Optimized Burst LSP Design for Absolute QoS Guarantees in GMPLS-Controlled OBS Networks

Pedro Pedroso, Jordi Perelló, Davide Careglio, Miroslaw Klinkowski, and Salvatore Spadaro

***Abstract*—Over the past decade, the scientific community has thrown itself into assessing optical burst switching (OBS) as the switching technology for next-generation all-optical networks. In this regard, a significant amount of work has concentrated on providing OBS with the required carrier-class features. During this process, however, little attention has been paid to fundamental questions on the interoperability and interworking issues that OBS will have to face in a heterogeneous network scenario such as the future Internet. This article introduces a generalized multi-protocol label switching (GMPLS)-based control plane architecture for future OBS networks. This GMPLS/OBS control plane solution leverages on the GMPLS interoperability to enable seamless vertical and horizontal OBS integration with different switching layers under a common control plane. The burst label switched path (b-LSP) entity has been introduced to accomplish this purpose, as well as to guarantee end-users' quality of service (QoS) requirements to effectively support emerging data applications. The establishment of a b-LSP does not entail explicit resource reservation, but the addition of new entries in the OBS node forwarding tables with the resources available for that b-LSP. Hence, by making a resource available to multiple b-LSPs, the statistical multiplexing nature of OBS is preserved. A mixed integer linear programing formulation has been presented to get the most out of the available resources given the expected traffic demands and their QoS requirements. Moreover, in the network operation phase, GMPLS-driven b-LSP capacity reconfigurations are dynamically triggered whenever unfavorable network conditions are detected. An exhaustive simulation campaign assesses the performance of the proposed GMPLS/OBS network architecture on different network scenarios. Finally, future research lines on the topic are outlined.**

***Index Terms*—GMPLS; Interoperability; OBS; QoS.**

I. Introduction

The evolution toward the future Internet has moved research efforts into the realization of multi-service optical networks performing wavelength and sub-wavelength switching, so as to seamlessly and efficiently support large amounts of data from different applications presenting diverse characteristics [1].

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In this context, optical burst switching (OBS) leverages on the statistical multiplexing of data plane resources to enable sub-wavelength switching in optical networks [2]. This is attained by aggregating packets arriving at ingress nodes and sending them as bursts over a bufferless optical network to the destination. High bandwidth utilization is achieved in OBS by means of one-way resource reservation schemes, which minimize the overhead introduced during the burst signaling process. However, these schemes do not ensure a successful burst delivery, as bursts can contend amongst themselves (due to the sharing of wavelength channels) and be lost.

Looking at the literature, a plethora of techniques have been proposed to upgrade OBS networks with carrier-class features. The main targets of these contributions have been: i) performance, by proposing enhanced route selection [3], burst scheduling [4,5], contention resolution [6] and contention avoidance techniques [7,8]; ii) reliability, by presenting protection and restoration schemes to increase OBS network resilience [9,10]; and iii) quality of service (QoS) differentiation to support the wide range of currently available Internet applications, each one with different QoS requirements. Specifically, QoS techniques for OBS networks have been divided into two main groups, depending on whether relative or absolute QoS guarantees are offered to the supported traffic classes (see [11] for a detailed survey on QoS support in OBS). Nevertheless, all the aforementioned techniques are devised to be implemented at the OBS layer. This may burden OBS core nodes with complex decisions that should typically be made on a per-burst basis, compromising the fast OBS network performance.

Aiming to move network intelligence to upper levels, the Internet Engineering Task Force (IETF) standardized generalized multi-protocol label switching (GMPLS) as the key enabler of a fast, flexible and unified service provisioning over multiple switching layers [12]. It consists of a set of signaling, routing and management protocols easing the unified control of a diverse range of switching technologies available nowadays, namely, MPLS, Ethernet, Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH), and wavelength and fiber switching, but not OBS so far. Therefore, GMPLS is a powerful control tool, responsible for the setup, maintenance and teardown of end-to-end label switched paths (LSPs) fitted to end-users' QoS requirements. Furthermore, control-plane-driven protection and restoration functionalities are also supported.

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In the light of this, GMPLS has been positioned as the *de facto* control plane for automatically switched optical networks (ASONs) [13], as well as for carrier-class Ethernet networks like the GMPLS Ethernet label switching (GELS) framework [14]. Following the same trend, this article concentrates on the integration of GMPLS as the control plane technology for OBS networks. Indeed, by properly extending the GMPLS framework to support the particularities of the OBS network, important benefits can be obtained from a GMPLS/OBS integration, as will be shown in the following sections.

The remainder of this article continues as follows. Section II states the motivations toward a GMPLS-controlled OBS network, presenting potential target network scenarios and expected benefits. This is completed by reviewing existing works on the topic. Section III presents the proposed GMPLS/OBS network architecture. Section IV introduces the proposed control model allowing absolute QoS guarantees to high-priority demands, together with a constrained routing to low-priority burst label switched paths (b-LSPs) and the required extensions to the GMPLS signaling protocol to operate properly in the proposed environment. Section V presents the mixed integer linear programing (MILP) formulation for the dimensioning of b-LSPs for the considered GMPLS/OBS scenario. This formulation was initially proposed in [15] and further generalized for any OBS scenario in [16]. Then, Section VI proposes a b-LSP performance monitoring mechanism, which enables a b-LSP capacity reconfiguration whenever unexpected traffic peaks degrading the offered QoS figures are detected. Section VII evaluates the performance of the proposed GMPLS/OBS architecture through extensive simulation results on different network scenarios. Finally, Section VIII concludes the paper and outlines future research work.

II. Motivations Toward a GMPLS-Controlled OBS Network

It is widely recognized that future metropolitan area networks (MANs) will rely on any type of sub-wavelength switching technology [17,18] in order to provide better access to network resources (increasing available capacity), as well as to increase flexibility to support the dynamics of end-users' data traffic. A strong candidate to this end is OBS technology, which is itself a good trade-off between complexity (i.e., cost) and performance. In this way, MAN networks around the world will be interconnected over regional and core networks that, most likely, will implement coarser dynamic wavelength switching technologies, which are very efficient when serving smooth permanent or semi-permanent aggregated traffic demands.

Fast and seamless end-to-end service provisioning will also be a key challenge for network operators in order to effectively use their network infrastructures. While large efforts have already been devoted to standardizing GMPLS as a framework for the unified control of heterogeneous switching capabilities [19,20], such as dynamic wavelength switching supported by the wavelength switched optical networks (WSONs) standard [21], emerging sub-wavelength switching technologies like OBS are still uncovered by the GMPLS umbrella and lack a well-defined control plane architecture. For instance, this will impose severe interoperability limitations when non-GMPLS-capable sub-wavelength switching MANs are confronted with GMPLS-enabled wavelength switching backbones.

Apart from network interoperability, an additional benefit that can be expected from such a GMPLS-controlled OBS network is QoS support. As pointed out before, a significant amount of work has been devoted to upgrading the OBS layer with QoS features. However, the vast majority of the work has been centered on relative QoS differentiation between traffic classes. In addition, those few works targeting absolute QoS guarantees result in very complex mechanisms, hard to adopt at OBS switches. In contrast, GMPLS is committed by design to providing QoS guarantees to the supported traffic, which is achieved through the establishment of end-to-end traffic engineering (TE) LSPs. Therefore, by extending GMPLS to also encompass OBS networks, the setup of end-to-end LSPs matching specific QoS figures can be envisaged. Delegating the QoS provisioning, as well as other control features such as protection and path computation, to the GMPLS control plane will keep the OBS layer simpler. Note that GMPLS is an intelligent control layer *per se*, provided with proper control mechanisms as mentioned before. In such a way, most of its features can be easily applied to OBS control without incurring an increase of complexity in GMPLS. In fact, very few extensions are required to the GMPLS standard to support OBS.

