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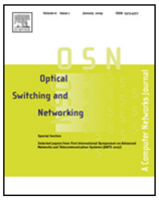

An overview of routing methods in optical burst switching networks

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ABSTRACT

In this article we present a survey of routing methods in Optical Burst Switching (OBS) networks. We begin with a description of routing approaches and follow the discussion with a detailed classification of routing algorithms in OBS. Afterwards, we discuss common OBS network loss models that are frequently used in routing optimization. As examples of such application, we present a linear and a non-linear formulation of a multi-path routing optimization problem with an indication on convenient resolution methods. The presented algorithms are appropriate for proactive load balancing routing and aim at the improvement of network-wide burst loss performance. To compare performance results, both methods are evaluated by simulation in a set of unified network scenarios.

1. Introduction

The optical burst switching paradigm [1,2] has attracted considerable interest as an optical networking architecture for efficient support of IP packet traffic and flexible access to the immense transmission capacity available with optical fibres and the Wavelength Division Multiplexing (WDM) technology [3]. OBS provides a compromise between technological requirements and bandwidth utilization efficiency. It achieves sub-wavelength granularity by assembling multiple IP packets, which are directed to the same egress node, into bursts and allocating a wavelength for each burst during the time required for its transmission. At the same time, it avoids optical buffering of data bursts at core switching nodes by reserving transmission resources in advance with the assistance of out-of-band signalling.

In general, OBS networks apply a one-way reservation protocol for setting up the necessary resources for each burst transmission [1]. Thanks to this feature, instead of waiting for an acknowledgment of successful resource reservation in the entire burst path, the transmission of a burst can be initiated as soon as the burst is assembled. This implies that bursts may contend for resources at core switching nodes. Given that unresolved contentions lead to burst losses it is clear that strategies for resolving or minimizing contention are of paramount importance in OBS networks. Contention can be resolved or minimized using strategies acting in the wavelength, time, and space domains [4,5].

The space domain is attractive to resolve contention because, unlike that in the wavelength and time domains, it does not require additional hardware. It consists of exploiting the capacity available on the lesser congested links,

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either through deflection routing, by locally deflecting contending bursts towards links with available capacity, or using global routing path optimization to determine the paths that are expected to minimize in advance contention on the network links. Nevertheless, the effectiveness of routing strategies depends on the network topology and traffic pattern.

The purpose of this article is to give a survey on routing methods for OBS networks together with a performance comparison of selected strategies in a set of unified network scenarios. A particular attention is given to a study of multi-path source routing algorithms that make use of linear and non-linear optimization methods. Additionally, the included identification of the state-of-the-art routing, network modelling, and optimization methods will help to identify open problems for further research.

The article is organized as follows. Routing strategies for OBS networks are classified in Section 2, whereas modelling principles of OBS networks are presented in Section 3. In Section 4, two optimization methods that are applied for proactive load balancing in an OBS network are described. The performance of these methods is evaluated using network simulation in Section 5. Finally, in Section 6 we present some concluding remarks and suggest future work.

2. Routing in OBS networks

In this section, we present a general overview of routing methods in OBS networks. To support the discussion, we recall basic terminology used in routing classification in communication networks. Next we present principal approaches considered in route management in OBS. Based on this framework we classify the OBS routing algorithms proposed in the literature.

2.1. Basic terminology

In general, routing algorithms in communication networks can be grouped into two major classes: *non-adaptive* and *adaptive* [6]. Non-adaptive, also called *static*, are the ones which do not base their routing decisions on measurements or estimates of the current traffic and topology, whereas adaptive, or *dynamic*, are the ones which do.

In static routing the choice of the route to use to get from a source node to a destination node is computed in advance, off-line, and uploaded to the nodes when the network is booted. Thus, routing variables do not change during the time. The simplest technique for static routing is based on a shortest path routing algorithm, where the routing objective is to find a routing path of minimum length. The path length in the shortest path routing can be calculated in several ways: the number of hops and the geographic distance are the easiest metrics.

On the other hand, adaptive algorithms, attempt to change their routing decisions to reflect changes in topology and the current traffic. Adaptive algorithms can be further divided into three families, which differ in the routing information they receive. The following types of routing can be distinguished (see Fig. 1):

- *centralized* (or *global*)—a single entity uses information collected from the entire network in an attempt to make optimal decisions,
- *isolated* (or *local*)—a local algorithm runs separately on each node, which only uses information available there, such as e.g., output link congestion,
- *distributed*—uses a mixture of global and local information.

A routing approach such that there is a single path between any pair of nodes and that all traffic between them should use it is usually called *single-path* routing. In many networks, there are several paths between pairs of nodes that are almost equally good. Better performance can frequently be obtained by splitting the traffic over several paths, to reduce the load on each of the communication links. The technique of using multiple routes is called *multi-path* routing. An advantage of multi-path routing over single-path routing is the possibility of sending different classes of traffic over different paths. It can also be used to improve the reliability of the network, in particular, if the routing tables contain disjoint routes.

Alternative routing, often referred to as *deflection* routing, is a special case of multi-path routing. Later we distinguish alternative routing as a technique where all the traffic is sent over a primary routing path. In case the primary path is unavailable for some period of time a secondary, alternative path is selected.

Another distinction in routing algorithms can be with respect to the place where the routing decision is taken. Whilst most of routing algorithms can perform in each node, in *source* routing only the source makes most or all of the routing decisions. Thus, with source routing the entire path to the destination is known to the sender and is included when sending data. Source routing allows a source to directly manage network performance by forcing data to travel over one path to prevent congestion on another.

2.2. Route management in OBS

2.2.1. Hop-by-hop vs. explicit routing

Routing of the burst through an OBS network can be performed either *hop-by-hop*, like in connectionless IP networks, or *explicitly*, like in connection-oriented multi-protocol lambda switching (MPLS) networks. In the hop-by-hop routing a routing decision is taken at each intermediate node and it concerns the selection of (only) next node to which the burst is routed. On the contrary, in explicit routing a set of predefined logical paths, also called the *label switched paths* (LSP), is setup over explicit physical routes. Such a collection of LSPs between various pairs of nodes forms a virtual network on top of the physical fibre network. In the explicit routing the routing decision concerns the selection of a path (or paths) the burst will follow.

