Joint Routing and Wavelength Allocation Subject to Absolute QoS Constraints in OBS Networks

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***Abstract*—From the network layer perspective, the problem of burst losses is one of the most challenging problems which restrain the development of optical burst switching (OBS) networks. Indeed, OBS is a buffer-less technology and the consequent lack of guarantees for data delivery may affect significantly the quality of service (QoS) perceived by end users. To overcome these obstacles, dedicated network mechanisms and design methods are required for QoS provisioning in the network. With this end in view, in this paper, we present a traffic engineering (TE) approach to support the end-to-end traffic delivery with absolute QoS guarantees, in terms of burst losses, in an OBS network. We focus on the establishment of explicit routing paths and minimum allocation of wavelength resources in network links under the requirement that certain absolute level of burst loss probability for a given set of traffic demands is guaranteed. In this paper, we call such an off-line problem the virtual topology (VT) design problem. Since the VT design problem is $\mathcal{NP}$-complete, as an alternative to the mixed integer linear programming formulation, we develop a local search heuristic algorithm to solve it. Moreover, we focus on a dynamic OBS network scenario, where the offered traffic is subject to a change. In this context, we propose an on-line VT maintenance mechanism that is responsible for traffic admission control and adaptation of the VT to traffic changes. Eventually, proposed algorithms and mechanisms for the TE-driven end-to-end QoS approach are verified both numerically and by means of network simulations for a number of network scenarios.**

***Index Terms*—Network design, optical burst switching (OBS), quality of service (QoS), routing, traffic engineering (TE).**

I. INTRODUCTION

OPTICAL burst switching has attracted considerable interest as an all-optical network architecture able to support efficiently the transport of IP packet traffic and which provides flexible access to the immense bandwidth of the optical fiber and the wavelength division multiplexing (WDM) technology [2], [3]. Optical burst switching (OBS) achieves sub-wavelength granularity of transmission and switching by assembling groups of IP packets into optical data bursts and reserving wavelength channels in WDM links for the time period just enough for the burst transmission.

In general, OBS is a buffer-less technology and OBS networks belong to the class of loss networks [4]. Indeed, the bursts may contend for link resources at core switching nodes and the contention when unresolved leads to burst losses. The problem of burst contention is of fundamental importance in OBS networks. A way to alleviate the problem is to make use of wavelength converters, which allow us to transmit a contending burst on another wavelength than the one used so far [5]. By these means, the burst is accepted as long as there are some free wavelength resources available in the transmission link during the burst reservation period.

The problem of burst losses has an impact on the service quality perceived by end users. In order to guarantee certain level of quality (or Grade) of service (QoS/GoS), in terms of burst losses, wavelength resources in network links have to be dimensioned properly [6]. The key aspect is to determine and allocate a subset of wavelengths, from the entire set of wavelengths available in the link, able to support offered traffic demands [7], [8]. Concurrently, bursts should be routed properly over the network so as to avoid congestion in bottleneck links and prevent from excessive burst losses. To the best of our knowledge, the joint problem of routing and wavelength allocation (WA) under QoS constraints has not been studied in the literature; for our recent surveys on QoS mechanisms and routing methods, the reader is referred to [9] and [10], respectively.

In this paper, we address a general problem of optimizing routing and WA in an OBS network subject to given QoS constraints. To treat such a problem, we take a traffic engineering (TE) approach. In particular, we develop a network model which is based on the nonreduced load approximation [11] of a common OBS network loss model [4]. The modeling assumptions result in a set of constraints that are applied whenever routing and WA decisions have to be taken.

We consider that the set of routing paths and allocated wavelengths form a virtual topology (VT). We focus both on off-line routing and WA—referred to as the VT design problem—and on on-line VT maintenance during the network operation. In the VT design, we are looking for such network routing that for a given offered traffic load and (strict) absolute QoS requirements on the connection end-to-end (e2e) burst loss probability (BLP) minimizes the number of allocated

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wavelengths, i.e., the wavelength usage, in network links. We formulate the problem as a mixed integer linear programming (MILP) problem and, additionally, we develop a local search (LS) heuristic algorithm. Concurrently, to support network operation, we present an on-line mechanism that is responsible for traffic admission control (AC) and adaptation of the VT to traffic changes. As the simulation results show, the TE-based on-line mechanism responds to traffic changes and maintains the e2e burst losses below certain target level for all burst flows that are carried over the VT.

The reminder of this paper is organized as follows. In Section II, we review the literature on QoS routing in OBS and, afterward, we present our contributions. In Section III, we present a framework for the TE-based absolute QoS. In Section IV, we discuss main network modeling steps. In Section V, we present an MILP formulation and the LS heuristic algorithm for the off-line VT design problem. In Section VI, we focus on on-line VT maintenance during the network operation. In Section VII, we present numerical and simulation results that allow us to compare the performance of proposed methods and validate our framework. Finally, in Section VIII, we conclude obtained results.

II. RELATED WORK AND CONTRIBUTIONS

There are two general models of QoS provisioning considered in OBS networks, namely, relative QoS and absolute QoS [9]. In the relative QoS model, the performance of a QoS class is defined with respect to other classes and, for instance, it is assured that the loss probability of bursts belonging to a higher quality class is lower than the loss probability of bursts belonging to a lower quality class. In the absolute QoS model, a target value of a performance metric such as, for example, an acceptable level of burst losses is defined for a class. Although most of QoS mechanisms proposed for OBS networks offer relative QoS guarantees only, still absolute QoS guarantees are required by upper level applications.

The provisioning of absolute QoS is very complicated in OBS networks due to the lack of viable optical buffering technologies. The solutions that allow us to achieve absolute QoS are based mainly on the use of two-way signaling [12], a burst preemption mechanism [13], an intentional burst dropping mechanism [14], and appropriate WA [7], [8]. For a more thorough discussion on these solutions as well as for other references, we refer to our survey [9].

The WA approach to absolute QoS is very attractive since it can be implemented easily in a wavelength conversion-capable switching node. Indeed, the mechanism is based on a logical allocation of a subset of wavelengths, from the entire set of wavelengths in the network link, to be accessible for bursts belonging to a given QoS class. Upon the arrival of a burst, the wavelength reservation decision that is taken by the node controller concerns the selection of a wavelength from the set of allocated wavelengths. Several WA policies have been considered in the literature and they differ in the way the wavelength resources are partitioned [15]. In detail, wavelengths can be either shared between QoS classes or they are dedicated for each individual QoS class. Moreover, the allocation is either fixed and then it assigns particular wavelengths to a class or elastic and, in such a case, it specifies only the maximal acceptable number of wavelengths that can be occupied by a class simultaneously.

Although the WA mechanism is simple, still the key question is how many wavelengths should be allocated in network links so that to provide absolute QoS and, at the same time, use the wavelength resources efficiently. For the shared-elastic WA policy, the problem of optimized WA was studied in [7] and [8]. The authors develop a link loss model that is used to determine the number of wavelengths required to satisfy certain strict burst loss probabilities for a number of QoS classes. Since the optimization approach is very complex, due to the nonlinearity of both the objective function and model constraints, the authors propose a heuristic algorithm to provide a near-optimal solution to the WA problem. Regarding the dedicated WA policy, it involves a simpler loss model since a QoS class does not share the wavelengths with other classes. In this case, the Erlang B loss formula is frequently used to estimate burst losses in a network link [7], [15].

Effective network-wide QoS provisioning requires the extension of the link level QoS guarantees to the network level. The simplest and the most common strategy considered in loss networks assumes that the burst losses are kept below a certain fixed level in all network links [13]. In this case, the e2e burst loss guarantees can be achieved if the length of the longest routing path is limited and known. An improved strategy, which preserves from the over-provisioning of resources, is based on the partitioning of the network into a number of clusters and, concurrently, the application of the previous strategy within each cluster [14]. Yet another extension to the strategy which differ in the method the target link losses are calculated was proposed in [7].

