Edge-Node Deployed Routing Strategies for Load Balancing in Optical Burst Switched Networks

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Optical burst switching is a promising switching paradigm for the next IP-over-optical network backbones. However, its burst loss performance is greatly affected by burst contention. Several methods have been proposed to address this problem, some of them requiring the network to be flooded by frequent state dissemination signaling messages. In this work, we present a traffic engineering approach for path selection with the objective of minimizing contention using only topological information. The main idea is to balance the traffic across the network to reduce congestion without incurring link state dissemination protocol penalties. We propose and evaluate two path selection strategies that clearly outperform shortest path routing. The proposed path selection strategies can be used in combination with other contention resolution methods to achieve higher levels of performance and support the network reaching stability when it is pushed under stringent working conditions. Results show that the network connectivity is an important parameter to consider.

Keywords: Optical networks, optical burst switching, path selection strategies, routing algorithms, network optimization and topology, burst loss.

I. Introduction

Optical burst switching (OBS) [1], [2] has emerged as a switching paradigm for the core of IP over optical networks. OBS avoids the inefficient resource utilization of optical circuit switching (OCS) and the requirements of buffers, optical logic processing, and the synchronization problems of optical packet switching (OPS).

In OBS the basic transport unit is the burst, an aggregate message that can be considered as an optical "super packet" containing multiple IP packets going to the same egress node and (if used) grouped by some quality of service (QoS) criteria. Bursts are assembled at the ingress nodes and their transmission is preceded by dedicated setup messages, one for each burst, transmitted on a dedicated control channel with the purpose of reserving bandwidth along the path for the upcoming data bursts. Based on the information carried by the setup messages, the intermediate nodes reserve switching resources along a pre-configured path, providing an optical channel through which data bursts can be transmitted from source to final destination after an adequate delay without any optical-electrical-optical (OEO) conversion [2], [3].

However, like other switching paradigms, OBS does not perform well in overloaded scenarios and can present low reliability. It generally uses one-way reservation protocols in which data bursts are transmitted without confirmation that resources along the path will be successfully reserved, which leads to an end-to-end transparent connection. Therefore, whenever the number of simultaneous reservation attempts exceeds the number of available resources, some fail. Consequently, due to the lack of sophisticated optical buffers, this result in burst loss. Burst loss degrades the global OBS performance since dropping leads to rescheduling of lost data

and to the holding of the network resources used for data burst transmission from the source node until the dropping point.

Considerable effort has been devoted to the study of different methods to handle contention, including burst scheduling, optical buffering, burst segmentation, wavelength conversion, and deflection routing [4], [5]. These are mainly reactive mechanisms driven by burst contention and requiring extra hardware and/or software components at each core-node, significantly increasing their cost and complexity, leading to scalability impairments. A simple and cost efficient solution is to deploy contention mechanisms at the edge nodes. This approach has been followed in methods which use burst assembly mechanisms [6]-[8] or path selection and wavelength assignment [9]-[11] and methods which balance the traffic load between alternate paths [12]-[16].

Path selection mechanisms at the ingress nodes can alleviate contention as compared to shortest path routing. The comparison of new routing strategies against the shortest path is an evaluation method commonly adopted in OBS studies because it is usually very difficult to make accurate comparisons against the new proposals of other researchers. That approach would result, of course, in a very useful work. However, the reported performance of path selection strategies is, in most cases, evaluated using custom developed applications, and some network operating conditions are not reported. Therefore it is difficult, sometimes impossible, to produce comparative research results [17]. For these reasons, the same evaluation against the shortest path is adopted here.

Although shortest path routing is successfully used in both circuit switching and packet switching networks, it does not take into consideration the traffic load offered to the network, and it often causes certain links to become congested while other links remain underutilized [13]. This is highly undesirable in bufferless OBS networks since a few highly congested links can lead to unacceptably high burst loss for the entire network. In [13], a path selection for source routing was obtained using a traffic engineering approach aimed at balancing the traffic load across the network. Recently, alternate path selection mechanisms at the ingress nodes have been explored in some studies [15]. In this approach, each ingress node maintains a list of alternate paths to each destination ranked according to their congestion status. The authors present a suite of path selection strategies, each utilizing a different type of information regarding the link congestion status. These adaptive and dynamic path selection schemes require a link state signaling protocol. The efficiency of a solution, characterized in terms of burst blocking probability, depends on both the ability of the scheme to provide good performance for a given traffic scenario characterized by a well known statistics and the convergence time of the link state advertisement protocol. The

convergence of the link state advertisement protocol is of key importance for a bursty traffic scenario.

The strategies proposed here address similar objectives but utilize only the mapping of the OBS nodes and their interconnections to make the routing decisions from all sources to all destinations in a way that congestion in the network is minimized. The problem is formulated as an integer linear programming (ILP) problem, which is a technique that is widely used to address both high-level and system-level synthesis [18]. This technique is known to be NP-complete in the strong sense; thus, it is characterized as having very high computation complexity [19]. However, for the proposals under study, optimal or near-optimal solutions can be reached in a range between a few tens of seconds and minutes, using regular computation power. Taking into account these computation times and the infrequent update requests expected as a consequence of changes in the OBS backbones whose topologies typically last for long time scales, this approach can be considered feasible for the real production of OBS networks. This can be carried out by means of a management process executed during its initial setup phase, either in a centralized manner, where routes are computed offline by a central node which has knowledge about the global topology and downloaded to the nodes when the network is booted, or in a distributed manner, if the nodes are equipped with topology searching capabilities.