Although a GMPLS-controlled OBS network scenario is commonly assumed in several works found in the literature, almost none of them focus on the GMPLS–OBS interoperability design. In particular, we build our work on the idea initially proposed in [22] and later extended in [23,24]. The so-called labeled OBS (LOBS) architecture is presented to integrate OBS and MPLS, which relies on a virtual topology (VT) of pre-computed LSPs. However, the proposal in [22] lacks details about the characterization of the LOBS paths and how to provide QoS guarantees to reduce burst losses in OBS networks. Moreover, the LOBS model can be seen as a packet-oriented MPLS-like control plane, failing at the purpose of broader unified control in heterogeneous multi-domain scenarios as pursued by GMPLS. Although the LOBS idea was extended in [23,24], specifying a more detailed architecture, those works did not come up with specific extensions to the GMPLS standards to support a real GMPLS–OBS integration and also did not answer the open questions left by Qiao in [22]. Furthermore, network performance studies are still missing to show both the feasibility and the reliability of the LOBS approach.

In light of the above, the following section elaborates on a well-defined GMPLS/OBS network architecture enabling the interoperability and absolute QoS goals. This will be achieved through vertical integration of the GMPLS and OBS control planes, so that the GMPLS control plane entity can be interfaced directly to external control plane entities (e.g., WSONs), while improving the OBS network performance through the management of end-to-end burst LSPs.

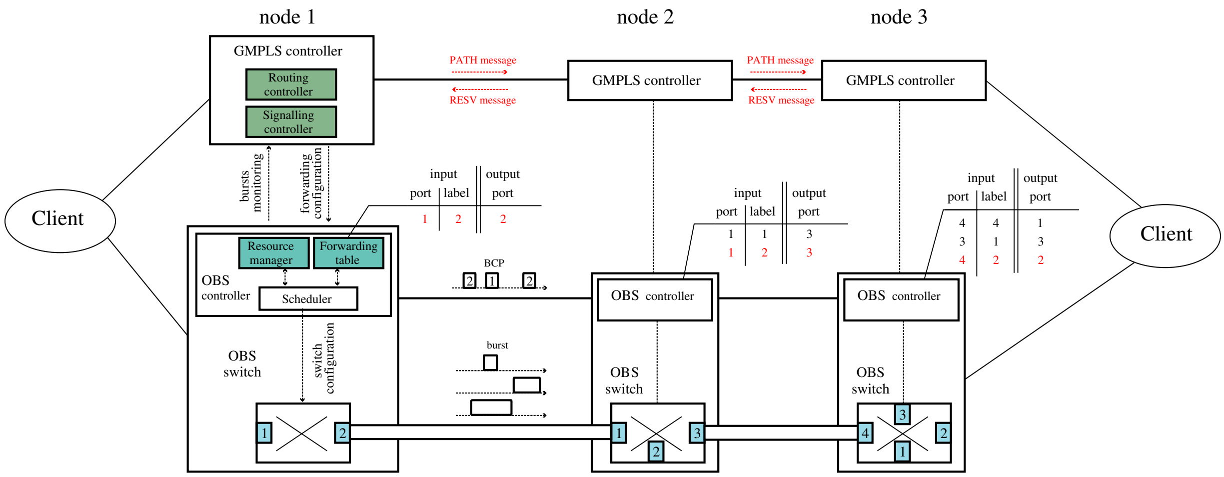

Fig. 1. (Color online) Example of a b-LSP establishment in the GMPLS/OBS network architecture.

III. GMPLS/OBS Network Architecture

In the proposed GMPLS/OBS network architecture, the extended GMPLS control plane lies on top of the actual OBS control plane (see Fig. 1). This results in an interoperable control plane composed of two control layers, namely, GMPLS and OBS. However, the transparent and bufferless all-optical OBS data plane will be controlled in a unique manner by this GMPLS/OBS control plane.

The GMPLS may be deployed out-of-band, in/out-of-fiber, and supported by any technology and topology. On the contrary, in OBS networks, bursts and their related burst control packets (BCPs) must keep a strict time relationship in order to make one-way reservation feasible. Hence, it is mandatory that OBS control and transport planes share the same resources and topology. This is the reason why an in-fiber out-of-band control plane configuration (i.e., signaling channels) has been considered at the OBS layer—either manually or automatically configured.

An effective and efficient control framework is then achieved based on the sharing of control tasks among these two control layers, according to their time scale demands. Those simple and local control operations (time scale varying of the order of microseconds/milliseconds) such as reading the forwarding table (FT) and selecting the outgoing wavelength from a given set for data burst transmission and local burst contention resolution (within such a set) are kept at the switching layer (OBS). On the other hand, all complex operations (time scale varying of the order of minutes, hours, days or even longer) involving global knowledge of the network status are assigned (i.e., GMPLS provides them) to the GMPLS control layer, such as TE and path computation, routing notifications, congestion resolution, QoS support or protection/restoration actions. Among them, in this article we focus on the capability of the proposed GMPLS/OBS network to provide absolute QoS for quality-demanding traffic. The details of such a solution are described in the following section.

Therefore, the GMPLS controller functions include the setup, maintenance, reconfiguration and release of end-to-end burst LSPs (hereafter simply referred to as b-LSPs) according to the client traffic demands and QoS requirements. The controller is also responsible for routing notification and congestion resolution whenever unfavorable network conditions are detected (see the mechanism proposed in Section VI).

In GMPLS/OBS, a b-LSP is merely a connection representation at the control plane only and does not entail any reservation of data plane resources (e.g., wavelengths in the OBS layer). In fact, a b-LSP, which is established by the GMPLS signaling protocol, determines both the end-to-end path that must be followed by all bursts belonging to it at the OBS level and the set of accessible wavelengths in the links of the path. Thus, unlike the approaches in [22,23], a b-LSP may consist of one or multiple wavelengths in each link along the path. This leads to a change in the label meaning. Henceforth, the b-LSP label identifies the LSP as a whole and remains unaltered end-to-end, so that no label swapping is performed. It is determined by the destination node and carried in the GENERALIZED_LABEL object of the GMPLS signaling RESV message, in the upstream direction (i.e., back to the source node).

In order to make this concept clear, Fig. 1 shows an example of b-LSP establishment. For instance, a new connection is required between two clients attached to nodes 1 and 3, respectively. Node 1 computes the path[1] to reach the destination, according to traffic and QoS demands, and starts the b-LSP signaling procedure as follows:

- A PATH message (an example of its extended format is presented in Section IV.C) follows the computed route and verifies its feasibility.
- A RESV message is sent back in the upstream direction by the destination node. Upon the reception of the RESV message, each node along the b-LSP route either i) confirms the previously configured forwarding entry and triggers the update of the FT at each OBS controller if the b-LSP is feasible, or ii) eliminates this temporary forwarding entry otherwise. In the former case, the FT stores an input/output port match associated with the b-LSP (input_port, label =>

[1] In principle any path computation can be adopted ranging from simple shortest path to complex optimization algorithms. In Section V we provide an example of optimal path computation for absolute QoS support.

output port, set of wavelengths) that is afterward looked up for data plane burst forwarding.