The network-wide QoS should be supported by network routing and a TE method. Indeed, a properly designed routing protocol may preserve from the selection of overloaded links when applying proper TE rules. In general, in OBS networks, either reactive or proactive routing strategies are considered [10]. In reactive routing, the routing decision is taken on-line, for instance, when burst contention occurs. Proactive routing strategies use either measurement-based or anticipated traffic demands to optimize, usually off-line, routing decisions. In the context of absolute QoS provisioning, proactive routing is a convenient approach since it allows us to introduce TE rules easily and, by this means, control the distribution of traffic over the network [16].

Our recent survey on routing methods [10] shows that the problem of routing with QoS guarantees has not been studied widely in OBS networks. The existing solutions belong mainly to the class of alternative (deflection) routing. These reactive-based strategies employ adaptive methods that introduce relative QoS guarantees by the differentiation of routing decisions with respect to the QoS class. Regarding absolute QoS, the common assumption in the literature is of the use of shortest path routing [7], [13] and network routing has not been explored to provide optimized solutions.

The contributions of this paper are the following. The concept of virtualization and, in particular, the joint problem of routing and WA with e2e QoS guarantees has not been considered in OBS to the best of our knowledge. Indeed, the common solutions for the e2e QoS provisioning are based on the shortest part routing assumption. Our framework for the absolute QoS provisioning takes several assumptions (as discussed in Section III) which are used to develop a (mathematically) tractable network loss model. In this case, the proposed optimization algorithms for off-line VT design and on-line VT maintenance are novel. Moreover, the burst loss models that are considered for TE differ from the models usually applied in IP/MPLS networks (as e.g., in [17]) due to the buffer-less transmission in OBS. Finally, the proposed framework facilitates the control and dynamic provisioning of resources for quality-demanding traffic in OBS.

III. TE FRAMEWORK FOR ABSOLUTE QOS

The objective of the proposed QoS framework is to provide BLP guarantees for the quality-demanding flows of bursts transmitted between pairs of source–destination nodes in the network. We assume, such e2e BLP can be achieved by means of a TE approach, in particular, by an appropriate setup of routing paths, hereafter referred to as paths, and adequate allocation of wavelengths on the links belonging to these paths.

A. VT

To this end, we define the VT as a set of explicit paths established between source–destination pairs of nodes to route quality-demanding bursts through the network and the set of wavelengths allocated in the links belonging to the VT, appropriately chosen so as to satisfy some (absolute) QoS. We consider, a (limited) number of VTs is maintained on top of the physical OBS transport network and each VT is dedicated to guarantee a given QoS (i.e., a given BLP level). We assume that the wavelengths allocated to a VT are accessible for any burst that is carried within the VT, without respect to its origin and destination.

To alleviate the burst contention problem and to use the transmission resources efficiently, we consider the OBS switching nodes are capable of wavelength conversion. In particular, within a VT, a burst when transmitted can reserve any wavelength from the set of allocated wavelengths. It is important to distinguish the difference between the WA and wavelength reservation terms. The former corresponds to the (logical) selection of wavelengths that are accessible within a VT; the latter represents the actual assignment of a wavelength (from the set of allocated wavelengths) to be used to transmit a burst.

In this paper, we assume the network applies the dedicated WA policy so that there is no sharing of wavelengths between VTs. It is motivated by a relatively simple burst loss model that can be derived for such policy which allows to estimate the number of wavelengths to be allocated in the function of offered traffic load and target BLP. Apart from that, we assume the network operates with unsplittable (nonbifurcated) routing. This single-path routing approach avoids the problem of the out-of-order burst arrival [18]. Despite such choices, still the proposed framework allows us to employ any other WA and routing approach as far as appropriate TE rules for the resource allocation within the VT design problem can be provided.

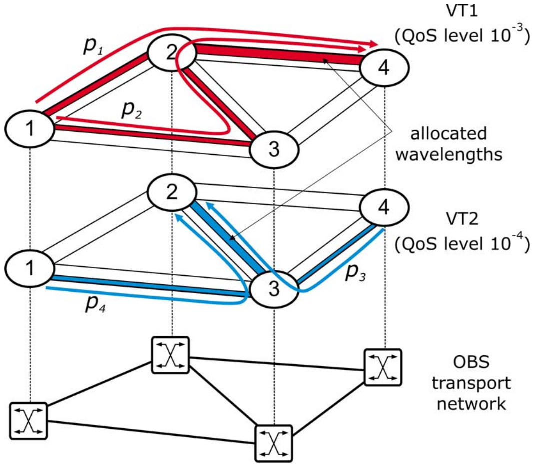

Fig. 1. Virtual topologies in an OBS network.

In Fig. 1, we can see an example of the OBS network with two VTs established, where two different levels of BLP are guaranteed, respectively, 10^{-3} and 10^{-4}. In this network, the burst contention will arise only within a VT and when two or more paths are routed over the same link. This can happen between paths p_1–p_2 and p_3–p_4 in the links connecting nodes 2-4 and 3-2, respectively. Accordingly, thanks to the dedicated WA for each VT, the traffic carried over a VT does not affect the traffic carried over other VT in network links.

Eventually, we consider the best effort (BE) class of traffic uses the spare network capacity.

B. OBS Transport Layer

At the OBS transport layer, whenever an ingress node has a quality-demanding burst to be transmitted to a destination egress node, it selects the corresponding routing path established within the VT with the specific QoS. Once the data burst is ready, the node releases its control packet that contains the information (e.g., a label) identifying the path. After the control packet has been transmitted over the control wavelength and the offset time has expired, the data burst is released. Both data burst and its control packet follow the same path within the VT.

At each intermediate node, the control packet is electrically terminated and processed. Based on the path identifier and the forwarding table, which contains information about VTs, the OBS node controller identifies the VT the burst belongs to. Accordingly, it has knowledge about the next burst hop and the set of allocated wavelengths that the burst can access at the output link. The controller chooses the output wavelength based on the local resource availability.

In Fig. 2, we can see an example of the transmission of two bursts, burst 1 and burst 2, both requiring QoS guarantees over path 1–2–3–4. Node 1 sends first the control packet 1 using the control wavelength Λ_0. Then, after the offset time expires, burst 1 is released using currently available wavelength λ_1 from the set of three wavelengths λ_1–λ_3 allocated to the VT in the link connecting node 1 and 2. At node 2, after the processing of the control packet 1, burst 1 is transmitted over λ_3 (wavelength available among the set of five allocated wavelengths).

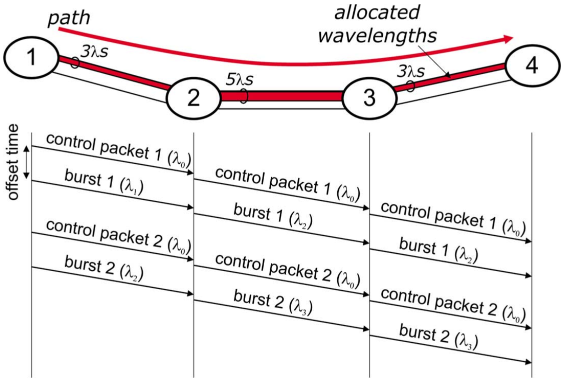

Fig. 2. Burst transmission over a VT.

At node 3, burst 1 is transmitted over λ_2. Control packet 2 follows the same path but burst 2 uses λ_2, λ_3, and λ_2 in each link, respectively.

C. Control Plane

We consider a control plane layer lays on top of the OBS transport layer and it has all means to maintain the VTs in the network. Among other tasks, such control plane sets up, reconfigures, and tears down (logical) routing paths as well as it allocates wavelengths in network links. All these tasks are performed subject to given traffic demands and QoS requirements and with the assistance of properly defined TE rules.