Routing decisions in both hop-by-hop and explicit routing are taken based on routing information carried by the burst control packet. On the contrary to the hop-by-hop routing in which the burst destination address is processed at each intermediate node, in the explicit routing an LSP identifier (label) has only to be matched to the

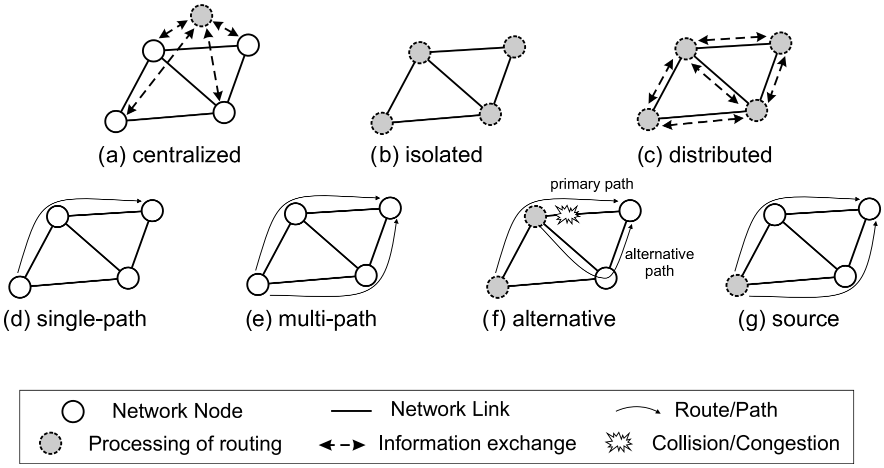


Fig. 1. Routing algorithms.

information stored in the lookup forwarding table. Since this operation is much faster than the processing of the entire burst destination address, explicit routing is a preferable solution for highly dynamic OBS networks. Moreover, explicit routing offers traffic engineering and quality-of-service (QoS) provisioning capabilities and hence it helps to overcome the difficulties of buffer-less OBS network architectures. As a result, the use of labelled optical burst switching (LOBS) has been proposed in [7] as a natural control and provisioning solution under the MPLS framework.

2.2.2. Route calculation and selection

Whichever routing approach is used, either connectionless or connection-oriented, the routing process involves two phases in an OBS network: *route (path) calculation* and *route (path) selection* [8].

In general, route calculation can be performed either centrally in a predestinated node or distributively in individual network nodes. The route calculation can be either static or dynamic. In a static-route calculation, one or more routes are calculated in advance, using some static link metric. For instance, paths can be computed as shortest paths, with respect to either the physical distance or the number of hops, using the Dijkstra algorithm. The static-route calculation is suitable if traffic does not change significantly over time. In some cases, however, it may be appropriate to re-compute the routes dynamically based on certain network statistics, such as link congestion or number of burst contentions, in order to adapt to actual network conditions.

In the route selection phase, one of the candidate paths that have been found during the route calculation phase is selected for the burst transmission. In principle, the route selection phase concerns multi-path routing since in single-path routing a (single) path is unambiguously determined after the route calculation phase. In static multi-path route selection, the decision variables do not change in time and routes are selected for incoming bursts with some fixed order or with an even probability. Dynamic route selection policies are based on the exchange of congestion state information between network nodes. Using this information, a cost function is calculated for each route so that the routes are valuated according to their congestion states. The cost function may either arise from network modelling, in particular, network loss models are frequently applied, or be a result of coarse calculation, e.g., a sum of network link loads. Then either a threshold-based or a probabilistic (traffic splitting) or a rank/priority-based path selection technique reacts accordingly in order to shift some part of traffic to less-loaded links. The threshold-based policy specifies a threshold value above which the routing decision is triggered. The probabilistic policy defines the ratio according to which the traffic is split over candidate paths. The rank-based policy orders paths and selects an available one that has the highest priority. These techniques may apply either an heuristic or an optimization method to adjust their attributes.

The information necessary to make a dynamic route computation or selection can be obtained in two ways, namely probe-based or broadcast-based [8]. In the probe-based approach, the source node sends a probe message into the network. The core nodes respond to the probe and return necessary information to the source. A particular case of probe messaging could be a feedback notification about successful or failed burst transmission. In the broadcast approach, the node is responsible for transmitting relevant congestion information periodically to other nodes. The probe can either be sent once for every connection request or periodically based on some interval. The second option is preferable in OBS networks since the duration of data bursts is usually short. In order to reduce the control traffic in the broadcast approach, the feedback information can be sent only if there is a significant change in the congestion status of a link with respect to the previous value.

2.3. A classification of the OBS routing strategies

In general, the routing strategies proposed for OBS networks in the literature can be classified as either *reactive* or *proactive*. The former comprises deflection routing [9], which is able to change the path used by a contending burst at the node where contention occurs and usually without

Table 1
Alternative routing algorithms in OBS networks.

Ref.	Class	Routing type	Route calculation	Route selection	Features
[9]	Non-adaptive	Isolated	Static	Fixed	–
[14]	Non-adaptive	Isolated	Static	Fixed	–
[15]	Non-adaptive	Isolated	Static	Fixed	–
[16]	Non-adaptive	Isolated	Static	Probabilistic	–
[17]	Non-adaptive	Isolated	Static	Fixed	–
[18]	Non-adaptive	Isolated	Static	Fixed	QoS-aware
[19]	Non-adaptive	Isolated	Static	Fixed	–
[20]	Non-adaptive	Isolated	Static	Fixed	–
[21]	Non-adaptive	Isolated	Optimized	Fixed	–
[22]	Adaptive	Centralized	Optimized	Fixed	QoS-aware
[23]	Adaptive	Centr. & Distrib.	Optimized	Threshold-based	QoS-aware
[24]	Adaptive	Centralized	Optimized	Probabilistic	QoS-aware
[25]	Adaptive	Distributed	Static	Rank-based	–
[26]	Adaptive	Distributed	Static	Threshold-based	–
[27]	Adaptive	Isolated	Static	Rank-based	–

awareness of network congestion in the downstream links of the new burst path. In theory, deflection routing has local load balancing properties, since the network nodes will more likely find available wavelengths on their lesser congested output links. Therefore, whenever needed, the nodes are able to shift burst traffic from their most congested output links to lesser congested ones. A recent comparative study of deflection routing strategies can be found in [10].

Proactive routing strategies use either measurements of the congestion at all of the network links or anticipated traffic demands to optimize, usually off-line, the set of paths and the distribution of traffic between ingress and egress network nodes. The goal is to minimize the probability of contention at the core nodes by balancing the burst traffic load across the network links. These routing path optimization strategies have recently received considerable attention [11], using as input the long-term network and traffic information, such as the network topology and average offered traffic load values, to compute paths for pairs of network nodes. Since they depend on the knowledge of the traffic load offered between all ingress and egress nodes, they can only update the routing paths in response to changes in the network and traffic conditions taking place over relatively long time scales. Both reactive and proactive routing methods were studied and compared in [12,13]. In [12] it was shown that a method based on combined reactive and proactive routing can reduce network congestion very effectively since it benefits from both long-term global and short-term local congestion state information when taking routing decisions.