Once the signaling procedure ends (i.e., resources are virtually assigned to a b-LSP), the optical bursts can be sent to the destination node along the established b-LSP. Note that only a single GMPLS signaling session is required to transmit all bursts belonging to a b-LSP, i.e., it is a per-demand and not a per-burst basis.

In turn, the OBS controller is the one that commits data plane resources for the incoming bursts. As in conventional OBS, once a burst is assembled and ready at the edge node, the corresponding BCP is first dispatched. However, the main difference here lies in the fact that the BCP and burst are restricted to follow the b-LSP. At each node along the path, the OBS controller processes the BCP, which contains the label identifying the b-LSP (the only routing information that it carries), and looks up the FT to determine the output port. A scheduling is then executed to reserve the required output resources, switching the burst accordingly. These committed resources are then released once the burst is completely transmitted. In this way, the statistical multiplexing benefit of OBS is preserved. To enable this operation, the OBS controller consists of only one processor (i.e., CPU) to coordinate the BCP processing (e.g., label reading) and the interaction either with the FT, which gives the set of wavelengths that could be reserved, or with the scheduling algorithm, which returns the proper outgoing wavelength among the wavelength set retrieved from the FT. Note that the optical bursts are simply forwarded according to the FT information.

IV. GMPLS/OBS Control Model

A. Enabling Absolute QoS

Absolute QoS differentiation is committed to delivering quantitative QoS levels for high-priority (HP) traffic classes, even in highly loaded network scenarios. Compared to relative QoS differentiation such as offset time-based differentiation (OTD) [25] or preemption [26], absolute QoS guarantees are more attractive for upper layer applications, as transport services can be tailored to the specific performance requirements. As shown in [27], the end-to-end burst loss probability (BLP) can be effectively controlled by tightly dimensioning the number of wavelengths that support the HP traffic. In this article, we extend this idea taking advantage of the proposed GMPLS/OBS network architecture. To this end, we define the following:

- The virtual topology (VT) as a set of explicit b-LSPs established between source–destination node pairs to route HP bursts through the network. A (limited) number of VTs is maintained on top of the physical OBS transport network and each VT is dedicated to guaranteeing a given QoS (i.e., a given b-BLP level).
- The set of allocated wavelengths in the links belonging to the VT, appropriately chosen so as to satisfy absolute QoS requirements. The wavelengths allocated to a VT are accessible to any burst carried within the VT, independently of its origin and destination.

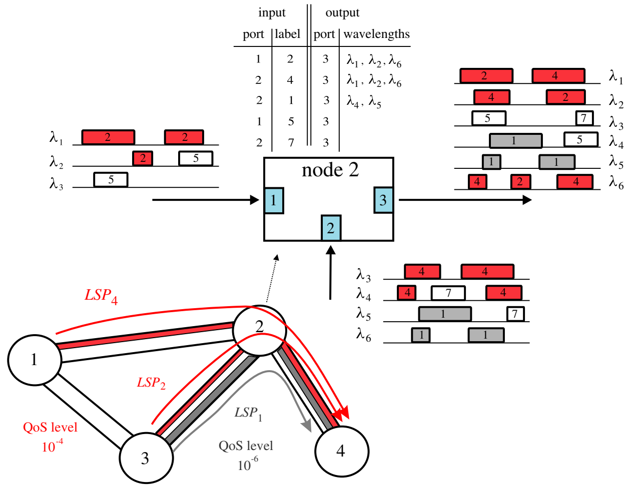

Fig. 2. (Color online) GMPLS/OBS virtual topology and the effect on the burst forwarding.

This means that when transmitting a burst belonging to a particular b-LSP (and thus to a VT), the controller can reserve a wavelength only from the set of allocated wavelengths. Such a set of allocated wavelengths is properly dimensioned beforehand, signaled during the establishment of the b-LSP, and stored in the FT of the OBS controller together with the label that identifies the b-LSP. Note that wavelength sharing within a set of allocated wavelengths—which fosters the statistical multiplexing of network resources—is limited to only those b-LSPs belonging to the same VT and thus with the same QoS level. Otherwise, OBS nodes would have to be provided with complex scheduling algorithms to enable QoS level differentiation over the same set of output wavelengths (as, e.g., in the case of [28]).

In this study, we assume that an estimation of the expected traffic matrix is given beforehand and thus offline dimensioning can be performed by an MILP formulation (described in Section V). This model intelligently defines the b-LSPs' routes and capacities, optimizing the network resource usage. This allows the proposed control architecture and model to accomplish the demanded QoS requirements in much higher loaded scenarios than the absolute QoS policy suggested in [27], as shown in Section VII. In addition, we deploy a GMPLS-driven mechanism to reconfigure the b-LSPs whenever unexpected changes in the volume of offered traffic occur. This not only guarantees QoS levels statistically but at any time during the entire lifetime of a b-LSP. This mechanism is detailed in Section VI.

An example of a GMPLS/OBS network is illustrated in Fig. 2, depicting two VTs appropriately configured to deliver burst losses (i.e., QoS levels) bounded to 10^{-4} and 10^{-6}, respectively. In this example, three HP b-LSPs and two BE b-LSPs crossing node 2 are currently established in the network, so five entries are hence configured in the forwarding table. Only HP b-LSPs are explicitly depicted in Fig. 2. All b-LSPs in the FT are identified by the input port and label.

While the allocated wavelengths and the output port are present in the HP b-LSPs entries, only the output port is required by those b-LSPs transporting BE traffic. Indeed, BE bursts can use any of the available wavelengths at the indicated output port. However, in order to ensure the HP objective QoS, they can be preempted (and thus dropped) by any HP burst that requires that particular wavelength allocated in its forwarding table.

Although all established b-LSPs use the same output port 3, only those HP b-LSPs with the same QoS share output wavelengths. In the example, bursts belonging to LSP_1 (with QoS at 10^{-6}) can leave node 2 only using either λ_4 or λ_5, while those belonging to LSP_4 and LSP_2 (both with QoS at 10^{-4}) can share λ_1, λ_2 and λ_6. At the top of the figure, an example of some burst arrivals at ports 1 and 2 is also depicted: gray bursts for LSP_1, red bursts for LSP_2 and LSP_4, and white bursts for BE traffic labeled LSP_5 and LSP_7. For bursts sharing the same group of output wavelengths, the OBS scheduler has to find and reserve the proper resources *on-the-fly*. Although some bursts can still be lost with this approach, the number of wavelengths assigned by GMPLS to every HP b-LSP ensures the required QoS levels.

For the sake of simplicity, only two service classes are considered in this work, namely, an HP with guaranteed QoS level and a BE-class. Therefore, only a single VT of b-LSPs for the HP-class has to be dimensioned in the network, restricting the BE-class to using the spare network capacity. Note, however, that the model in Section V can be easily employed to dimension multiple VTs.