In such a scenario, the overall network intelligence is moved to the control plane, while the OBS transport layer is only responsible for the data burst transmission and local burst contention resolution (as explained in Section III-B). This approach allows us to maintain the fast performance of the OBS transport layer since only simple, local, and limited decisions are required in the OBS node controller such as, for instance, reading the forwarding table and selecting a wavelength from a given set. Conversely, routing decisions, congestion notifications, connection AC, and protection/restoration actions are moved to the control plane.

In this context, the generalized multiprotocol label switching (GMPLS) technology has (potentially) all the features to realize the OBS control plane and to provide the required functionality. GMPLS extends the concept of MPLS which, on the other hand, has been considered as a natural control and provisioning solution for OBS networks within the labeled OBS framework [19]. Evidently, the adaptation of GMPLS in order to control the dynamic OBS operation will require extensions in the current GMPLS protocol stack. For instance, the GMPLS control plane should allow us to allocate the wavelength resources in individual network links and, concurrently, update such information in the forwarding table of the OBS node controller.

The concept of VT and the separation of global network decisions in the control layer from local node decisions in the OBS transport layer should facilitate the interoperability of GMPLS and OBS. Nonetheless, such extensions are out of the scope of this paper and are left to future studies. The reader may refer to [20] for some preliminary ideas on this topic.

D. Dynamic Network Operation

During the network operation, whenever the set of traffic demand changes, e.g., upon acceptance of a new burst flow connection by the AC mechanism, we assume the control plane has all means to update the corresponding VT adequately. The changes in the VT may concern the increase of the number of allocated wavelengths in congested links, the change of the routing path, or even either partial or complete reconfiguration of the VT. Similar actions may be taken whenever a connection is terminated. In Section VI, we present an on-line resource provisioning mechanism which adapts the VT, by allocating wavelength resources in network links, whenever the admitted quality-demanding burst traffic might violate the QoS provided within the VT.

Also, the network might be equipped with a monitoring function at the network links so as to verify the actual BLP statistics. In case, the burst traffic profile is such that the target BLP is not met at a particular link; the control plane may decide to increase the number of allocated wavelengths in the link. In [21], we study such a monitoring mechanism which triggers WA procedures whenever unexpected traffic peaks that affect the provided service (i.e., QoS) levels are detected.

IV. VT MODELING

In this section, we define a set of TE rules that are based on analytical modeling of the OBS network and that are used in optimizing and maintaining a VT. The network modeling concerns the definition of routing constraints, the estimation of burst losses, the strategy for burst loss guarantees, and the WA function. These assumptions result in a set of constraints that are taken into account in the off-line and on-line algorithms presented in Sections V and VI.

For sake of simplicity, in this paper, we focus on the design of a single VT, i.e., on the provisioning of absolute QoS guarantees with one level of BLP in the network only. Since our approach assumes dedicated WA in network links and, in particular, there is no sharing of wavelength resources between QoS classes, the formulation of the VT design problem can be extended straightforwardly to account for multiple VTs.

A. Notation

We use $G = (V, E)$ to denote the graph of an OBS network, where V and E denote, respectively, the set of nodes and the set of unidirectional links. Link $e \in E$ comprises W_e wavelengths. Let $W = \max\{W_e : e \in \mathcal{E}\}$.

We use the so-called path-link approach [22] for the network flow representation of the VT model. Let P denote the set of predefined candidate paths between source s and termination t nodes, where $s, t \in V$ and $s \neq t$. Each path $p \in P$ is identified with a subset of network links, i.e., $p \subseteq E$. Adequately, subset $P_e \subseteq P$ identifies all paths that go through link e. Let $\delta = \max\{\delta_p : p \in P\}$ be the length of the longest path in the network, where δ_p is the length (in hops) of path p.

Let D denote the set of demands with QoS guarantees, where each demand corresponds to a pair of source-termination nodes. Let $P_d \subseteq P$ denote the set of candidate paths supporting demand d; $P = \bigcup_{d \in D} P_d$. Each subset P_d comprises a (small) number of paths, e.g., k shortest paths, and a burst belonging to demand d can follow one of them. According to [23], we assume that the traffic is characterized by a Poisson process. Let $h_d = \lambda_d/\mu$ denote the offered traffic load for demand $d \in D$, where λ_d is the arrival rate and μ^{-1} is the mean burst holding time; for convenience, we consider $h_p = h_d$ for $p \in P_d$. Let $\rho_p \in \mathbb{R}_+$ and $\rho_e \in \mathbb{R}_+$ denote the offered load to path $p \in P$ and the offered load to link $e \in E$, respectively.

We maintain the following assignment of indices: $e = 1,\ldots,|\mathcal{E}|$, $p = 1,\ldots,|\mathcal{P}|$, $d = 1,\ldots,|\mathcal{D}|$, which identify, respectively, links, paths, and demands, and w is used to count wavelengths in link e.

B. Routing

We assume that the network applies source-based routing, i.e., the path to be followed by a burst is determined in the source node. For all burst belonging to demand d the selection of path p from set P_d is performed according to decision variable x_p, also referred to as the routing variable. In this paper, we consider unsplittable (nonbifurcated/single-path) routing, which allows us to avoid out-of-order burst arrivals. Therefore, the routing variables are binary variables, and consequently, a burst flow is routed over path p iff $x_p = 1$ and there is only one path $p \in P_d$ such that $x_p = 1$. These assumptions result in the following routing constraints:

$$\sum_{p\in\mathcal{P}_d} x_p = 1, \forall d \in D, \text{ and } x_p \in \{0,1\} \quad \forall p \in P. \tag{1}$$

Note that multipath routing can be modeled easily by assuming real-valued variables $x_p \in \langle 0,1\rangle, p \in P$.

Finally, traffic ρ_p offered to path $p \in P_d$ is calculated as

$$\rho_p = x_p h_d. \tag{2}$$

C. Burst Losses

To treat the QoS provisioning problem analytically, a burst loss model has to be developed so as to estimate the level of burst losses in network links. A common OBS network loss model is based on the reduced load approximation, which applies the Erlang fixed-point calculation [4]. However, due to its computational complexity, we assume a simplified model based on the nonreduced load calculation [11]. In this model, to estimate traffic load ρ_e offered to link e, we sum up the traffic load ρ_p offered to each path $p \in P$ that crosses this link:

$$\rho_e = \sum_{p\in\mathcal{P}:p\ni e} \rho_p = \sum_{p\in\mathcal{P}:p\ni e} x_p h_p \quad \forall e \in E. \tag{3}$$

The use of such approximation is justified by its accuracy, particularly under low overall burst losses (below 10^{-2}) [11].

The BLP L_p along path $p \in P$ can be calculated as

$$L_p = 1 - \prod_{e\in p}(1 - B_e) \tag{4}$$

where we account for blocking probabilities B_e in all links e that belong to path p. This approximation is based on general assumption that burst blocking events occur independently in network links.

The blocking probability Λ_d of a burst belonging to demand $d \in D$ can be calculated as a weighted sum of path loss probabilities. Hence, using (2) we have

$$\Lambda_d = \frac{\sum_{p\in\mathcal{P}_d}\rho_p L_p}{h_d} = \sum_{p\in\mathcal{P}_d} x_p L_p. \tag{5}$$

The main difficulty of the aforementioned model is the calculation of losses B_e in network links, which depends highly on the burst traffic model. Under the common in the literature assumption of i.e.d burst arrivals, i.i.d burst durations, together with the assumption of the full-wavelength conversion capability in network nodes and the dedicated WA policy, the Erlang B-loss formula can be used to estimate the probability a burst is lost in link $e \in E$:

$$B_e(\rho_e, c_e) = \frac{(\rho_e)^{c_e}/c_e!}{\sum_{k=1}^{c_e}(\rho_e)^k/k!} \tag{6}$$

where B_e is a function of offered traffic load ρ_e and the number of provided (allocated) wavelengths c_e.