A great number of reactive and proactive routing algorithms have been proposed for OBS networks in the literature. These algorithms can be further categorized as alternative (deflection), multi-path (source-based), and single-path routing algorithms. In the remainder of this section we review the main routing concepts corresponding to each category. For the clarity of presentation the references are listed in Tables 1–3. The keywords used in the tables correspond essentially to the definitions presented through Sections 2.1–2.3. The entries of the tables are ordered with respect to successive criteria.

2.3.1. *Alternative routing*

A great part of research on the routing problem in OBS networks concerns alternative routing. In alternative routing, when the burst contention occurs, a deflective mechanism reacts to it and re-routes a blocked burst from the primary to an alternative route. Deflection routing can be combined with other burst contention resolution mechanisms [18,28].

Routing strategies considered for alternative routing in OBS networks can be either non-adaptive or adaptive.

In non-adaptive alternative routing both primary and alternative routing paths are fixed (static), and in most cases calculated with the Dijkstra algorithm. A number of alternative paths can be given from a source to a destination. Routing decision is taken in isolation, based only on local node congestion state information. Finally, the routes are selected in a fixed way, for instance, according to the first-fit policy or with even probability.

Adaptive alternative routing strategies apply a proactive calculation of alternative paths as well as their dynamic selection. The calculation of alternative paths is performed in an optimized way, usually with the assistance of linear programming formulations. These methods require the information about network topology and traffic demands. Regarding the dynamic alternative route selection, some heuristics methods are used, and they include either threshold-based or path rank (priority) or probabilistic route selection techniques. The adaptability of these techniques to the changes in the network state is achieved either in a centralized or in a distributed way.

Some of alternative routing strategies, especially the adaptive ones, support the QoS provisioning by differentiation of the routing decision with respect to the traffic class.

Table 1 summarizes the key literature on alternative routing in OBS networks.

2.3.2. *Multi-path routing*

In OBS networks, multi-path routing strategies aim at a dynamic (adaptive) distribution of traffic over candidate paths in order to balance load and reduce congestion in the network.

The calculation of candidate paths is performed mostly with the Dijkstra shortest path algorithm; the application

Table 2
Adaptive multi-path routing algorithms in OBS networks.

Ref.	Routing type	Route calculation	Route selection	Selection method
[11]	Centralized	Optimized	Probabilistic	Optimized
[29]	Centralized	Static	Probabilistic	Optimized
[30]	Centralized	Static	Probabilistic	Optimized
[31]	Distributed	Static	Probabilistic	Heuristic
[32]	Distributed	Static	Probabilistic	Heuristic
[33]	Distributed	Static	Probabilistic	Heuristic
[34]	Distributed	Static	Probabilistic	Optimized
[8]	Distributed	Static	Rank-based	Heuristic
[35]	Distributed	Static	–	Heuristic
[36]	Distributed	Static	Rank-based	Heuristic
[37]	Distributed	Static	Rank-based	Heuristic
[38]	Distributed	Static	–	–
[39]	Distributed	Static	Rank-based	Heuristic

Table 3
Adaptive single-path routing algorithms in OBS networks.

Ref.	Routing type	Route calculation	Information	Features
[41]	Centralized	Optimized	Traffic demands	–
[42]	Centralized	Optimized	Traffic demands	–
[43]	Centralized	Optimized	Traffic demands	Failure-aware
[44]	Centralized	Optimized	–	–
[11]	Centralized	Optimized, Heuristic	Traffic demands	–
[45]	Centralized	Optimized, Heuristic	Traffic demands	Failure-aware
[46]	Centralized	Heuristic	–	–
[47]	Centralized	Heuristic	Traffic demands	–
[48]	Distributed	Heuristic	Broadcasted	Failure-aware
[49]	Distributed	Heuristic	Broadcasted	Failure-aware
[50]	Distributed	Heuristic	Broadcasted	Failure-aware

of optimization methods is occasional. In practice a small number of disjoint shortest paths is calculated between each source–destination pair of nodes and with respect to the number of hops.

The multi-path routing algorithms proposed for OBS take routing decisions at the source node. The selection of path is performed for each burst either according to a given probability, so that the traffic load is split over available paths, or according to the path rank, so that the currently highest ranked path is selected. The traffic splitting vector is calculated in a centralized way using some optimization method, or in a distributed way, mostly by applying an heuristic calculation. A ranking of less congested paths is usually obtained by means of heuristics and is applied in distributed routing algorithms. All distributed methods require the congestion state information of intermediate/destination nodes to be updated on the source nodes. The signalling messages can be either broadcasted or sent triggered by some events, for instance, the burst dropping events.

Table 2 summarizes the key literature on multi-path routing in OBS networks.

2.3.3. *Single-path routing*

Both non-adaptive (static) or adaptive (dynamic) strategies are considered for single-path routing in OBS networks. Static routing is usually based on Dijkstra's shortest path calculation with respect to the number of hops [40].

The main objective of adaptive single-path routing is to avoid the burst congestion by applying a proactive path calculation. The path calculation can be performed either in a centralized or in a distributed way. Centralized (or pre-planned) routing in OBS, in most cases, makes use of optimization methods, such as (mixed) integer linear programming methods. For this purpose, the route computation element should have a knowledge of the network topology and (long-term) traffic demands. On the contrary, distributed routing algorithms employ some heuristics to process the information that is being exchanged between network nodes. In particular, the node state statistics are broadcasted, usually in a periodical manner, so that the network link weights (costs) are calculated in the respective nodes. Then a Dijkstra-like algorithm is applied in order to find the lowest cost route. Some adaptive single-path routing strategies support network resilience by computing backup paths which can be used in case of failures.

Table 3 summarizes the key literature on adaptive single-path routing in OBS networks.

3. OBS network modelling

In this section, we review basic analytical models proposed for OBS networks with explicit routing. The presented models are based on the information of traffic demands and for a given set of candidate routing paths allow to estimate, in the first instance, the traffic load offered to network links and, in the second instance, the burst loss probability in the entire network. These models, together with appropriate optimization procedures, can be effectively applied in load balancing routing algorithms, as described in the next section.

3.1. Network and traffic model

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

For the simplicity of analysis it is convenient to use the so-called path-link formulation when representing a network and the corresponding routing model [51]. In such formulation we assume that the set of paths is given between network nodes and each path is identified by a subset of network links (as in [30]). Other possibility would be to use a link-node formulation (see e.g., [11]), in which network flow variables are associated with individual links, instead of individual paths. Although such representation allows to explore any route in the network, it increases significantly the complexity of a related routing problem.

Therefore, let $\mathcal{P}$ denote the set of paths predefined between source s and destination d nodes, $s, d \in \mathcal{V}$, and $s \neq d$. Each individual path $p \in \mathcal{P}$ is identified with a subset $p \subseteq \mathcal{E}$. Adequately, subset $\mathcal{P}_e \subseteq \mathcal{P}$ identifies all paths that go through link e.