B. Constrained Routing for BE b-LSPs

The establishment of the VT for HP traffic may increase the burst loss figures experienced by the BE traffic. In view of this, the GMPLS controller implements a constrained shortest path (CSP) source routing algorithm to determine the most appropriate routes for the BE b-LSPs. In fact, the BE routing can be highly improved by being HP-class b-LSP aware. Thereby, by knowing the wavelengths committed at each link for the HP b-LSP routes, a constrained SP heuristic is devised. Specifically, in addition to the common hop-count metric, we also take into account the number of committed HP-class wavelengths in the bottleneck link of the computed spatial route, $\lambda_{committed}$. k SP routes are computed and the least cost path between the source–destination pair is selected. The cost function is defined as follows:

$$c = \frac{H}{D} + \frac{\lambda_{committed}}{\lambda_{total}}, \quad (1)$$

where H is the hop-count value for the computed k-shortest path route, D is the highest hop-count shortest path in the network and λ_{total} is the maximum wavelengths per link. To prevent the overloading of BE routes over the same links, the route is selected only if the cost gain compared to the shortest hop-count path is above a given threshold (e.g., 20%).

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 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|L|    Type     |    Length     |    Reserved (Must be zero)    |
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|                           Router ID                           |
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|                    Interface ID N (32 bits)                   |
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Fig. 3. RSVP-TE extensions.

C. GMPLS Signaling Extensions

The GMPLS framework needs to be extended to support the particularity of the OBS network. First, the GMPLS LSP hierarchy must be extended to incorporate a burst switching region. For instance, the GENERALIZED_LABEL_REQUEST object of the GMPLS signaling PATH message requires a proper definition of the switching type and the LSP encoding type fields. Second, the GMPLS RSVP-TE signaling protocol requires additional features to manage the b-LSPs. Finally, the computation of the b-LSPs requires knowledge of the global network status and therefore extensions to the OSPF-TE GMPLS routing protocol are also required to appropriately disseminate OBS transport layer resource usage.

In this article, we only introduce minor extensions required for the GMPLS RSVP-TE signaling protocol to manage the b-LSPs, albeit those extensions are not only OBS-specific and may be easily adapted to any sub-wavelength switching technology. The rest of the GMPLS protocol extensions, for instance, those involving the GMPLS OSPF-TE routing functionality, are left for future work, as will be detailed in Section VIII. In fact, in this article we do not consider the possibility of having new connection requests nor node or link failure, so no major changes are experienced in the global network status.

In standard RSVP-TE [29], explicit routing is achieved by means of an EXPLICIT_ROUTE object in PATH messages. This object encapsulates a list of sub-objects determining the nodes and links along the explicit route. In the case of unnumbered links [30], Unnumbered interface ID sub-objects contain, for each traversed node, the router IP address (Router ID) and the identifier of the interface associated with the desired output link. As mentioned before, however, a b-LSP may bundle several wavelengths per hop. In this case, the Router ID field is followed by the IDs of the interfaces associated with each wavelength to be assigned to the b-LSP on the downstream link. Figure 3 presents the extensions to the Unnumbered interface ID sub-object for b-LSP signaling.

As explained before, b-LSPs are only set up at the control plane level without actually committing resources in the data plane (i.e., cross-connection is not performed at this phase). Such an operation is already contemplated in the RSVP-TE framework for GMPLS multi-layer/multi-region networks, as detailed in [20].

V. MILP Dimensioning of b-LSPs

In order to guarantee a certain level of QoS in terms of burst losses, wavelength resources have to be dimensioned properly. In this section, we address the problem of the VT design that concerns the establishment of explicit b-LSPs (also referred to as paths in this section) and the allocation of wavelengths in network links to support connections with QoS guarantees. More specifically, we are looking for a network routing that for a given set of (long-term) traffic demands and end-to-end requirements on the burst loss rate minimizes the overall number of allocated wavelengths (i.e., the wavelength usage) in the network. To treat the problem of absolute QoS guarantees analytically, we employ the non-reduced load approximation [31] of a common OBS network loss model [32]. The modeling assumptions are then represented as a set of constraints in an MILP formulation.

The main modeling steps are summarized in this article. For more details as well as some heuristics for the VT design problem we refer to [15] and [16].

A. Notation

We use $\mathscr{G} = (\mathscr{V}, \mathscr{E})$ to denote the graph of an OBS network; the set of nodes is denoted as $\mathscr{V}$, and the set of unidirectional links is denoted as $\mathscr{E}$. Link $e \in \mathscr{E}$ comprises W_e wavelengths.

Let $\mathscr{P}$ denote the set of predefined candidate LSPs between source s and termination t nodes, $s,t \in \mathscr{V}$, and $s \neq t$. Each path $p \in \mathscr{P}$ is identified with a subset $p \subseteq \mathscr{E}$. Adequately, subset $\mathscr{P}_e \subseteq \mathscr{P}$ identifies all paths that go through link e. Let $\delta = \max\{\delta_p : p \in \mathscr{P}\}$ be the length of the longest path in the network, where δ_p is the length (in hops) of path p.

Let $\mathscr{D}$ denote the set of demands with QoS guarantees, where each demand corresponds to a pair of source–termination nodes. For each demand $d \in \mathscr{D}$, $h_d \in \mathbb{R}_+$ denotes the volume of traffic; for convenience, $h_p = h_d$ for $p \in \mathscr{P}_d$.

Let $\mathscr{P}_d \subseteq \mathscr{P}$ denote the set of candidate LSPs supporting demand d; $\mathscr{P} = \bigcup_{d \in D} \mathscr{P}_d$. Each subset $\mathscr{P}_d$ comprises a (small) number of paths, e.g., k shortest paths, and a burst can follow one of them.

B. Modeling Assumptions

1) Routing: The network applies source-based routing. The selection of path p from set $\mathscr{P}_d$ is performed according to a decision variable x_p (also referred to as the routing variable). We assume unsplittable routing; in particular, a burst flow is routed over path p iff $x_p = 1$ and there is only one path $p \in \mathscr{P}_d$ such that $x_p = 1$. Accordingly, traffic ρ_p offered to path $p \in \mathscr{P}_d$ is calculated as $\rho_p = x_p h_d$.

2) Burst Losses: Due to the complexity of the Erlang fixed-point computation in the common OBS network loss model [32], we assume a simplified model based on the non-reduced load calculation [31]. In this model, to estimate traffic load ρ_e offered to link e, we add up the traffic load ρ_p offered to each path $p \in \mathscr{P}$ that crosses this link: $\rho_e = \sum_{p \in \mathscr{P}: p \ni e} \rho_p = \sum_{p \in \mathscr{P}: p \ni e} x_p h_p, e \in \mathscr{E}$. The use of such an approximation is justified by its accuracy, particularly under low overall burst losses (below 10^{-2}) [31]. Moreover, we take the common assumption in the literature of i.e.d. burst arrivals, i.i.d. burst durations, together with the assumption of the full wavelength conversion capability in network nodes. Accordingly, the Erlang-B loss formula $\mathscr{B}(\rho, w)$ is used to model the probability B_e that a burst is lost in link e.

3) Burst Loss Guarantees: We assume that each demand belonging to a QoS-class has the same end-to-end (e2e) BLP B^{e2e} requirements. To meet the goal of the e2e QoS for each demand $d \in \mathscr{D}$, we assume that at each link the burst losses are kept below a certain level B^{link}, i.e., $B_e \leq B^{link}, \forall e \in \mathscr{E}$. For the rest of the article, we consider B^{link} fixed, the same for each link, and determined according to $B^{link} = 1 - \left(1 - B^{e2e}\right)^{1/\delta}$. This model is a common model frequently used to assure QoS guarantees in loss networks and it is also applicable under unsplittable source routing in OBS [15].