Remark: In the optimization problem in Section V-B, we rely on numerical approximations of function B_e and its inverse. Therefore, any other dimensioning function that counts for different burst traffic characteristics can be represented straightforwardly in the formulation.

D. BLP Guarantees

In the framework defined in Section III, we assume that all the bursts routed within VT are delivered with certain absolute BLP guarantees. In particular, for each demand $d \in D$, the following constraints should hold:

$$\Lambda_d \le B^{e2e} \quad \forall d \in D \tag{7}$$

where B^{e2e} denotes the acceptable $e2e$ BLP within the VT.

Constraints (7) may bring some difficulties when involved into the optimization problem due to the nonlinearity of Λ_d in the function of x [see (5)]. In order to simplify the problem, an alternative solution is to replace (7) by a set of more restrictive, but treatable inequalities representing constraints on acceptable burst blocking probabilities in network links. A particular, yet convenient, case is when the BLP is kept below certain fixed level B^{link} at each link. In this paper, we take such an approach and, similarly as in [13], we consider B^{link} to be equal to

$$B^{\text{link}} = 1 - (1 - B^{e2e})^{1/\delta}. \tag{8}$$

It can be shown easily that the burst loss guarantees given by (7) are satisfied in OBS with unsplittable routing. Using (1)–(5), a proof consists in showing that if $B_e \le B^{\text{link}}, \forall e \in E$, then for each $p \in P$, we have $L_p \le B^{e2e}$ and, since for the active path q (i.e., such that $x_q = 1$), we have $\Lambda_d = \sum_{p\in\mathcal{P}_d} x_p L_p = L_q$, it results in $\Lambda_d \le B^{e2e}$, what ends the proof.

In the reminder of this paper, we assume B^{link} is a fixed value, the same for each link, and determined by the QoS objectives given by B^{e2e} and calculated according to (8).

E. WA

The last modeling step concerns the definition of the dimensioning function $F(\,\cdot\,)$ that for given traffic load ρ_e determines the minimum number of wavelengths to be allocated in link e so that to meet given B^{link} requirements on the BLP. Such an estimation is given by a discontinuous, step-increasing function

$$F(\rho_e) = \lceil \mathcal{B}^{-1}(\rho_e, B^{\mathrm{link}}) \rceil \tag{9}$$

where $B^{-1}(\rho_e, B^{\mathrm{link}})$ is the inverse of the Erlang B Loss formula (6) extended to the real domain [24], and $\lceil\cdot\rceil$ is the ceiling function; note that $B^{-1}(\,\cdot\,)$ is (strictly) concave. Because B^{link} is a predetermined parameter, for simplicity of presentation, we skip it from the list of arguments of function $F(\,\cdot\,)$.

It is convenient to define a_w as the maximal load supported by w wavelengths given target-blocking probability B^{link}, i.e., $a_w = B^{-1}(w, B^{\mathrm{link}})$. Note that the inverse function $B^{-1}(w, B^{\mathrm{link}})$ is expressed with respect to w and B^{link}, on the contrary to the inverse function used in (9).

Although there is no close formula to calculate the inverse of (6), still we can use a line search method (see, e.g., [25]) to find the root ρ^* of function $f(\rho) = B^{\mathrm{link}} - B(\rho, w)$ so as to approximate the value of a_w by $a_w = \rho^*$ for each index w, where $0 < w \leq W$; obviously, $a_0 = 0$.

Vector $a = (a_0, \ldots, a_W)$ can be further used to determine $F(\rho_e)$ according to the following simple algorithm:

Algorithm 1 Wavelength Allocation (WA)

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while $a_w < \rho_e \& w \leq W_e$ do $w++$
if $w \leq W_e$ then return $F \leftarrow w$
else return $infeasibility$
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Algorithm 1 is a polynomial time algorithm of complexity $O(W)$. It is applied in the LS heuristic in Section V-C and in the online resource provisioning in Section VI.

Eventually, the number of allocated wavelengths in link $e \in E$ must not exceed the total number of available wavelengths W_e. This capacity constraint results in the upper bound on the offered load $\rho_e^{\max} = a_{W_e}$ and can be represented as

$$\rho_e \leq \rho_e^{\max} \quad \forall e \in E. \tag{10}$$

V. OFF-LINE VT DESIGN

In this section, we address the off-line VT design problem where a set of traffic demands is given. Such a problem concerns a variety of network scenarios, for instance, whenever the VT has to be rebuilt after a failure or an update in the network, or if there is some information available about admitted, estimated, or long-term traffic demands [7], [13] that might be used to establish the VT, or if the VT is already operating in the network but its resource allocation needs to be reoptimized.

A. VT Design Optimization Problem

In the off-line VT design problem, we focus on the optimization of the resource (i.e., wavelength) allocation in the network. The motivation is that when minimizing the resources allocation for the VT, there is more resources left to be used for other classes of traffic. To this end, we define two wavelength usage functions as follows.

1) The overall wavelength usage in the network, given by $U_1(x) = \sum_{e \in \mathcal{E}} F(\rho_e(x))$.
2) The wavelength usage in the most congested link, $U_2(x) = \max\{F(\rho_e(\mathbf{x})) : e \in \mathcal{E}\}$.

Here, $F(\,\cdot\,)$ is the WA function defined by (9) and $\rho_e(x)$ is the link load function defined by (3).

Note that routing vector $x = (x_1, \ldots, x_{|\mathcal{P}|})$ determines the distribution of traffic over the network and thus the traffic load offered to network links. Consequently, in order to minimize the usage of wavelengths in network links, x should be optimized. Taking into account the modeling assumptions introduced in Section IV, the off-line VT design problem can be formulated as a nonconvex optimization problem:

$$\begin{aligned} &\underset{\mathbf{x}}{\textbf{minimize}} && \Phi(\mathbf{x}) = f(U_1(\mathbf{x}), U_2(\mathbf{x})) && \text{(NLP)} \\ &\textbf{subject to} && (1) \text{ and } (10) && \text{(11a)} \end{aligned}$$

where $\Phi(x)$ is a function of $U_1(x)$ and $U_2(x)$.

The difficulty of formulation (NLP) relies in the fact that there is no close formula to express $F(\,\cdot\,)$ since no such formula exists for the inverse of the Erlang function $\mathcal{B}^{-1}(\,\cdot\,)$. A way to solve the problem is to substitute function $F(\,\cdot\,), e \in \mathcal{E}$ with its piecewise linear approximation and reformulate problem (NLP) as an MILP problem.

B. MILP Problem Formulation

For a single link $e \in E$, whenever $\rho_e \leq \rho_e^{\max}$, the piecewise linear approximation of $F(\,\cdot\,)$ can be expressed as $F(\rho_e) = \min\{w : a_w \geq \rho_e\}$, or by means of a 0–1 integer linear programming (ILP) formulation:

$$\begin{aligned} &\underset{\mathbf{u}}{\textbf{minimize}} && F = \sum\nolimits_{w=1,\ldots,W_e} u_e^w && \text{(ILP1)} \\ &\textbf{subject to} && \sum\nolimits_{w=1,\ldots,W_e} u_{ew} b_w \geq \rho_e, && \text{(12a)} \\ & && u_{ew} \geq u_{e(w+1)}, w = 1, \ldots, W_e - 1, && \text{(12b)} \\ & && \mathbf{u} \in \{0,1\}^{W_e}, && \text{(12c)} \end{aligned}$$

where $\mathbf{u} = (u_{e1}, \ldots, v_{eW_e})$ are decision (binary) variables and $b_w = a_w - a_{w-1}$ for each $w = 1, \ldots, W_e$.