The reservation (holding) times on each link are independent and identically distributed random variables with the mean equal to the mean burst duration h; for simplicity we assume $h = 1$. The demand traffic pattern is described by matrix $[t_{sd}]_{s,d\in\mathcal{V}}$ and bursts destined to given node d arrive at node s according to a Poisson process of (long-term) rate $t_{sd}/h = t_{sd}$. It should be stressed that although such an assumption may not correspond to the real nature of burst traffic (e.g., self-similar), it has the advantage of making the problem analytically treatable. Evaluation results presented in Section 5 show that routing optimization under such assumption improves performance even when the burst traffic has different properties from those of Poisson.

Later we use ρ_p and ρ_e to denote the traffic offered to path $p \in \mathcal{P}$ and the traffic offered to link $e \in \mathcal{E}$, respectively.

3.2. Calculation of link loads

A common method of the link load calculation in an OBS network was proposed by Rosberg et al. [52] and it makes use of the so-called *reduced load* (RL) calculation. This model is an extension of the model proposed by Kelly [53] for circuit switching (CS) networks. In the OBS network, it is assumed that the traffic offered to link e is obtained as a sum of the traffic offered to all the paths that cross this link reduced by the traffic lost in the preceding links along these paths. This relation can be expressed as:

$$\rho_e = \sum_{p\in\mathcal{P}_e} \rho_p \Lambda_{pe}, \quad e \in \mathcal{E}, \tag{1}$$

where

$$\Lambda_{pe} = \prod_{g\in r_{pe}} \left(1 - E_g\right), \quad p \in \mathcal{P},\ e \in \mathcal{E}, \tag{2}$$

with subset $r_{pe} \subset p$ identifying all links that precede link e along path p, whilst E_g represents the fraction of traffic lost in each of those links.

The difference between this model and the CS network model is that in the latter the subset r_{pe} contains all the links that succeed link e along path p, on top of all preceding links. This difference reflects the fact that a burst offered to path p in OBS uses a single wavelength from each link along the path until the first link where it is being blocked or until it exists in the network. On the contrary, a connection in CS either occupies a channel in all the links along the path or is blocked.

The main difficulty in the RL model is the calculation of losses E_e in network links. Indeed, there is no closed-form expression to compute link losses if a wavelength-continuity constraint (i.e., a burst cannot change the wavelength) is imposed in the network. Therefore, the common simplification in the literature is that the network has a full wavelength conversion capability, i.e., any wavelength can be assigned to a burst in a link if only it is available. In such case the blocking probability E_e on each link is given by the following Erlang loss formula (see [52]):

$$E_e = E(\rho_e, C_e) = \frac{\rho_e^{C_e}}{C_e!}\left[\sum_{i=0}^{C_e} \frac{\rho_e^i}{i!}\right]^{-1}, \quad e \in \mathcal{E}. \tag{3}$$

The calculation of link loss probabilities E_e, $e \in \mathcal{E}$, together with the calculation of offered burst traffic ρ_e, given by the reduced load model (1), leads to a fixed point equation with a solution known as the *Erlang fixed point*. The fixed point cannot be solved in a closed form but its approximation can be found through repeated substitution of (3) in (1). It is known that the fixed point exists in both CS and OBS networks (see [53] and [52], respectively). Although the fixed point is unique in CS networks, still, its uniqueness has not been proved in OBS networks.

Although, according to our assumption, the traffic offered to a route is Poisson, still it may be thinned by blocking at the consecutive links and thus no longer follows the Poisson statistics. Since there is no straightforward solution to this problem the common simplification is that the burst arrival process to each link is assumed to be Poisson.

Eq. (1) may bring some computational difficulties, especially, with regard to the calculation of partial derivatives for optimization purposes. Also, it can hardly be used in linear programming formulations due to its non-linear character. Therefore, it is sometimes convenient to consider a simplified *non-reduced load* (NRL) model, where the traffic offered to link e is calculated as a sum of the traffic offered to all paths that cross this link:

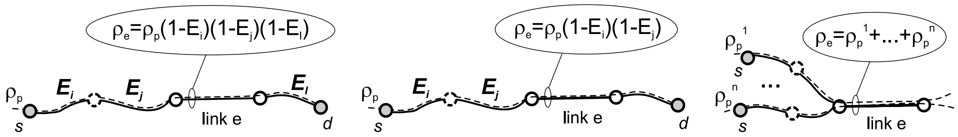
$$\rho_e = \sum_{p\in\mathcal{P}_e} \rho_p, \quad e \in \mathcal{E}. \tag{4}$$

The rationale behind this assumption is that under low link losses E_g, $g \in \mathcal{E}$, observed in a properly dimensioned network, model (1) can be approximated by (4).

Fig. 2(a)–(c) present illustrative examples of the reduced load calculation for both CS and OBS networks, as well as of the non-reduced load calculation.

3.3. Network loss models

Having calculated traffic loads ρ_e offered to individual links, given by (1) or (4), and burst loss probabilities E_e



(a) Reduced load model in CS networks.
(b) Reduced load model in OBS networks.
(c) Non-reduced load model.

Fig. 2. Link load models.

on links, given by (3), in the next step we may estimate the network-wide burst loss/blocking probability. Such a calculation for an OBS network has been presented in [52], and it uses the same formulation as the one proposed for CS networks [53]. Hereafter, we name this model an overall network loss (NL) model. The main modelling steps include the calculation of loss probabilities L_p of bursts offered to paths, according to:

$$L_p = 1 - \prod_{e \in p} (1 - E_e), \quad p \in \mathcal{P}, \tag{5}$$

and the overall burst loss probability B_{NL}, given by:

$$B_{\mathrm{NL}} = \sum_{p \in \mathcal{P}} \rho_p L_p \left[\sum_{p \in \mathcal{P}} \rho_p \right]^{-1}. \tag{6}$$

In the NL model, in order to calculate the path loss probability L_p, $p \in \mathcal{P}$, we assume that burst blocking events occur independently at the network links. Consequently, Eq. (5) accounts for blocking probabilities in all links e that belong to path p. Finally, the overall burst loss probability B_{NL} is calculated simply as the volume of burst traffic lost in the network normalized to the volume of burst traffic offered to the network.

Another approximate method for calculation of burst losses in the entire network is based on an overall link loss (LL) model [54]. In this method we simply sum up the volumes of traffic lost on individual network links. Accordingly, such a sum relative to the overall traffic offered to the network, denoted as B_{LL}, can be expressed as:

$$B_{\mathrm{LL}} = \sum_{e \in \mathcal{E}} \rho_e E_e \left[\sum_{p \in \mathcal{P}} \rho_p \right]^{-1}. \tag{7}$$

Note that LL overestimates actual burst losses given by (6) in NL, because it counts twice the intersection of blocking events that occur on distinct links. In fact, B_{LL} may be greater than 1 and thus it cannot be considered as the probability metric. Nevertheless, for $E_e \to 0$, $e \in \mathcal{E}$, the blocking events that occur simultaneously vanish rapidly and model (7) converges to model (6).