4) Wavelength Allocation: The last modeling step is to define a dimensioning function $F_e(\cdot)$ which for given traffic load ρ_e determines the minimum number of wavelengths to be allocated in link e so as to satisfy the blocking B^{link} requirements. Such a function is given by a discrete (discontinuous, step-increasing) link dimensioning function $F_e(\rho_e) = \left\lceil \mathscr{B}^{-1}(\rho_e, B^{link}) \right\rceil$, where $\mathscr{B}^{-1}(\rho_e, B^{link})$ is the inverse of the Erlang-B loss formula extended to the real domain [33], and $\lceil \cdot \rceil$ is the ceiling function. Note that we consider that each QoS-class has a number of wavelengths allocated in network links which are not shared with other QoS classes. Although in this article we focus on a single QoS-class, still the restricted approach allows the model to be easily extended to the scenario with multiple QoS classes.

C. Problem Formulation

It is convenient to define a_w as the maximal load supported by w wavelengths given target blocking probability B^{link}, i.e., $a_w = \mathscr{B}^{-1}(w, B^{link})$. Although there is no close formula to calculate $\mathscr{B}^{-1}$, still we can use a line search method (see, e.g., [34]) to find the root ρ^* of function $f(\rho) = B^{link} - \mathscr{B}(\rho, w)$ so as to approximate the value of a_w by $a_w = \rho^*$ for each $w \leq \max\{W_e : e \in \mathscr{E}\}$. Also, we introduce a segmentation on load segments: $b_w = a_w - a_{w-1}, w = 1 \ldots \max\{W_e : e \in \mathscr{E}\}$.

Our VT design problem can be formulated as an MILP problem:

$$\text{minimize} \quad \sum_e \sum_w u_e^w \tag{MILP}$$

subject to

$$\sum_{p \in \mathscr{P}_d} x_p = 1, \quad \forall d \in \mathscr{D}, \tag{2a}$$

$$\sum_{p \in \mathscr{P}: p \ni e} h_p x_p - \rho_e = 0, \quad \forall e \in \mathscr{E}, \tag{2b}$$

$$\rho_e \leq a_{W_e}, \quad \forall e \in \mathscr{E}, \tag{2c}$$

$$\sum_{w=1\ldots W_e} u_e^w b_w - \rho_e \geq 0, \quad \forall e \in \mathscr{E}, \tag{2d}$$

$$u_e^w - u_e^{w+1} \geq 0, \quad \forall e \in \mathscr{E}, w = 1\ldots W_e - 1, \tag{2e}$$

$$u_e^w \in \{0,1\}, \quad \forall e \in \mathscr{E}, w = 1\ldots W_e, \tag{2f}$$

$$\bar{x} \in \{0,1\}^{|\mathscr{P}|}, \qquad \bar{\rho} \in \mathbb{R}_+^{|\mathscr{E}|}, \tag{2g}$$

where ρ_e is an auxiliary variable representing the load in link e. Note that we have substituted the link dimensioning function $F_e(\cdot)$ by its piecewise linear approximation, $F_e(\rho_e) = \min\{w : a_w \geq \rho_e\}$, which further allows us to express the dimensioning function by means of a 0–1 integer programming (IP) formulation [31]. This formulation makes use of a set of binary variables $\{u_e^w : e \in \mathscr{E}, w = 1\ldots W_e\}$; u_e^w is active iff w or more wavelengths are allocated in link e.

The objective of the optimization problem is to minimize the total number of wavelengths utilized in the network. Constraints (2a) are the routing constraints. Constraints (2b) are auxiliary constraints of the non-reduced load calculation. Constraints (2c) are the link capacity constraints. Constraints (2d) and (2e) result from the 0–1 representation of function $F_e(\cdot)$. In particular, the number of wavelengths in link e should be such that the maximum traffic load it can support (calculated as the sum of active load segments b_w) is greater than or equal to the offered traffic load ρ_e. Besides, constraints (2e) are ordering constraints, i.e., if w wavelengths are utilized then $w-1$ wavelengths are utilized as well. Finally, constraints (2f) and (2g) are the variable range constraints.

Note that (MILP) is a variant of the well-known discrete cost multicommodity flow problem (DCMCF), which is a difficult problem [35]. Still, the experiments performed show that a good sub-optimal solution (optimality gap below 2%) can be found in reasonable time (from several to some hundreds of seconds) for a 28-node network using the CPLEX v.11.1 solver [15].

VI. GMPLS-Driven b-LSP Reconfiguration

In highly dynamic networks, such as OBS networks, the volume of offered traffic may change abruptly and unexpectedly. In these scenarios, the previous offline b-LSP dimensioning would be inefficient only by itself. Therefore, we deploy an auxiliary mechanism to induce a dynamic character on the transport network and guarantee QoS levels not only statistically but at any time during the entire lifetime of a b-LSP.

The devised mechanism is triggered and operated from the GMPLS control plane. It acts in a proactive manner to avoid the b-LSPs reaching full capacity, which would increase the number of dropped bursts, or an inefficient use of wavelengths. The decision to increase/decrease the number of wavelengths associated with a b-LSP can be taken either locally or on an end-to-end basis, spanning *n-hops*. Here, only locally based decisions spanning one single hop are considered, leaving end-to-end alternatives for further work. The dynamic reconfiguration of the b-LSP capacity works as follows.

Each OBS node $n \in \mathscr{V}$ is responsible for monitoring the HP traffic being offered by all HP b-LSPs supported on any of its output links i, $i = \{1, \ldots \deg(n)\}$, over a sliding temporal window of duration T. Note that by considering only one high-priority class, the b-LSPs share the same set of wavelengths at each output link, facing the same wavelength occupancy. Therefore, the offered high-priority traffic load to an output link i in the node can be expressed as

$$\rho_{(i)} = \frac{\sum_{b \in B} t_b}{T}, \tag{3}$$

where t_b is the duration of the incoming burst $b \in B$, and B denotes all the incoming HP bursts to be switched at node n within T.

At every monitoring interval, the OBS controller sends a *trap* message to its respective GMPLS controller reporting the current HP traffic being offered to its output links. Upon reception, the GMPLS controller is then responsible for detecting sudden traffic changes and triggering b-LSP reconfiguration if required. Given $\rho_{(i)}$, it verifies whether the b-LSPs' size at link i, L_i (i.e., the number of wavelengths), is still appropriate. To this end, it estimates the current HP traffic BLP—for this purpose we apply the Erlang-B loss formula ($\mathscr{B}$)—and checks whether the value remains below the demanded QoS threshold Ω. For this, the following assessment condition is verified:

$$e\mathrm{BLP}_{\mathrm{HP}} = \mathscr{B}(\rho_{(i)}, L_i) < \Omega \quad \forall_i. \tag{4}$$

This mechanism does not trigger the reconfiguration request before W consecutive windows with $e\mathrm{BLP}_{\mathrm{HP}} \geq \Omega$ (per each output link i). Such a decision helps to maintain the stability of the system by remaining insensitive to short-term traffic changes. If W is reached, however, the traffic peak is considered as significant and a 1-hop b-LSP expansion is triggered. To this end, GMPLS computes the new set of wavelengths for the b-LSPs on output link i to properly face the measured HP traffic load. This set of additional wavelengths is given by $\phi(i) = \mathscr{B}^{-1}(\rho_{(i)}, \Omega) - L_i$, where $\mathscr{B}^{-1}(\rho_{(i)}, \Omega)$ returns the number of wavelengths needed to satisfy Ω for the new estimated traffic.