In (ILP1), variable u_{ew} is active whenever wavelength w in link e is allocated and, as a result, F is the sum of all active u_{ew}. In constraint (12a), each active variable u_{ew} increases load budget by b_w so that to achieve a value greater or equal to ρ_e. Thanks to ordering constraints (12b), first F^* variables u_{ew} are active and, therefore, we have $\sum_{w=1,\ldots,W_e} u_{ew} b_w = a_{F^*} - a_0 = a_{F^*} \geq \rho_e$, where F^* is the solution to (ILP1).

Formulation (ILP1) is analogous to formulation (4.3.25) in [22]. In [22], there is yet another formulation considered for concave dimensioning functions, namely (4.3.24), which may be used for modeling $F(\,\cdot\,)$. Although both formulations might not be computationally equivalent [26], still they provide the same linear programming relaxations and bounds when used with an MILP solver and the branch-and-bound method [27]. Indeed, our numerical experiments (not reported here) show there is no particular gain when using one formulation or the other. Hereafter, we make use (arbitrarily) of formulation (ILP1).

Eventually, taking account all network links and introducing routing variables, problem NLP can be reformulated as an MILP problem. Next, we present an MILP formulation with a multiobjective function, where the primary optimization objective is to minimize the overall wavelength usage and the secondary objective is to minimize the wavelength usage in the most congested link, i.e., $\Phi(x) = \alpha U_1(x) + U_2(x)$:

$$\begin{aligned}
&\underset{\mathbf{x}}{\textbf{minimize}} && \Phi = \alpha \sum_{e\in\mathcal{E}} F_e + G && \text{(MILP)}\\
&\textbf{subject to} && \sum_{w=1,\dots,W_e} u_{ew} = F_e \quad \forall e \in \mathcal{E} && \text{(13a)}\\
&&& \sum_{p\in\mathcal{P}_d} x_p = 1 \quad \forall d \in \mathcal{D} && \text{(13b)}\\
&&& \sum_{p\in\mathcal{P}:p\ni e} h_p x_p = \rho_e \quad \forall e \in \mathcal{E} && \text{(13c)}\\
&&& \rho_e \le \rho_e^{\max} \quad \forall e \in \mathcal{E} && \text{(13d)}\\
&&& \sum_{w=1,\dots,W_e} u_{ew} b_w \ge \rho_e \quad \forall e \in \mathcal{E} && \text{(13e)}\\
&&& u_{ew} \ge u_{e(w+1)} \quad \forall e \in \mathcal{E},\ w = 1,\dots,W_e - 1 && \text{(13f)}\\
&&& F_e \le G \quad \forall e \in \mathcal{E} && \text{(13g)}\\
&&& \mathbf{u} \in \{0,1\}^{W_e}, \quad F_e \in \mathbb{Z}_+ \quad \forall e \in \mathcal{E} && \text{(13h)}\\
&&& \mathbf{x} \in \{0,1\}^{|\mathcal{P}|}, \quad \rho \in \mathbb{R}_+^{|\mathcal{E}|}, G \in \mathbb{Z}_+ && \text{(13i)}
\end{aligned}$$

where variables F_e and G represent the wavelength usage, respectively, in link e and in the most congested link, $\rho = (\rho_1, \dots, \rho_{|\mathcal{E}|})$ are auxiliary variables representing the traffic load offered to links, and weighting factor $\alpha = W + 1$ is selected so that to give absolute priority to the overall wavelength usage objective. The introduction of the secondary objective will result in more balanced WAs.

Constraints (13a) count the allocated wavelengths in network links. (13b) are the routing constraints. (13c) are auxiliary constraints of the nonreduced load calculation. (13d) are the link capacity constraints. (13e) and (13f) result from the 0–1 IP representation of function $F(\cdot)$. In particular, the number of wavelengths allocated 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 or equal to offered traffic load ρ_e. Besides, (13f) are ordering constraints, i.e., if w wavelengths are utilized so $w - 1$ wavelengths are utilized as well. Constraints (13g) are used to obtain the WA in the most congested link. Finally, (13h) and (13i) are the variable range constraints.

As discussed in Section IV-E, the WA function $F(\cdot)$ comes from a concave dimensioning function. Therefore, by applying similar arguments as in Section 4.3.3 in [22], the optimal routing solutions of (MILP1) will be nonbifurcated with highly unbalanced WAs in network links. Indeed, the marginal cost of allocating a new wavelength on the already occupied link is lower than on the empty link due to the character of $F(\cdot)$.

Note that MILP is a variant of the well-known discrete cost multicommodity flow problem [22], which was shown to be very difficult [26].

C. LS Heuristic

As an alternative to the MILP approach, here we propose an LS heuristic algorithm. Typically, for this kind of algorithms, the heuristic starts with a feasible solution and it searches for improved solutions in consecutive iterations. At each iteration, a number of solutions neighboring to the so far best solution is checked.

In the proposed algorithm, we assume a neighboring solution is achieved by means of a flip operation which concerns a permutation of active routing paths of selected demands. The heuristic makes use of the method proposed in [28] for generating neighboring solutions. Accordingly, at each iteration very long sequences of flips are considered, even while it appears to be making things worse, in the hope that some neighboring solution will allow us to escape from the traps of the local optimum. In the following, we discuss the algorithm details.

Similarly as in MILP, the objective of LS is to improve the wavelength usage defined by function $\Phi(x)$, where $x = (x_1, \dots, x_{|\mathcal{P}|})$ is the routing vector. Clearly, Φ is a function of x since x determines unambiguously traffic load offered to network links and, as a consequence, the number of allocated wavelengths, as discussed in Section IV. Accordingly, $\Phi(x) = f(F(\rho_e(x)))$. To compute $F(\rho_e)$, we apply Algorithm 1, which searches for the lowest w such that $a_w \ge \rho_e(x)$. Notice that the routing vector which results in link overload will lead to infeasibility. In such a case, we assume $\Phi(x) = \infty$.

Let the single-flip neighborhood of routing vector $\mathbf{x}$ with respect to demand d, denoted as $\lceil \mathbf{x} \rfloor_{d(q)}$, be such vector $\hat{\mathbf{x}}$ that $\hat{x}_p = 0$ if $x_p = 1, p \in \mathcal{P}_d$, then $\hat{x}_q = 1$ for some $q \in \mathcal{P}_d, q \ne p$, and $\hat{x}_r = x_r$ for the rest of paths $r \in \mathcal{P}, r \ne p, r \ne q$. Let Ω be the set of demands that have not been yet the subject of the flip operation during the algorithm performance; initially $\Omega = \mathcal{D}$.

A feasible solution $\mathbf{x}_0$ to start with can be found by solving the following ILP problem:

$$\begin{aligned}
&\underset{\mathbf{x}}{\textbf{minimize}} && 0 && \text{(ILP2)}\\
&\textbf{subject to} && \sum_{p\in\mathcal{P}_d} x_p = 1 \quad \forall d \in \mathcal{D} && \text{(14a)}\\
&&& \sum_{p\in\mathcal{P}:p\ni e} h_p x_p \le a_{W_e} \quad \forall e \in \mathcal{E} && \text{(14b)}\\
&&& \mathbf{x} \in \{0,1\}^{|\mathcal{P}|}. && \text{(14c)}
\end{aligned}$$

Since the objective function of (ILP2) is constant, either a feasible routing vector that satisfies both routing (14a) and link capacity (14b) constraints is found or a notification that such solution does not exist is returned by the solver.