Eventually, taking into account different methods to describe the link load and the network loss calculation, which were presented above, several network loss models can be distinguished.

1. *NL–RL*. The link load is calculated according to the RL model given by (1), and the network loss is calculated according to the NL model given by (6):

   $$B_{\mathrm{NL\text{-}RL}}(\boldsymbol{\rho}) = \sum_{p \in \mathcal{P}} \rho_p L_p^{(\mathrm{RL})}, \tag{8}$$

   where $L_p^{(\mathrm{RL})}$ denotes that L_p is calculated under the RL model.
2. *NL–NRL*. The link load is calculated according to the NRL model given by (4), and the network loss is calculated according to the NL model given by (6):

   $$B_{\mathrm{NL\text{-}NRL}}(\boldsymbol{\rho}) = \sum_{p \in \mathcal{P}} \rho_p L_p^{(\mathrm{NRL})}, \tag{9}$$

   where $L_p^{(\mathrm{NRL})}$ denotes that L_p is calculated under the NRL model.
3. *LL–NRL*. The link load is calculated according to the NRL model given by (4), and the network loss is calculated according to the LL model given by (7):

   $$B_{\mathrm{LL\text{-}NRL}}(\boldsymbol{\rho}) = \sum_{e \in \mathcal{E}} \rho_e E_e = \sum_{e \in \mathcal{E}} E_e \left(\sum_{p \in \mathcal{P}_e} \rho_p \right). \tag{10}$$

In the argument of function B there is the vector $\boldsymbol{\rho}$ of traffic loads ρ_p offered to network paths. In each case, the normalization factor $[\sum_{p \in \mathcal{P}} \rho_p]^{-1}$ has been omitted because we assume it to be a constant value.

The last possible combination of the link load and the network loss calculation is LL–RL. Because such a model does not bring much gain with respect to the NL–RL one, since it does not avoid the complexity of fixed point calculation, we do not consider it in this analysis.

In [55] we studied the accuracy of both NR–NRL and LL–NRL network loss approximations relative to NL–RL, which is a well-known OBS network loss model. The accuracy of both approximate models is very strict for the blocking probability in the network below 10^{-2}. Therefore, we can assume that any of the presented analytical models can be effectively applied for network optimization purposes as far as the network is properly dimensioned, i.e., it experiences low burst losses.

4. Optimization methods for load balancing routing in OBS

In this section, we will focus on load balancing methods that apply multi-path source routing and make use of analytical models presented in the previous section. The multi-path routing approach allows to improve network performance by splitting the offered traffic over several paths, permitting to reduce the load on the more congested links. In addition, source routing allows a source to directly control network performance by forcing data to travel over one path to prevent congestion on another. We assume a probabilistic traffic splitting approach, i.e., a fraction of traffic load is routed over each candidate path.

We present two routing optimization methods that are based on (1) linear and (2) non-linear problem

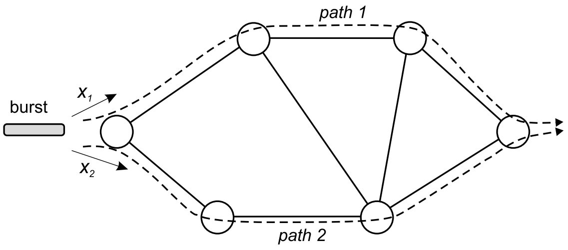


Fig. 3. An OBS network with multi-path source routing; x_1 and x_2 are the traffic splitting factors such that $x_1 + x_2 = 1$.

formulations. The common idea behind these methods is to solve an optimization problem in order to find a vector of average fractions (splitting factors) of burst traffic routed through the candidate paths such that minimize the burst contention. In a network scenario, the calculated traffic splitting factors, when uploaded to source nodes, can be used to make routing decisions, such as selection of routing paths, for individual bursts or flows of bursts.

Throughout this section we use the notation that was introduced in the previous section.

4.1. A multi-path routing model

In the considered model of multi-path routing, subset $\mathcal{P}_{sd} \subseteq \mathcal{P}$ identifies all paths from source s to destination d. Each subset $\mathcal{P}_{sd}$ comprises a (small) number of paths, e.g., k shortest paths, and a burst can follow one of them. The sets $\mathcal{P}_{sd}$ are disjoint in the model. Moreover, we assume that the network applies source-based routing, so that source determines the path of a burst that enters the network (see Fig. 3). We assume that the selection of a route from set $\mathcal{P}_{sd}$ is random for each burst and is performed according to a given traffic splitting factor x_p, such that

$$\sum_{p \in \mathcal{P}_{sd}} x_p = 1, \quad s, d \in \mathcal{V}, s \neq d. \tag{11}$$

$$0 \leq x_p \leq 1, \quad p \in \mathcal{P}. \tag{12}$$

The first set of constraints guarantees that the entire traffic load offered between a pair of nodes is offered to the available candidate paths, while the second set of constraints assures that x_p is a positive fractional number.

Thus traffic ρ_p offered to path $p \in \mathcal{P}_{sd}$ can be calculated as

$$\rho_p = x_p \tau_p, \tag{13}$$

where $\tau_p = t_{sd}$ is the total traffic offered between s and d.

Here, vector $\boldsymbol{x} = (x_1, \ldots, x_{|\mathcal{P}|})$ determines the distribution of traffic over the network. This vector should be optimized to reduce congestion and to improve overall performance.

4.2. A link congestion reduction optimization method

The main objective of this method is to reduce congestion at the bottleneck links by reducing the burst traffic load offered to those links. Clearly, contention will occur more often in the most congested links of the network (bottleneck links), wherein the limited number of wavelengths is being shared by the largest amount of burst traffic.

Assuming that the OBS network is operated with small burst losses, the traffic load offered to link ρ_e, $e \in \mathcal{E}$, accounting for losses at the preceding nodes, does not significantly differ from the traffic load observed in the absence of losses, and it can be estimated with (4). Under this assumption, and since ρ_e is a linear function of $\rho_p, p \in \mathcal{P}$, the problem of traffic load distribution over the set of candidate paths can be solved using Linear Programming (LP).

The following LP models can be sequentially solved to obtain the path load distribution that minimizes the traffic load offered to the bottleneck link at the expense of minimum increase on the average offered traffic load per link. Let y be a variable which represents the average offered traffic load on the bottleneck link. In the first instance we solve the following problem:

(LP1) minimize y

subject to

$$\sum_{p \in \mathcal{P}_e} x_p \tau_p - y \leq 0, \quad e \in \mathcal{E}, \tag{14}$$

and subject to the multi-path routing constraints given by (11) and (12).

In this formulation, the first set of constraints (14) is used to obtain the average offered traffic load on the bottleneck link.