The routes obtained can be applied as single-path static routes and used alone to provide load-balancing without the need for resource-update signaling messages regarding the congestion status of the network links. Alternatively, they can be combined with some other dynamic contention resolution schemes (like deflection or segmentation, for example) and used occasionally as a default routing option to assume whenever the network needs to recover from instability. This can particularly be done when the activity of multiple dynamic network elements, reacting simultaneously to congestion, may result in oscillation between congestion and decongestion states on certain links [20].

The aim of this paper is to investigate edge-router-based routing strategies able to minimize burst contention, for a given traffic scenario, using only topological network information. We assume that the network operates with source-based routing, that is, the ingress edge-node selects a path for a burst that enters the network from a set of K previously calculated paths. Therefore, the strategy comprises two stages: first, the calculation of K eligible paths for each pair of nodes and second, the selection of one path from the set of K eligible paths for each pair of nodes so that the chosen paths minimize the global network contention. For the second stage, two path selection strategies to prevent congestion are proposed and

evaluated, the first addressing contention on a link basis, and the second considering the entire path between source-destination node pairs.

The reminder of this paper is organized as follows. Section II explains the strategies proposed. In section III, we present the simulation model developed for testing. In section IV, the performance of the proposed strategies is evaluated. Section V concludes the paper with some final remarks.

II. Contention Avoidance Strategy

In the following discussion, let $G(N,L)$ be the graph representing an OBS network, where N is the set of optical switches, taken as nodes, and L is the set of unidirectional fiber links. We define a path over which a burst must travel, v, as a connected series of directed links, written as $v: s(v) \rightarrow d(v)$, from source node $s(v)$ to destination node $d(v)$. The set of paths that can be used to deliver a burst from source node s to destination node d is defined as $V_{s,d} = \{v: s(v) \rightarrow d(v) \mid s=s(v), d=d(v)\}$, and the set including all $V_{s,d}$ is defined as V. We also define $p_l^v = 1$ if link $l \in L$ is included in v, and $p_l^v = 0$ otherwise. We define $q^{v,v'} = 1$ if the two paths v and v' share at least one link. A demand matrix $\mathbf{T}$ can also be considered, where $t_{s,d}$ represents a relative load from source node s to destination node d. However, we note that the following formulations are independent of the details of the demand model, which may include the total or average number of demands over a period of time or some integer value that reflects the local demand weight over the total network demand.

With the aim of minimizing contention using only topological network information, we consider two path selection strategies: minimizing the maximum congested link (MCL) and minimizing the maximum end-to-end congested (MEC) path. These strategies are formulated in two ILP problems for which a single path for each pair of nodes must be selected. That is, for the overall network, $N(N-1)$ paths must be chosen and resources allocated for burst delivery. For both strategies, input information includes a set of eligible paths which are computed in advance. The optimization problems are solved using the ILOG CPLEX [21] optimizer, and the results obtained are used to populate the routing tables in order to achieve a global contention reduction.

1. Pre-calculation of Eligible Paths

To calculate the set of K eligible paths, we propose to compute the K shortest paths with less links in common. That is, if several paths exist with an equal number of hops, then the more non-overlapping ones are chosen. The K shortest paths

for a specific pair of nodes (s,d) can be computed using the ILP optimization discussed next.

The ILP objective function is written as

$$\min \sum_{k \in \{0,1,\cdots,K\}} \beta_k^{s,d} - \sum_{l \in L} \frac{\gamma_l^{s,d}}{|L|+1}. \qquad (1)$$

The objective function has two components. The first component accounts for the total number of hops of all K paths, where $\beta_k^{s,d}$ denotes the number of hops of the k-th path from source node s to destination node d. The second component accounts for the total number of links used by the K paths, where $\gamma_l^{s,d}$ is a binary variable that indicates if link l is used by any path from node s to node d. The minimization is subject to the following constraints.

Flow conservation:

$$\sum_{l \in L: s(l)=m} \varepsilon_{k,l}^{s,d} - \sum_{l \in L: d(l)=m} \varepsilon_{k,l}^{s,d} = \begin{cases} 1 & \text{if } s=m, \\ -1 & \text{if } d=m, \\ 0 & \text{otherwise,} \end{cases} \qquad (2)$$
$$\forall k \in \{0,1,\cdots,K\}, \quad \forall m \in N.$$

Hop count:

$$\beta_k^{s,d} = \sum_{l \in L} \varepsilon_{k,l}^{s,d}, \qquad \forall k \in \{0,1,\cdots,K\}. \qquad (3)$$

Link usage:

$$\gamma_l^{s,d} \le \sum_{k \in \{0,1,\cdots,K\}} \varepsilon_{k,l}^{s,d}, \qquad \forall l \in L. \qquad (4)$$