At each iteration, the main routine of the LS algorithm generates $|\mathcal{D}|$ neighboring solutions. Solution $\mathbf{x}_k$, where $k = 1, \dots, |\mathcal{D}|$, is obtained as the best, among all possible $q \in \mathcal{P}_d, d \in \Omega$ and with respect to the usage Φ, single-flip neighborhood $\mathbf{x}_k = \lceil \mathbf{x}_{k-1} \rfloor_{d(q)}$ of the vector $\mathbf{x}_{k-1}$ found in the previous iteration. When a neighborhood is found, the demand d that is the subject to the flip operation is excluded from Ω. When Ω is empty, the algorithm selects, among all $\mathbf{x}_k$, vector $\mathbf{x}^*$ such that it minimizes the usage, i.e., $\mathbf{x}^* \in \{\mathbf{x}_k : \Phi(\mathbf{x}_k) \le \Phi(\mathbf{x}_m), 0 \le k \le |\mathcal{D}|, 0 \le m \le |\mathcal{D}|\}$. If $\Phi(\mathbf{x}^*) < \Phi(\mathbf{x}_0)$, a new iteration is started with $\mathbf{x}_0 = \mathbf{x}^*$

and $\Omega = \mathcal{D}$; otherwise, the algorithm terminates. Algorithm 2 presents the pseudocode of LS.

An upper bound on the computation time of the main routine of LS is given by $O(W|\mathcal{E}||\mathcal{D}||\mathcal{P}|)$, where $W|\mathcal{E}|$ is the bound on the number of iterations at the worst case improvement (one per iteration) of the cost function, $|\mathcal{D}|$ is the number of generated neighboring solutions, and $|\mathcal{P}|$ is an upper bound on the number of single-flip candidates that are considered in the search for a neighboring solution. Although the complexity of this routine is polynomial in time, still the feasibility problem (ILP2) is $\mathcal{NP}$-complete (see Proposition 4.2 in [22]). Nevertheless, as the results in Section VII-A show, LS performs quickly.

Algorithm 2 Local Search (LS) Heuristic

```
Require $\mathcal{P}, \mathcal{D}$
Ensure $\mathbf{x}^*, \Phi$
if $\mathbf{x}^* \leftarrow$ solution of ILP2
if $\mathbf{x}^*$ is infeasible then
  return infeasibility
else
  repeat
    $\mathbf{x}_0 \leftarrow \mathbf{x}^*$, $\Omega \leftarrow \mathcal{D}$
    for $k = 1$ to $|\mathcal{D}|$ do
      $\Phi^k \leftarrow \infty$
      for all demand $d \in \Omega$ do
        for all path $q \in \mathcal{P}_d$ such that $x_q = 0$ do
          $\hat{\mathbf{x}} \leftarrow \lceil \mathbf{x}_{k-1} \rfloor_{d(q)}$ (where flip is defined as:
          $\hat{\mathbf{x}} \leftarrow \mathbf{x}_{k-1}$, $\hat{x}_q \leftarrow 1$, and $\hat{x}_p \leftarrow 0$, where $p$ is
          the active path for demand $d$ in $\mathbf{x}_{k-1}$
          if $\Phi(\hat{\mathbf{x}}) \leq \Phi^k$ then
            $\mathbf{x}_k \leftarrow \hat{\mathbf{x}}$, $\Phi^k \leftarrow \Phi(\hat{\mathbf{x}})$, $d_k \leftarrow d$
          end if
        end for
      end for
      $\Omega \leftarrow \Omega \backslash \{d_k\}$
    end for
    $\mathbf{x}^* \leftarrow \text{argmin}_{x \in \{x_1,\ldots,x_{|\mathcal{D}|}\}} \Phi(x)$
  until $\Phi(\mathbf{x}_0) \leq \Phi(\mathbf{x}^*)$
  return $\mathbf{x}^* \leftarrow \mathbf{x}_0$, $\Phi \leftarrow \Phi(x_0)$
end if
```

VI. ON-LINE VT MAINTENANCE

In this section, our focus is on the e2e QoS provisioning for quality-demanding burst traffic in a dynamic network scenario. We assume that the QoS guarantees are achieved with the aim of a VT which is maintained in the network.

We consider that the clients of the OBS network, such as IP networks, send requests and notify the control plane of the OBS network regarding the volume of the quality-demanding data traffic which they are going to offer to the network. In order to meet the QoS objectives and satisfy the e2e BLP requirements for the traffic supported within the VT, we assume there are AC mechanisms implemented in the network. Such mechanisms should react both to the changes in the offered traffic load that are notified to the control plane—we will refer to it as the flow admission control (FAC) mechanism and during the burst assembly process performed at the edge node—referred to as the AC mechanism. FAC is responsible for admitting data flows from the clients of the OBS network under the condition there are wavelength resources available so that the traffic might be accommodated either within the current VT or after its modification. Concurrently, AC should take care that any excessive traffic which arrives at the OBS ingress node and which does not comply the FAC agreement either is sent through the OBS network as the BE traffic or is dropped at the ingress node.

In the following discussion, let $\tilde{x} = (\tilde{x}_1, \ldots, \tilde{x}_{|\mathcal{P}|})$ be the routing vector which determines single routing paths that are used between source and termination nodes in the VT. Also, let $\tilde{h} = (\tilde{h}_1, \ldots, \tilde{h}_{|\mathcal{D}|})$ be the vector of the burst traffic load which is actually admitted to the VT. Without loss of generality, we consider that the VT is already established and operating in the network. In particular, the routing vector is obtained either with the assistance of off-line optimization algorithms presented in Section V or by some other method (e.g., the shortest path algorithm). Eventually, let $\tilde{F} = (\tilde{F}_1, \ldots, \tilde{F}_{|\mathcal{E}|})$ be the WA vector which represents the number of wavelengths allocated in network links within the VT. Here, we assume that $\tilde{F}$ is a function of vectors $\tilde{x}$ and $\tilde{h}$ (i.e., $\tilde{F} = f(\tilde{\mathbf{x}}, \tilde{\mathbf{h}})$) and is determined using the model presented in Section IV-E.

In the considered here on-line VT maintenance mechanism, under a request of augmentation of offered burst load for demand d (i.e., between a pair of source–termination nodes) by volume h_d^+, the FAC mechanism performs the following steps.

1) *Let* $\hat{h} = (\tilde{h}_1, \ldots, \tilde{h}_d + h_d^+, \ldots, \tilde{h}_{|\mathcal{D}|})$ be an augmented traffic vector resulting from the actually admitted traffic and the new burst flow request. *Let* $\hat{F} = f(\tilde{\mathbf{x}}, \hat{\mathbf{h}})$ be a WA vector required to support the augmented traffic.
2) *If* at least one element of vector $\hat{F}$ exceeds the link capacity (i.e., $\exists \hat{F}_e, e \in E : \hat{F}_e > W_e$) *then* reject the request.
3) *Else if* $\hat{F} = \tilde{F}$, *then* accept the request ($\tilde{h} \leftarrow \hat{h}$) and maintain the VT without changes.
4) *Else* accept the request ($\tilde{h} \leftarrow \hat{h}$) and increase the allocation of wavelengths in the VT whenever necessary (i.e., $\tilde{F} \leftarrow \hat{F}$).

The control plane should also act whenever it is notified about a diminishment of the burst flow load offered to demand d by volume h_d^-. In this case, we consider the following mechanism.

1) *Let* $\check{h} = (\tilde{h}_1, \ldots, \tilde{h}_d - h_d^-, \ldots, \tilde{h}_{|\mathcal{D}|})$ be a diminished traffic vector after the reduction of the actually admitted traffic by h_d^-. *Let* $\check{F} = f(\tilde{\mathbf{x}}, \check{\mathbf{h}})$ be a WA vector required to support the diminished traffic.
2) Accept the request ($\tilde{h} \leftarrow \check{h}$).
3) *If* $\check{F} = \tilde{F}$, *then* maintain the VT without changes.
4) *Else* reduce the allocation of wavelengths in the VT whenever necessary (i.e., $\tilde{F} \leftarrow \check{F}$).

In Section VII-B, we evaluate this VT maintenance mechanism in a simulation environment of a dynamic OBS network.