Although (LP1) minimizes the average offered traffic load on the bottleneck link, multiple solutions for this problem may exist and some of which can exploit longer paths, increasing resource utilization. Therefore, a second LP model can be formulated in order to determine the routing solution which minimizes the traffic load on the bottleneck link with minimum increase of the average traffic load offered to the remaining network links. Let y^* be an optimal solution of LP1. In the second instance we solve the problem:

(LP2) minimize $\sum_{e \in \mathcal{E}} \sum_{p \in \mathcal{P}_e} x_p \tau_p$

subject to

$$\sum_{p \in \mathcal{P}_e} x_p \tau_p \leq y^*, \quad e \in \mathcal{E}, \tag{15}$$

and subject to the multi-path routing constraints given by (11) and (12).

In (15) we constraint the value of the average offered traffic load on a link to the solution y^* of LP1.

Since all variables x_p, $p \in \mathcal{P}$, and y are real numbers, the LP models are expected to be promptly solved even for large-sized networks.

4.3. A network-wide BLP optimization method

A load balancing method presented below aims at the optimization of overall burst loss probability (BLP). The network-wide BLP is the primary metric of interest in an OBS network since it adequately reflects the congestion state of the entire network. In the optimization problem, this metric is represented by a properly selected objective function. To define the objective function any of the network loss models presented in Section 3.3 may be used. In particular, such objective function $B(\boldsymbol{x})$ can be defined from (8) and (9), or (10), respectively as, $B_{\text{NL-RL}}(\boldsymbol{x})$, $B_{\text{NL-NRL}}(\boldsymbol{x})$, or $B_{\text{LL-NRL}}(\boldsymbol{x})$, with the argument $\boldsymbol{x}$ replacing ρ according to (13). Note that the usefulness of the approximate loss models is justified by their high accuracy, as discussed in [55].

The same formulation of optimization problem is given for each variant of the objective function $B(\boldsymbol{x})$, namely:

(NLP) minimize $B(\boldsymbol{x})$

subject to the multi-path routing constraints given by (11) and (12).

Since in each case $B(\boldsymbol{x})$ is a non-linear function of problem variables $\boldsymbol{x}$, NLP is a Non-Linear Programming problem. Taking into account the form of network loss model constraints (1) and (4), which have to be incorporated into the problem, a particularly convenient optimization method is the Frank–Wolfe reduced gradient method (algorithm 5.10 in [51]); this algorithm was used for a similar problem in circuit switched (CS) networks [56].

Another option for solving the problem is to simplify and represent the objective function by its piecewise linear approximation, e.g., as in [11], and solve the resulting problem as an LP problem. This solution might be very effective computationally (at the expense of lower accuracy), however, it is out of the scope of this article.

4.3.1. *Calculation of partial derivatives*

In general, gradient methods are iterative methods used in the optimization of non-linear functions. Gradient methods require the calculation of partial derivatives of the objective function (i.e., the gradient) as a way to find the direction of improvement of this function. In [55] we provide appropriate formulae for the gradient calculation for each of the considered objective functions of NLP. Below we summarize the main results.

The partial derivative of $B_{\text{NL-RL}}$ with respect to x_q, $q \in \mathcal{P}$, can be derived directly by a standard method involving the solution of a system of linear equations. Nevertheless, there is some difficulty in the method since it involves an iterative fixed point approximation procedure, with repeated recalculation of partial derivative equations. Therefore, the calculation of partial derivatives in the NL–RL model is extremely time consuming.

The partial derivative of $B_{\text{NL-NRL}}$ with respect to x_q, $q \in \mathcal{P}$, could be derived directly by a standard method involving the resolution of a system of linear equations, similarly to NL–RL. Although there is no need for a fixed point calculation in the NL–NRL model, still such a computation would be time consuming. Therefore, in [30] we propose instead a fast exact calculation based on Kelly's approach [57] for CS networks. The gradient calculation in the NL–NRL model is no longer an issue.

Finally, the partial derivative of $B_{\text{LL-NRL}}$ with respect to x_q, $q \in \mathcal{P}$, can be derived directly from formulae (3), (4) and (10); see [55] for details.

4.3.2. *Properties of the objective function*

In [57] Kelly shows that the reduced load loss model of a CS network is in general not convex. Taking into account an analogy of the reduced load calculation in both CS and OBS networks, we can expect that function (8) is not convex as well. Therefore, a solution of optimization problem NLP may not be unique.

Similarly as in case of the RL–NL model, it can be shown numerically that the objective function (9) is not necessarily convex; in particular, under high traffic load conditions, there can be found 2 feasible vectors $\mathbf{x}_1, \mathbf{x}_2$, such that:

$$B_{\text{NL-NRL}}(\lambda\mathbf{x}_1 + (1-\lambda)\mathbf{x}_2) > \lambda B_{\text{NL-NRL}}(\mathbf{x}_1) + (1-\lambda)B_{\text{NL-NRL}}(\mathbf{x}_2), \tag{16}$$

where $0 \le \lambda \le 1$.

Eventually, an advantageous property of the LL–NRL model is the convexity of its objective function (10); a detailed proof can be found in [58]. For this reason, a corresponding optimization problem has a unique solution.

4.3.3. *Computational effort*

In Table 4 we compare the computation times of both the objective function (with the gradient calculation included) and the `fmincon` solver function for solving constrained non-linear optimization problems in the MATLAB environment; in the table they are denoted as OF and SOLV, respectively. For comparison, in the last column we provide the computation times for the LP method presented in Section 4.2 and solved with the LP solver of [59]. The evaluation is performed on a Pentium D, 3 GHz computer. The results are obtained for SIMPLE (6 nodes, 8 links, and 60 paths) and NSF (14 nodes, 21 links, and 364 paths) mesh network topologies (both depicted in Fig. 4), and larger EON28 network (28 nodes, 39 links, and 1512 paths). The number of wavelengths per link is 32, each source–destination pair of nodes has $k \in \{2, 4\}$ shortest paths available, the traffic load is equal to 25.6 Erlangs and 9.6 Erlangs, respectively, for SIMPLE/NSF and EON28 scenarios. In case the iterative procedure of the Erlang fixed point approximation is used, this calculation terminates if the maximal discrepancy between two consecutive link loss calculations is smaller then 10^{-6}. The starting traffic splitting vector is $\mathbf{x} = k^{-1} \cdot (1, \ldots, 1)$, meaning that the traffic is equally distributed over the paths computed for routing each demand. The termination tolerance parameter of the `fmincon` solver function is setup to 10^{-6} for all scenarios except the last EON28 scenario for which it is equal to 10^{-3}.