On the other hand, GMPLS can verify that the capacity of the b-LSP is over-dimensioned (i.e., $\phi(i) < 0$). In such a case, a given number of wavelengths may be released.

From the GMPLS control plane perspective, the rearrangement of those wavelengths assigned to the downstream link of a given b-LSP is quite straightforward. In particular, the RSVP-TE module in the GMPLS controller records the information of all configured b-LSPs in the node following the path state block (PSB) structure defined in [36,37]. For each b-LSP, the information contained in the PSB describes a similar structure to the PATH message that originally signaled it, namely, a Session, a Sender Template and an ERO object. As previously detailed in Fig. 3, the Unnumbered interface ID sub-objects in the PATH message ERO has been here extended so that multiple wavelengths can be allocated at every b-LSP hop. Therefore, the allocation of additional wavelengths to a certain b-LSP is as easy as including in the specific Unnumbered interface ID sub-object those interface IDs associated with the wavelengths. Conversely, if some wavelengths already associated with the b-LSP would have to be released, the associated interface IDs would be removed from the specific Unnumbered interface ID sub-object. In this way, assuming that the b-LSP would have to be released, that information in the PSB would be used to deallocate the resources supporting it.

VII. Numerical Evaluation

In this section, we run a set of simulations in order to estimate the performance of the proposed QoS-aware GMPLS/OBS control architecture and model under different network scenarios and conditions. The objective is to demonstrate the effectiveness of the b-LSP dimensioning model in the provisioning of absolute QoS for HP traffic demands, as agreed with potential OBS network clients through service level agreements (SLAs). In addition, a dynamic, GMPLS-driven mechanism reacting to unexpected traffic variations is also shown. The simulations are executed on the *ad hoc*, event-driven JAVOBS simulator reported in [38], here extended to implement the proposed architecture and model.

A. Simulation Scenario

Each GMPLS/OBS node entity is composed of two dedicated controllers, one for OBS and another for GMPLS, which may be physically co-located or not (in this study, we assume they are). However, a generic out-of-fiber GMPLS configuration is assumed. The GMPLS controller is responsible for generating, transmitting and processing GMPLS-related messages (e.g., RSVP-TE, OSPF-TE, LMP), in order to manage the b-LSPs carrying the HP traffic at the OBS layer. In turn, the OBS controller is responsible for the burst generation and transmission, BCP processing and consequent reservation of resources in the data plane (BCP congestion is neglected). In this work, we assume a one-way signaling protocol [2], just in time (JIT) resource reservation [39] and first fit unused channel (FFUC) scheduling policy, but other OBS resource reservation protocols and scheduling policies can be used.

Each network node is both an edge node and a core switching node capable of generating bursts destined for any other nodes. Nodes are equipped with full wavelength conversion[2] to exploit the maximum statistical multiplexing property of OBS, a non-blocking switching matrix, a sufficient number of add/drop ports, one FT and one b-LSP occupancy reporting system.

We assume that source nodes do not buffer the bursts after assembly and the delay for BCP processing (i.e., offset time) is compensated by a short extra fiber delay line (FDL) of appropriate length at the input port of the node (E-OBS architecture is assumed [41]), albeit FDLs are not available at network nodes for buffering purposes. To communicate, both controllers exchange information to keep track of the system's conditions, i.e., OBS sends resource usage information (e.g., output link usage) while GMPLS sends configuration messages (e.g., FT updates).

Two reference network scenarios are used in order to claim topology independence, namely, the 14-node NSF network [42] with 21 links and the 28-node EON network [43] with 41 links, where all links support 32 bidirectional wavelengths with a transmission rate of 10 Gbps.

[2] Note that it is applied to all schemes used in the simulation campaign. Nevertheless, there is available literature showing that the use of partial conversion would reduce network cost while achieving the same performance [40].

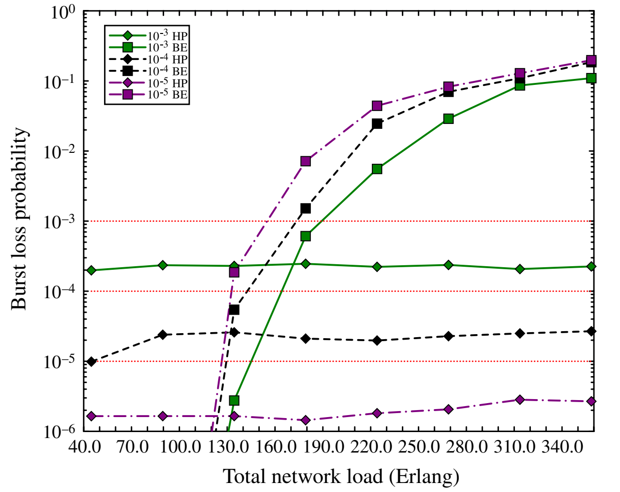

Fig. 4. (Color online) GOBS control model: validation of the LSP dimensioning model with respect to 3 different QoS demands of 10^{-3}, 10^{-4}, 10^{-5} in the NSF network.

The traffic is uniformly distributed between network nodes. We assume that each edge node offers the same amount of burst traffic to the network; this offered traffic is normalized to the transmission bit rate and expressed in Erlang. In our context, an Erlang corresponds to an amount of traffic that occupies an entire data wavelength; for example, 51.2 Erlang indicates that each edge node generates 512 Gbps. Apart from that, a non-uniform traffic pattern is equally considered in the following b-LSP dimensioning validation subsection.

Bursts are generated according to a Poisson arrival process and have exponentially distributed lengths. The mean burst duration is 1 ms. All simulations are performed under a static traffic scenario; that is, the traffic demands do not change during a simulation. Two classes of service are considered, HP and BE. Different HP–BE traffic ratios are defined during the simulations. The requested QoS constraints for HP traffic demands are set in terms of BLP.

A full-mesh VT of b-LSPs to route HP-class traffic is set up according to the MILP dimensioning model. There are $|N| * (|N| - 1)$ HP b-LSPs in each network scenario, where N is the number of nodes in the network. Conversely, the BE-class traffic is routed using the constrained SP heuristic algorithm described in Section IV.

B. Analysis of Results

1) Validation of the b-LSP Dimensioning Model: The first objective is to validate the proposed dimensioning model of HP b-LSPs, described in Section V, on real network topologies. Figure 4 illustrates the overall behavior of the model for different QoS demands, namely, 10^{-3}, 10^{-4} and 10^{-5}, in the 14-node NSF network. As expected, the proposed model is successful for all the three HP-class traffic thresholds and under any network load scenario. In fact, we can state that

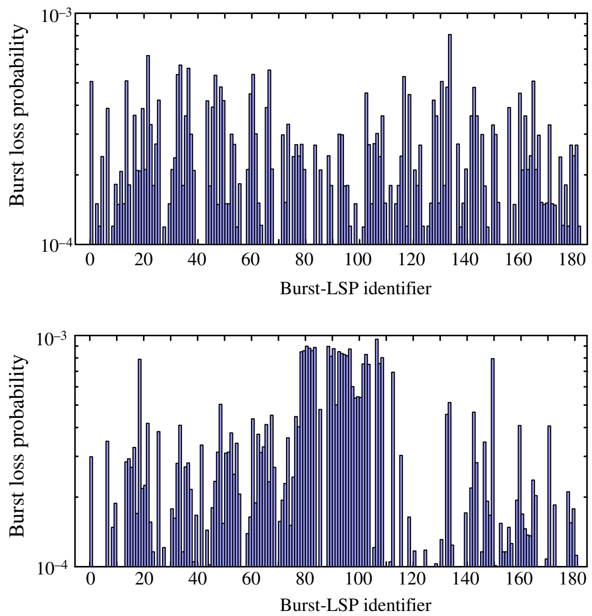

Fig. 5. (Color online) HP burst losses with uniform (top) and non-uniform (bottom) traffic in the NSF network (QoS = 10^{-3}).

the proposed model is independent of the network load and QoS demands. As regards the BE-class traffic performance, we would like to highlight that only in exceptionally high loads is the 10^{-1} threshold overcome. The performance of the BE-class is further improved by applying the intelligent constrained SP heuristic and burst preemption.