Apart from modifying the number of wavelengths, more advanced on-line mechanisms shall involve routing decisions and, for instance, the selection of alternative single paths. In this case, it will be advantageous, with respect to the wavelength usage, to rely the joint routing and wavelength assignment decisions on a modified version of optimization algorithms discussed in

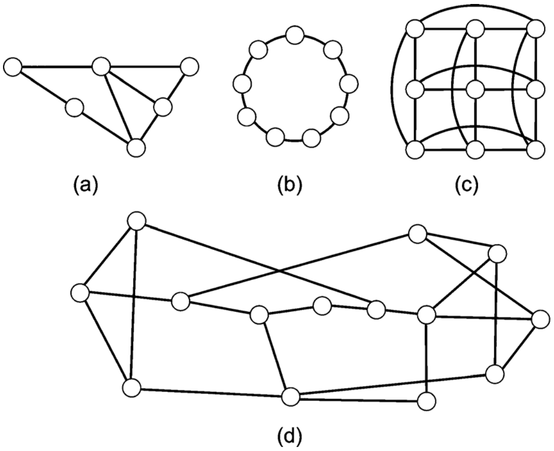

Fig. 3. Networks. (a) SIMPLE6. (b) RING9. (c) TORUS9. (d) NSF14.

Section V. Moreover, additional features, such as fairness in the burst flow admission, might be taken into account in FAC. Such extensions are left out of the scope of this paper.

VII. PERFORMANCE RESULTS

A. Evaluation of Off-Line VT Design Algorithms

Here, we compare the performance of off-line VT design algorithms presented in Section V, namely, MILP and LS.

The results are obtained for SIMPLE6 (6 nodes, 16 links), RING9 (9 nodes, 12 links), and TORUS9 (9 nodes, 36 links) network topologies (see Fig. 3). In the analyzed scenarios, we consider each demand has $|\mathcal{P}_d| \in \{2, 4\}$ candidate paths (the shortest paths), each network link has $W \in \{16, 32, 64\}$ wavelengths, and $B^{e2e} = 10^{-3}$, which is an acceptable level for the TCP traffic carried over OBS (e.g., see, [29]). We use IBM ILOG Cplex v.12.2 [30] on an Intel i3 2.27 GHz 2 GB computer to solve MILP problems.

We consider nonuniformly distributed traffic matrices. Each matrix is built by going through all demands (i.e., node pairs $s, t \in V$ with $s \neq t$) and randomly generating, with equal probability, an integer number $m_d : 1 \leq m_d \leq 10$. Then, $h_d = \rho W m_d |\mathcal{V}| (\sum_{d \in \mathcal{D}} m_d)^{-1}$, where ρ is a load factor introduced to scale the volume of traffic. Note that if $m_d = 1, \forall d \in D$ and $\rho = 1$, then the matrix is uniform and each node generates to the rest of nodes the traffic load that occupies the entire link (i.e., W wavelengths). The results are averaged over ten randomly generated matrices.

We report both the overall wavelength usage (U_1), the usage in the most congested link (U_2), the computation time (T), and the difference in the usage (ΔU_1 and ΔU_2).

1) Optimality: In Table I, in both SIMPLE6 and RING9 networks, the LS heuristic provides near-optimal solutions that differ only slightly from the MILP ones. In most cases, the difference in the primary optimization objective, i.e., the overall wavelength usage (ΔU_1), is below 0.5%. It means that the overhead in the WA is below 0.5% in average when optimizing the VT with LS (i.e., only 1 additional wavelength is required if 200 wavelengths are allocated). This optimality gap is a bit higher (up to 2.3%) in the scenario with lower number of wavelengths $(W = 16)$. Note that the secondary objective, i.e., the most congested link usage (ΔU_2), is lower for LS in some scenarios.

2) Computation Times: The computation times of the LS algorithm range from several milliseconds for SIMPL6 to about 200 ms for TORUS9, and take some seconds for a larger NSF14 network (not reported in Tables; depicted in Fig. 3). Except the dependence on the topology, no particular dependence on other problem parameters has been observed.

Although the solution of MILP can be found in a short time in SIMPLE6, still it is time consuming even for relatively small networks such as RING9 and TORUS9. It takes about 1 h to solve MILP for RING9 if the number of wavelengths is high $(W = 64)$ and the offered load is low $(\rho = 0.1)$. For TORUS9, there is a difficulty even for a low number of wavelengths $(W = 16)$.

Another issue is the high memory usage that have been observed for some problem instances for which the Branch&Bound (B&B) tree of the MILP solver is not being reduced significantly due to rather poor lower bounds obtained in the solver. For instance, for TORUS9 with $W = 32, \rho = 0.3$ (not reported in Tables), the memory used to store the nodes of the B&B tree is about 1 GB after only 400 s of the algorithm performance.

3) Impact of the Number of Candidate Paths: In Table I, when increasing the number of candidate paths $|\mathcal{P}_d|$ from 2 to 4, we can observe the wavelength usage increases as well. The reason is that the length of the longest path in the extended set of candidate paths is longer and, therefore, the value of B^{link} decreases (see the modeling details in Section IV). Consequently, more wavelengths are required to accommodate given traffic demands.

4) Impact of Topology: In Table II, we present the wavelength usage results for two distinct network topologies, namely, for a RING network and a highly connected TORUS network, and the same traffic demand sets. The evaluation shows that the overall wavelength usage is lower in the highly connected TORUS network what is an expected result since the routing paths are shorter than in the RING network and less link resources are occupied by transmitted bursts. Accordingly, there may be more traffic with quality guarantees accommodated within the VT in such a network than in a weakly connected network.

B. Dynamic Network Operation and On-Line VT Maintenance

In this section, we evaluate the performance of the on-line VT maintenance mechanism in an OBS network with dynamic traffic changes.

The results are obtained for NSF14 ($|\mathcal{V}| = 14$ nodes, $|\mathcal{E}| = 42$ links) network topology (see Fig. 3). We consider that each network link has $W = 32$ wavelengths.

Let the total network load E, expressed in Erlangs, be defined as the total traffic load that is offered by all nodes, where each node generates traffic load that occupies ρ percents of the link capacity, i.e., $E = \rho W |\mathcal{V}|$. For instance, for $\rho = 0.5$, $W = 32$, and $|\mathcal{V}| = 14$, we have 224 Erlangs of the total network load. In the evaluation, we consider that 25% of E is the quality-demanding (HP, or high priority) traffic and the rest 75% is served

TABLE I
PERFORMANCE COMPARISON OF OFF-LINE ALGORITHMS IN TERMS OF WAVELENGTH USAGE (U_1 AND U_2) AND TIME COMPLEXITY (T)

Scenario			**MILP**			**LS**			**MILP vs LS**	
W	ρ	$\lvert P_d\rvert$	U_1	U_2	T [*sec.*]	U_1	U_2	T [*msec.*]	ΔU_1	ΔU_2
SIMPLE6										
16	0.1	2	86.8	10.7	1.25	88.8	10.1	7.9	2.3%	−5.6%
16	0.3	2	160	15.6	2.07	161.6	15.5	6.3	1.0%	−0.6%
32	0.3	2	237	27.5	6.16	238.3	27.1	3.1	0.5%	−1.5%
32	0.4	2	289.9	28.5	5.03	290.8	28.4	4.6	0.3%	−0.4%
32	0.4	4	296.1	28.6	26.8	297.3	29.8	20.3	0.4%	4.2%
64	0.3	2	378	42.8	17.5	378.6	41.2	6.4	0.2%	−3.7%
64	0.5	2	548.2	56.3	10.0	549.8	55.4	1.5	0.3%	−1.6%
64	0.5	4	558.3	58.2	76.6	558.7	58.7	28.1	0.1%	0.9%
RING9										
16	0.2	2	246.9	15.3	25.6	247.2	15.2	96.8	0.1%	−0.7%
64	0.1	2	371.9	23.1	3620	372.1	23.3	77.9	0.1%	0.9%
64	0.3	2	785.7	49.8	37.2	785.7	50	40.8	0%	0.4%
TORUS9										
16	0.1	2	160.6	6.6	1532	165.5	7.1	201.4	3.1%	7.6%
16	0.2	2	218.5	9.4	6787	222	10.2	154.7	1.6%	8.5%