We can see that the calculation of the objective function and the gradient is highly time consuming in the NL–RL model, even in a small network scenario. On the contrary, such a calculation is not an issue if either NL–NRL or LL–NRL model is used. It is worth to mention that by decreasing the value of the termination tolerance parameter, which determines the termination condition of the solver function, we significantly accelerate the optimization procedure (more than three times) without substantial decreasing the routing performance (compare 'BLP' value in both EON28 scenarios). Moreover, we can see that when increasing the number of paths the computation time of the solver function increases considerably in a larger (NSF) network scenario. Also, the application of fast gradient calculation in NL–NRL speeds up significantly computations with respect to the standard method.

Table 4
Comparison of computation times.

Network	Paths	BLP	NL–RL		NL–NRL			LL–NRL		LP (s)
			OF	SOLV	OFs[a] (s)	OFf[b] (s)	SOLV (s)	OF (s)	SOLV (s)	
SIMPLE	2	$2.4 \cdot 10^{-3}$	64 s	1.5 s	0.3	0.1	1.4	0.1	1.4	–
SIMPLE	4	$2.4 \cdot 10^{-3}$	243 s	3 s	0.46	0.1	3.4	0.1	3.1	–
NSFNET	2	$4.6 \cdot 10^{-2}$	>5 h		9.9	0.38	22.3	0.37	24	0.18
NSFNET	4	$3.1 \cdot 10^{-2}$	>5 h		139	1.3	850	1.1	852	0.31
EON28	2	$3.07 \cdot 10^{-2}$	>5 h		1483	7.4	1757	7.2	1789	–
EON28[c]	2	$3.09 \cdot 10^{-2}$	>5 h		356	1.8	509	1.6	508	–

[a] Standard gradient calculation method is used.
[b] Fast gradient calculation method (as in [30]) is used.
[c] The termination tolerance parameter is equal to 10^{-3}.

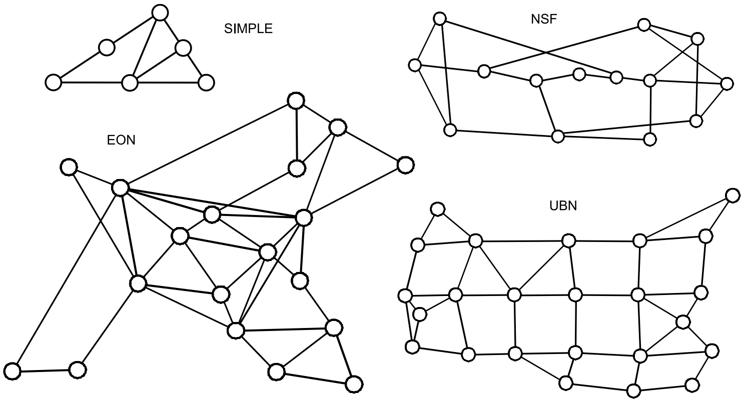


Fig. 4. Reference network topologies.

Finally, the computation times of the LP method (see last column) are significantly faster than of the non-linear optimization method, what is expected in view of the simpler approach. It is worth to mention that the computation times of this latter method might be possibly improved since to solve the problem we used a general-purpose solver function of MATLAB, which was not optimized for this method.

5. Numerical results

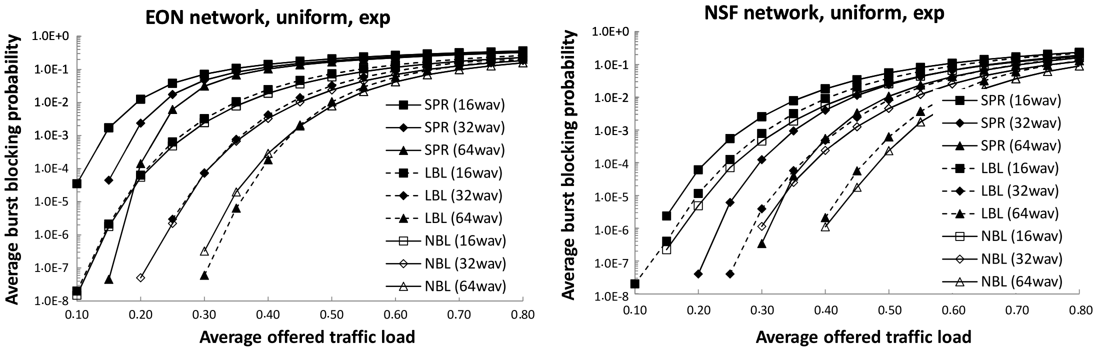
In this section, we evaluate the average (network-wide) Burst Loss Probability (BLP) performance of (proactive) multi-path source routing that operates with optimized traffic splitting vectors, calculated by linear and non-linear optimization methods presented in the previous section. In the remainder, the routing algorithm that applies the LP optimization method (see Section 4.2) is referred to as the Load Balancing based on Lossless approximation (LBL) algorithm, whereas the algorithm using the NLP optimization method (see Section 4.3) is referred to as the Network-wide Burst Loss model-based (NBL) algorithm. NBL makes use of the NL–NRL network loss model. As a reference, a Shortest Path Routing (SPR) algorithm is considered. In this study, static traffic conditions are assumed, i.e., long-term traffic demands are given and they do not change during the evaluation period.

5.1. *Evaluation scenario*

The evaluation of algorithms is performed using an event-driven OBS network simulator. The LP and NLP optimization problems are solved using, respectively, the LP solver of [59] and the `fmincon` solver of the optimization toolbox of MATLAB.

The 14-node NSF, the 19-node COST239 European Optical Network (EON), and the 24-node US Backbone Network (UBN) reference network topologies are used (see Fig. 4). The OBS network has $C \in \{16, 32, 64\}$ wavelengths per link, a wavelength capacity of 10 Gb/s, a switch fabric configuration time of 10 μs, and an average burst size of 100 kB. A negative exponential distribution is used for burst size, whereas the burst inter-arrival time (IAT) follows either an exponential or a log-normal distribution. The log-normal distribution is parameterized [60] for a coefficient of variation equal to 10, with this coefficient being defined as the ratio between the variance of the inter-arrival time and the square of the average value of the inter-arrival time. Using this distribution significantly increases traffic burstiness when compared to the case of an exponential distribution, which has a unitary coefficient of variation.

Let Γ denote the average offered traffic load per link normalized to the network capacity under the assumption of shortest path routing. A uniform traffic pattern is assumed for all topologies. Apart from that, a non-uniform traffic pattern is considered for the UBN network. In this case, the traffic matrix is built by going through all node pairs $s, d \in \mathcal{V}$ with $s \neq d$ and randomly generating with equal probability an integer number m such that $1 \leq m \leq M$ and $M \in \{10, 20\}$. For a given node pair, m represents the ratio between the average traffic load offered to the node pair and that offered to a node pair with $m = 1$.



(a) The EON network.

(b) The NSF network.

Fig. 5. BLP as a function of the average offered traffic load under uniform traffic.