Besides the optimization of the overall network resource usage, the model also makes each individual b-LSP strictly meet the required QoS demands. Figure 5 is focused on the previous 10^{-3} QoS network scenario, considering a network offered load of 224 Erlang. As can be seen, the experienced BLP in all individual b-LSPs is below the demanded BLP, for both uniform (top) and non-uniform (bottom) traffic demands.

These results not only validate the proposed dimensioning model but also show that it behaves independently of the traffic volume and distribution in the network.

2) Benchmarking of GMPLS/OBS (GOBS): In order to position our model among other state-of-the-art proposals, comparisons with some of the current best practices are performed. We compare the performance of the proposed GOBS architecture against conventional OBS architectures augmented either with the classic burst preemption mechanism (relative QoS technique) or the dynamic wavelength grouping (DWG) policy [27] (absolute QoS technique). Both techniques route their traffic (HP and BE) over shortest path routes. The numerical results are extracted from both the 14-node NSF and 28-node EON networks. Only the uniform matrix of traffic demands is considered here.

Figures 6 and 7 illustrate the comparison of the proposed model against those two benchmark techniques. Quite similar behavior is observed in both network scenarios. From both figures, one can easily observe the outstanding performance of the proposed model over those two QoS techniques in any

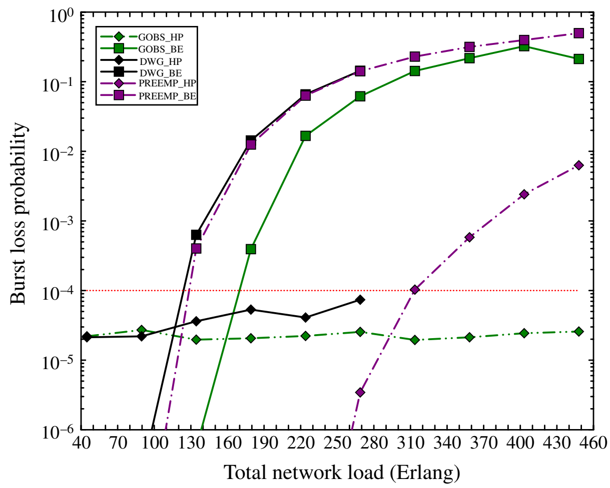

Fig. 6. (Color online) NSF network: HP–BE traffic ratio of 40%–60% for the three QoS techniques: i) GOBS, ii) DWG and iii) preemption.

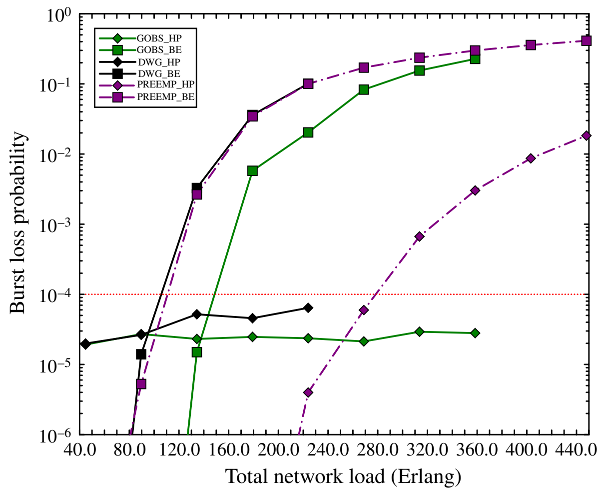

Fig. 7. (Color online) EON network: HP–BE traffic ratio of 40%–60% for the three QoS techniques: i) GOBS, ii) DWG and iii) preemption.

network scenario (either topological or load), even for BE-class traffic.

Regarding the HP-class traffic performance, it remains constant and considerably below the demanded QoS (10^{-4}) for the GOBS case; it grows (almost linearly) with the offered load in the DWG case, although never crossing the QoS threshold; and in the preemption case, it grows exponentially with the offered load (common OBS behavior), crossing the demanded QoS threshold at approximately 310 Erlang in the NSF network and at approximately 280 Erlang in the EON network. Note, however, that the DWG policy cuts off (i.e., it cannot cope with the traffic demands) at approximately 268 Erlang and 313 Erlang in the NSF and EON networks, respectively. This means that there are one or more links without enough wavelengths to satisfy the offered load. Nothing is suggested in [27] to overcome this constraint. In contrast, the GOBS model goes much further due to a better and more intelligent resource usage by its b-LSPs, which

TABLE I
PERCENTAGE OF RESOURCE USAGE BY GOBS AND DWG QOS TECHNIQUES IN THE NSF AND EON NETWORKS TO ALLOCATE HP TRAFFIC DEMANDS

Load (Erlang)		44.8	89.6	134.4	179.2	224.0	268.8	313.6	358.4	403.2	448.0
NSF	GOBS	23.21	31.37	38.99	45.39	50.89	56.70	62.43	67.56	72.62	77.75
	DWG	25.89	33.78	40.48	46.43	52.53	57.29	/	/	/	/
EON	GOBS	22.79	30.41	36.93	42.42	47.52	52.93	63.64	67.84	/	/
	DWG	23.86	30.56	36.13	41.62	46.42	/	/	/	/	/

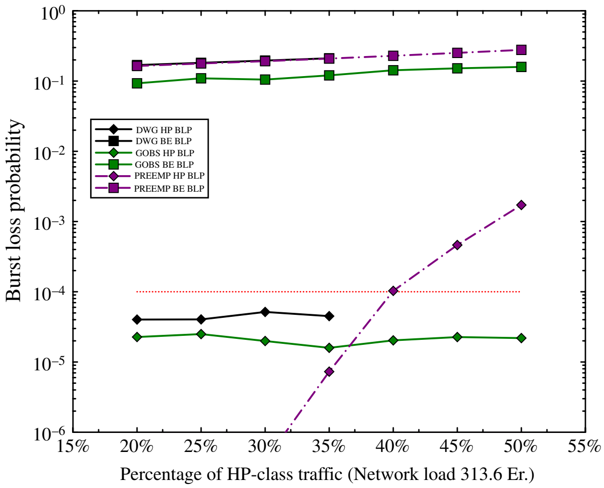

Fig. 8. (Color online) BLP behavior according to the percentage of HP-class traffic in the NSF network.

allows it to support higher loads (approximately 40% more). Although it cuts off for an approximate load of 400 Erlang in the EON network, it equally supports a 37.5% higher load than DWG. Both models run out of channels to commit to HP-class traffic owing to the EON topology's intrinsic properties, which has some nodes concentrating a lot of traffic and consequently routes. In the preemption case, there is no limiting load theoretically, although in practice both HP and BE performances become even worse as the load increases, being impractical after a certain value. In fact, the HP-class BLP in the preemption case is already one order of magnitude above the demanded threshold at approximately 300 Erlang in the EON network and 380 Erlang in the NSF network. Note also that the break-even point is achieved much earlier in the EON network than in the NSF one.