TABLE II
WAVELENGTH USAGE VERSUS NETWORK TOPOLOGY; LS ALGORITHM, $|\mathcal{P}_d| = 2$

	RING9		**TORUS9**		**Difference**	
W	16	32	16	32	16	32
ρ	0.2	0.3	0.2	0.3	0.2	0.3
U_1	247.2	490	222	396.7	11%	23%
U_2	15.2	30.4	10.2	19.5	49%	56%

as BE traffic. The VT is initially dimensioned, using the LS algorithm presented in Section V, to accommodate 70% of the HP traffic, which comes from a static matrix of uniformly distributed traffic demands that does not change during the simulation. The remaining 30% corresponds to the requests of dynamic traffic flows offered to the network. Such burst flow requests arrive in average at every $\bar{\lambda}^{-1} = 500$ s and have a mean duration of $\bar{\mu}^{-1} = 600$ s for each pair of source–destination nodes. Accordingly, the average interarrival time of the burst flows offered to the network is equal to $\bar{\lambda}^{-1}/(|\mathcal{V}|(|\mathcal{V}|-1)) \approx 2.74$ s. The source and destination nodes for arriving burst flows are selected according to a uniform distribution. The network either admits or rejects the burst flow requests with the assistance of the VT maintenance mechanism presented in Section VI. The e2e BLP of the HP traffic supported by the VT is on the level of 10^{-4}. If not mentioned differently, the network load is equal to $E = 224$ Erlangs.

The burst loss probabilities are calculated in a cumulative way, i.e., taking into account all bursts offered and lost in the network until a given instant of time. The results are obtained with a full burst preemption mechanism implemented, which is presented in [31]. In this mechanism, we consider that the BE bursts are allowed to use unoccupied wavelengths that are allocated to the VT HP and be preempted whenever an HP burst needs these resources. The simulations are executed using the *ad hoc* JAVOBS simulator [32]

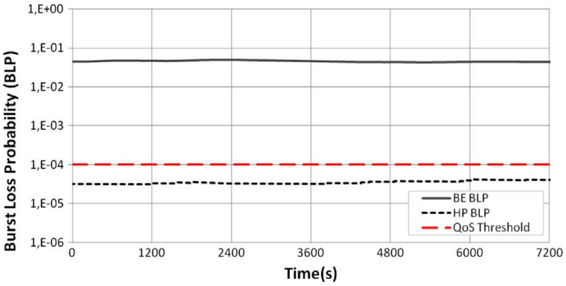

Fig. 4. Burst loss probabilities for a given demand versus time; $E = 224$ Erlangs.

In Fig. 4, we present BLP results for the HP and BE traffic obtained as a function of time. These temporal samples are taken for a period of 7200 s for an (arbitrary) pair of source–destination nodes (i.e., demand) in the network. The VT is adapted whenever a new traffic flow arrives such that it cannot be satisfied using the current allocated resources. The BLP threshold is accomplished with respect to the HP traffic. They show some small variations in HP BLP that take place in the network due to the arrivals and departures of burst traffic flows. We observe that the changes in the offered HP traffic load do not have a significant impact on the BE BLP results, which vary between 4.2×10^{-2} and 4.9×10^{-2}. This is achieved thanks to the burst preemption mechanism which allows us to make use of the VT resources for the BE bursts.

In Fig. 5, we present the BLP results and the overall wavelength usage results obtained as a function of time. The samples are taken again for a period of 7200 s. In Fig. 5, the HP BLP metric represents the largest observed e2e BLP among all the demands at each time step. Since the observed results are below the level of 10^{-4}, it shows that for each demand the e2e guarantees are satisfied. The BE BLP represents the average e2e BLP with respect to the BE traffic. Although it can be hardly observed in the logarithmic scale, the BE BLP results vary slightly. The

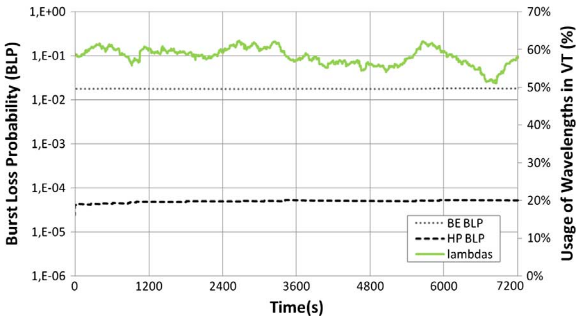

Fig. 5. Maximum and average burst loss probabilities versus time; $E = 224$ Erlangs.

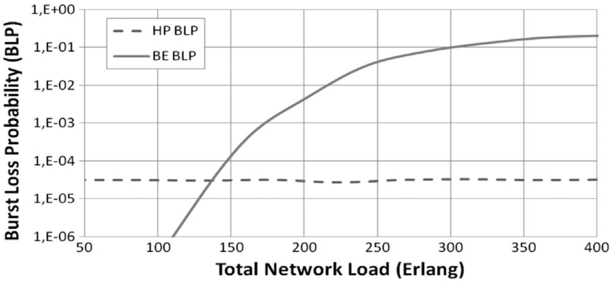

Fig. 6. BLP versus total network load.

TABLE III
BLOCKING PROBABILITY OF THE QUALITY-DEMANDING BURST FLOW REQUESTS

Load (E)	224	268.8	313.6	358.4	403.2
Blocking	0%	1.6%	4.23%	7.5%	12.42%

overall wavelength usage, which is expressed as a percentage of wavelengths (λ) allocated to VT to the overall number of wavelengths in the network, varies with the arrivals of quality-demanding burst flows which cannot be served with the already allocated VT resources. Similarly, every time a burst flow is terminated, any excessive VT resources are released.

In Fig. 6, we show the overall BLP results for the HP and BE traffic after the performance of dynamic network simulations. The results are obtained for different loads (E) offered to the network. We can see that the quality guarantees are provided for the HP traffic independently of the traffic load. As regards the BE traffic, the BLP increases as the load increases.

It is also worth to mention that for traffic loads above 268 Erlangs, we notice the blocking of some requests of dynamic burst flows due to the lack of wavelength resources in the network. The results for different traffic loads are presented in Table III.

VIII. CONCLUDING REMARKS

In this paper, we present a TE approach to the problem of e2e burst traffic delivery with absolute QoS guarantees in the OBS network. In particular, we address the off-line VT design problem and the on-line VT maintenance problem. The former concerns optimal setup of routing paths and allocation of wavelength resources under the requirement to guarantee certain absolute level of BLP for a set of traffic demands. Such a problem arises whenever the VT has to be established, reconfigured, or rebuilt. The objective of the latter is to adapt the VT dynamically during the network operation and according to traffic changes. We take several simple assumptions in order to develop a treatable yet valid network model. This model is used to formulate a set of constraints that support routing and WA decisions in off-line and on-line algorithms.

For off-line VT design, we formulate an MILP problem and we develop an LS heuristic algorithm which, as numerical results show, is a practical and efficient alternative to MILP. To support network operation under dynamic traffic changes, we study a VT maintenance mechanism that is responsible for traffic AC and adaptation of the VT. As the simulation results show, the TE-based on-line mechanism responds to traffic changes and maintains the e2e burst losses below certain target level for all burst flows that are carried over the VT. The considered on-line VT adaptation mechanism modifies the allocation of wavelengths only. The development of more advance mechanisms allowing for modification of routing paths is left for future work.

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