.

Fig. 5(a) and Fig. 5(b) show the wavelength and regenerator overbuild, respectively. When the regenerator can be exploited also as wavelength converters, the wavelength overbuild is
improved by up to 17% with respect to the scenario in which regenerator usage is only for QoT (see Fig. 3(a)).

Greater improvements are achieved in terms of regenerator overbuild. Both improvements indicate that the wavelength conversion can help to increase effectively and efficiently the sharing of the protection resources. Due to the wavelength conversion capabilities, the wavelength overbuild as well as the regenerator overbuild are both affected by the wavelength selection strategy.

Results on resource overbuild highlight a clear trade-off between the strategies that minimize the regenerator utilization (i.e., RS and RA) and the strategies that minimize the wavelength utilization (i.e., WS, LF, and FF). The former strategies achieve an excellent regenerator overbuild at the expense of the wavelength overbuild. On the other side, the latter strategies worsen the regenerator overbuild by more than 40% but improve the wavelength overbuild. Among all the strategies, in the considered scenario, RS is the most appealing, as it achieves a minimum blocking and regenerator overbuild, while the wavelength overbuild is mildly affected.

VI. CONCLUSION

Cost-effectiveness and energy-efficiency of survivable WSON can be ameliorated by sharing the regenerators supporting protection LSPs, in addition to sharing the wavelengths. The paper proposed an implementation that guarantees 100% survivability against single-link failures and QoT, for a distributed GMPLS control plane supporting shared path protection scheme. Different wavelength selection strategies were tested in a network with a limited number of regenerators.

When the regenerators are used only for ensuring QoT, strategies affect the wavelength overbuild but not the regenerator overbuild and the blocking. However, regenerators can be exploited also as wavelength converters and this can help to improve the resource sharing. In such case, the strategies impact the resource overbuild as well as the blocking and there is strong interdependence between selection of regenerators and wavelengths. Indeed, minimizing the regenerator utilization may lead to higher wavelength overbuild, while minimizing the wavelength utilization may lead to a higher regenerator overbuild.

Future works may need to address a more coordinated approach in order to intelligently use the scarce regenerators and optimally select the wavelengths to share.

REFERENCES