On the other hand, the BE-class traffic performance of GOBS is again better than DWG and at least as good as the preemption technique (for higher loads), in both network scenarios. However, we shall reiterate that the main goal is to demonstrate that our model guarantees the QoS figures for HP traffic. BE burst preemption is applied both in the GOBS and the DWG techniques, which explains why the DWG and preemption BE BLP values go side by side along the load range. Again, GOBS performs better than the other approaches due to its resource usage optimization and constrained SP heuristic to route BE traffic. It is worth mentioning that the previous HP-BLP values for the preemption case were achieved at the expense of worse BE performance. Note that in lower loaded scenarios, the differences between GOBS and preemption BE BLP values span from one to two orders of magnitude (while preemption has no HP losses—too far from the demanded QoS). In Fig. 6, an unexpected decrease of the BLP between 430 and 460 Erlang is observed. In this particular case, the model found a distribution of b-LSPs such that it "released" more resources to the BE traffic.

Regarding the resource (i.e., wavelength) usage, it is interesting to see how the three approaches make use of them to satisfy the same requirements (either load or QoS). The GOBS and OBS augmented with the DWG models share the same principle, yet GOBS applies it in an optimized way (i.e., better resource distribution) and, more importantly, implements it from an interoperable GMPLS-enabled OBS control plane. In Table I, one can see that there are slight differences in the percentage of wavelength usage to allocate to HP traffic demands, especially in highly loaded scenarios. However, in terms of (both HP and BE) BLP performance, higher gains are clearly achieved by the GOBS model (as observed in the figures). For instance, more wavelengths are used by DWG than by GOBS to provide the same BLP equal to 10^{-4} in the NSF network. The GOBS model starts with a 2.68% usage gain to end up with a 0.60% gain under a load of 268.8 Erlang (note that GOBS continues while DWG cuts off). In the EON network, the differences are even smaller. In fact, after 134.4 Erlang, DWG uses a lower number of wavelengths than GOBS. Nevertheless, due to an optimized distribution of the b-LSPs and its capacity, the GOBS model can cope with much more load than the DWG model. Moreover, the HP-class BLP behavior of the proposed model is more stable along the load range (due to a better wavelength assignment per b-LSP). We recall that the classic preemption model makes use of the entire set of wavelengths in each link (i.e., 100% usage), much more than the other two models.

In Fig. 8, we fix the network load (313.6 Erlang) and vary the percentage of HP-class traffic in the network. Once again, GOBS outperforms the other approaches. As regards the classical burst preemption, the break-even point occurs at 40% of the HP-BLP curve with a 10^{-4} QoS threshold, while the BE-BLP curve is always above the one of the proposed model. The DWG model suffers from the same problem as before. It does not support a percentage of HP-class traffic higher than 35%.

3) GMPLS-Driven b-LSP Reconfiguration: In order to evaluate the GMPLS-driven b-LSP reconfiguration mechanism proposed in Section VI, we enforce a peak of HP traffic of limited duration in one of the b-LSPs of the network. This leads to the following two main operations: i) expansion of the b-LSP capacity to accommodate the extra traffic when the peak-increment is detected and, on the other hand, ii) return to the original b-LSP configuration after the peak-decrement

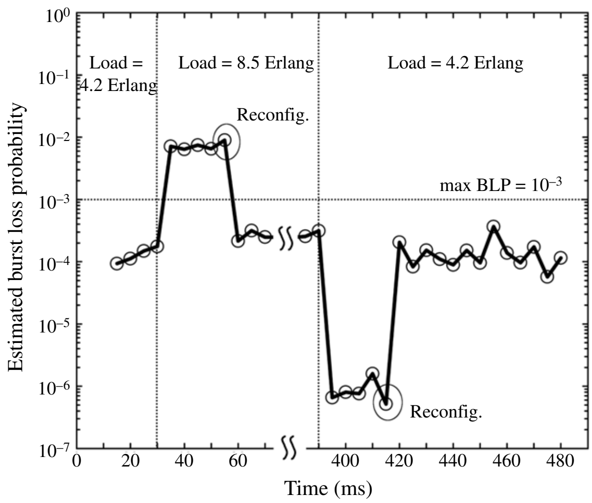

Fig. 9. Time sample showing a GMPLS-driven b-LSP reconfiguration when a traffic peak is detected and the return to the original b-LSP configuration after its decrement.

time. Figure 9 shows a sample of the execution time during which we monitor the traffic occupancy of an output link in the NSF network. The QoS control is performed in terms of HP burst loss probability (eBLP), which is estimated every T window with $|T| = 5$ ms. From the figure, we observe that, as soon as the traffic peak occurs, at around $t = 30$ ms (the offered load goes from 4.2 to 8.5 Erlang), the GMPLS instance detects it and remains on a holding stage during $W = 5$ consecutive T windows (i.e., 25 ms) with an eBLP above the QoS level to avoid any system instability. Following the process as described in Section VI, the interface IDs of each additional wavelength are included in the specific Unnumbered interface ID sub-object maintained in the PSB at the RSVP-TE module of the GMPLS controller. Once the PSB is updated, the OBS controller is notified in order to update its forwarding table and the b-LSPs acquire extended properties. As a result, the eBLP returns to values below the QoS threshold. At approximately 400 ms, however, the offered load is reduced back to its previous value of 4.2 Erlang (the traffic peak ends), so that the b-LSP now becomes over-dimensioned for the current offered load. Therefore, in order to achieve good resource usage, a counterpart process is triggered. After $W = 5$ consecutive T windows with extra allocated resources (i.e., wavelengths), the b-LSPs return to their initial configuration.

This reconfiguration mechanism induces a dynamic character (due to GMPLS) on the proposed architecture to properly handle unexpected traffic demands that may arise. It is worth mentioning, however, that long-term changes in the traffic matrix would eventually require a full reconfiguration of the VT.

VIII. Conclusions

This article introduces a GMPLS-controlled OBS network architecture that leverages on the GMPLS interoperability to enable seamless vertical and horizontal OBS integration with different switching layers under a common control plane. The burst label switched path (i.e., b-LSP) entity is here introduced as a means to provide QoS-aware burst transport services for HP-class traffic, besides its main purpose of providing end-to-end connectivity among different domains. As a way to optimize the network resource usage, an MILP formulation is presented to compute an optimal VT of the b-LSPs over the OBS data plane, defining their routes and capacities. In this study, a static scenario with a single QoS level has been considered as the first attempt to validate the b-LSP dimensioning model. Extensive simulation results highlight the effectiveness of the proposed method, which allows absolute BLP figures to be guaranteed, even in highly loaded situations, compared to state-of-the-art QoS techniques. Furthermore, the proposed dynamic GMPLS-driven b-LSP reconfiguration mechanism yields a successful adaptation to unexpected traffic surges, keeping the BLP of the HP traffic below the requested maximum values.

As future work, we are planning to extend the GMPLS-controlled OBS model with dynamic setup and reconfiguration of the VT of b-LSPs. Such a scenario involves the GMPLS routing protocol and relative OSPF extensions. First, the concept of shared wavelength must be included in the flooding messages so as to advertise the network resource status to all nodes of the network. Second, a proper routing algorithm must be designed to deal with the online computation of the b-LSPs.

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