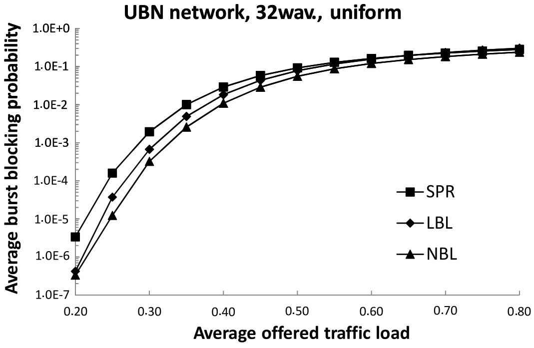


Fig. 6. BLP as a function of the average offered traffic load under uniform traffic in the UBN network.

Each source–destination pair of nodes has $k = 2$ candidate shortest paths (not necessarily disjoint) available for the NBL routing algorithm. The set of candidate paths for the LBL algorithm is generated with an upper bound on the number of hops equal to 12.

All the simulation results have 95% level of confidence.

5.2. Uniform and non-uniform traffic

Fig. 5(a) and (b) plot the average BLP as a function of Γ under uniform traffic with exponential burst IATs for different number of wavelengths per link for the EON and the NSF network, respectively. In both networks we can observe similar results. Both LBL and NBL outperform SPR, whichever link dimension is given. The performance gain of multi-path routing is significant, especially under low and moderate traffic loads. Comparing LBL and NBL, we can see that optimization methods used in both algorithms allow to achieve similar results, with a slight prominence of NBL that benefits from the application of a more accurate network loss model. It is worth to notice that NBL distributes the load very effectively over the network, even when it explores only $k = 2$ paths per each source–destination pair of nodes. Similarly, although LBL may distribute traffic over a large number of candidate paths, still it makes use of at most two paths per node pair in our simulations.

In Fig. 6 we can see that the gain of multi-path routing over shortest path routing may not be so high in a network that is relatively well balanced in terms of the node connectivity, such as the UBN network. Indeed, in such network there is no significant bottlenecks even when routing is just made through the shortest paths. To show that this behavior is maintained for other traffic patterns, we present in Fig. 7 results for $M = 10$ and $M = 20$, considering the case of non-uniform traffic.

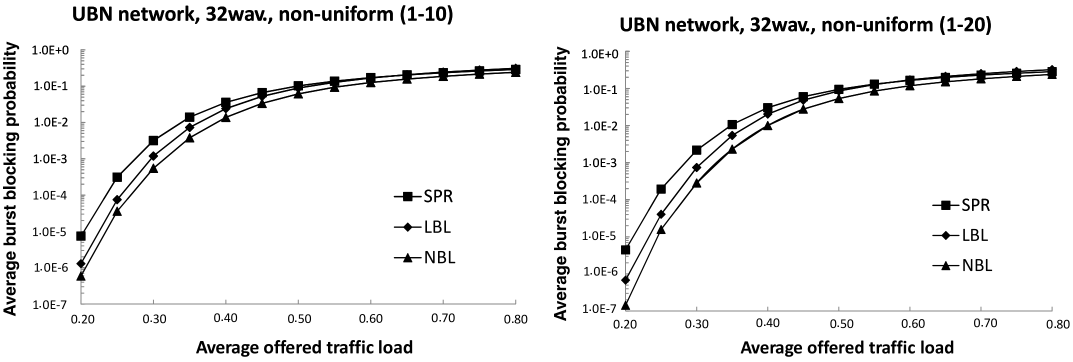
5.3. Non-Poisson traffic

Apart from the above results obtained for exponentially distributed burst inter-arrival times, in Fig. 8 we present performance results obtained for log-normal distributed IATs. First we can observe that in the presence of other traffic characteristics than the Poisson ones, the studied routing optimization models preserve their properties and allow to improve the network performance, in comparison to SPR, even they are based on different traffic assumptions. As an additional conclusion it must be referred that both linear and non-linear optimization methods achieve equally good results in the whole range of traffic loads.

6. Concluding remarks

In this article we have focused on the routing problem in optical burst switching networks. We have presented a broad overview of routing algorithms considered for OBS and, in the rest of the paper, we have addressed the issues of OBS network modelling and routing optimization. The case study has concerned multi-path source routing approach for which we have proposed two alternative solutions based on linear and non-linear optimization methods. The algorithms presented are appropriate for proactive load balancing routing with the aim of improving the network-wide burst loss performance. To support the discussion we have also presented simulation results obtained in a set of unified network scenarios.

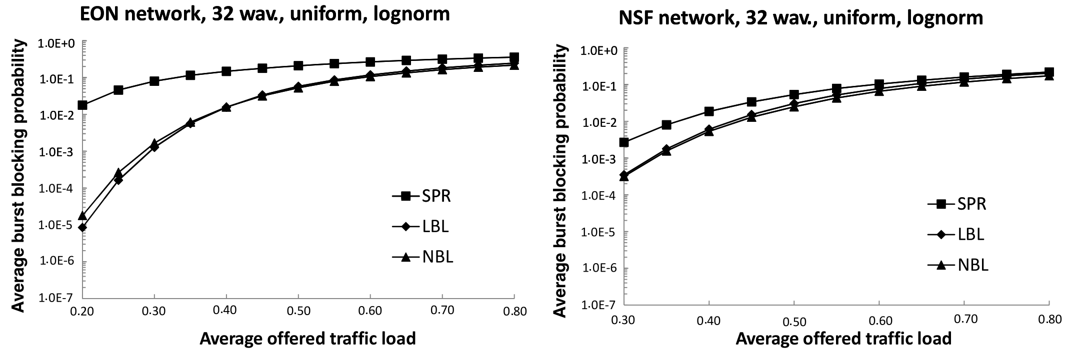
The intention of this article was to review the state-of-the-art literature on routing algorithms, network models, and optimization methods, in order to identify directions for further research, instead of covering completely all the issues related to the routing problem in OBS networks. Our study shows that both linear and non-linear optimization methods deal effectively with the routing problem in OBS networks. Proposed methods are designed



(a) Traffic pattern 1–10.

(b) Traffic pattern 1–20.

Fig. 7. BLP as a function of the average offered traffic load under non-uniform traffic.



(a) The EON network.

(b) The NSF network.

Fig. 8. BLP as a function of the average offered traffic load with log-normal burst IAT distribution.

in particular for networks with a full wavelength conversion capability. To support networks with wavelength-continuity constraints imposed, more advanced network loss models are required. It must be noticed that so far few routing solutions intended for wavelength conversion-less networks have been proposed in the literature. Another observation that may stimulate research is that optimization-based proposals can hardly be found for the problem of quality of service routing in OBS. Finally, another problem, perhaps not much easier even if feasible, concerns optimized distributed single-path routing.

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