Similarity avoidance of paths:

$$\psi_{k,k',l}^{s,d} \le \varepsilon_{k,l}^{s,d} + \varepsilon_{k',l}^{s,d}, \quad \forall k,k' \in \{0,1,\cdots,K\}, k \ne k', \qquad (5)$$

$$\psi_{k,k',l}^{s,d} \le 2 - \left(\varepsilon_{k,l}^{s,d} + \varepsilon_{k',l}^{s,d} \right),$$
$$\forall l \in L, \quad \forall k,k' \in \{0,1,\cdots,K\}, k \ne k', \qquad (6)$$

$$\sum_{l \in L} \psi_{k,k',l}^{s,d} \ge 1, \quad \forall k,k' \in \{0,1,\cdots,K\}, k \ne k'. \qquad (7)$$

Loop avoidance:

$$\sum_{l \in L, s(l)=i} \delta_{k,l}^{s,d} - \sum_{l \in L, d(l)=i} \delta_{k,l}^{s,d} = \begin{cases} \beta_k^{s,d} & \text{if } i=s, \\ -\sum_{l, d(l)=i} \varepsilon_{k,l}^{s,d} & \text{otherwise,} \end{cases} \qquad (8)$$
$$\forall k \in \{0,1,\cdots,K\}, \quad \forall i \in N,$$

$$\delta_{k,l}^{s,d} \le \varepsilon_{k,l}^{s,d} \times L, \qquad \forall k \in \{0,1,\cdots,K\}, \forall l \in L, \qquad (9)$$

$$\sum_{l \in L: d(l)=m} \varepsilon_{k,l}^{s,d} \le 1, \qquad \forall k \in \{0,1,\cdots,K\}, \forall m \in N. \qquad (10)$$

Binary and integer variables:

$$\varepsilon_{k,l}^{s,d}, \gamma_l^{s,d}, \psi_{k,k',l}^{s,d} \in \{0,1\}, \quad \beta_k^{s,d} : \text{non-negative integer.} \qquad (11)$$
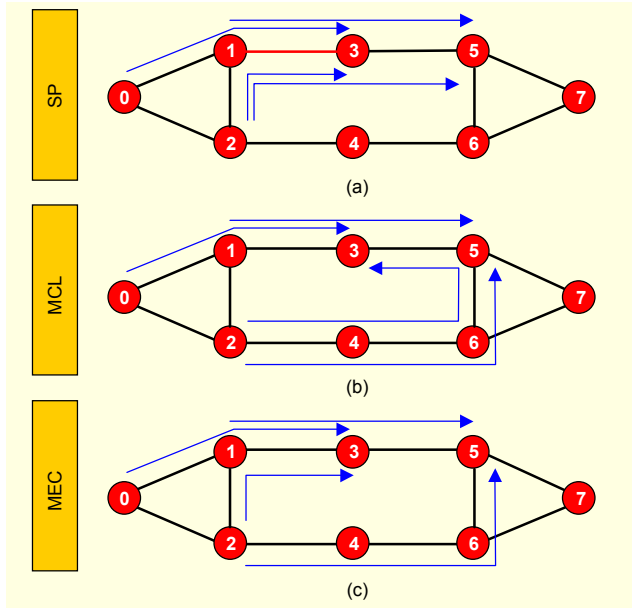
Fig. 1. Illustrative example of the algorithms.

The flow conservation constraint expressed in (2) builds the paths using the binary variables $\varepsilon_{k,l}^{s,d}$, which indicate if the k-th path from source node s to destination node d uses link l. The hop count and link usage constraints determine the values of $\beta_k^{s,d}$ and $\gamma_l^{s,d}$ which were previously described. Constraints (5) to (7) prevent the K paths from being equal, that is, two paths must differ at least in one link. Finally, constraints (8) to (10) prevent the occurrence of loops in the paths.

This stage is independent of the next two path selection strategies. Also note that, instead of the ILP algorithm proposed here to calculate the K most link-disjoint shortest paths, heuristic approaches can be used. However, the most common heuristics do not fulfill the previously mentioned requirements.

2. MCL Path Selection Strategy

This strategy is based on the idea that the more a certain link is included in the chosen paths for source-destination pairs, the higher its blocking probability can be. This situation is represented by the small network of Fig. 1(a), where, considering the paths between nodes 0→3, 1→5, 2→3, and 2→5, the shortest path algorithm can bring an excessive load to the link 1−3, leaving other links underutilized. Therefore, paths for source-destination pairs should be selected with the objective of minimizing the blocking probability of the link with the highest expected contention value, denoted by ζ_{MAX}. This is achieved by the following ILP optimization problem:

$$\min \zeta_{\text{MAX}}, \tag{12}$$

subject to

$$\sum_{v \in V_{s,d}} \sigma^v = 1, \quad \forall s,d \in N \tag{13}$$

$$\sum_{s,d} \sum_{v \in V_{s,d}} \sigma^v \times p_l^v \times t_{s,d} \leq \zeta_{\text{MAX}}, \quad \forall l \in L \tag{14}$$

$$\sigma^v \in \{0,1\}, \ \zeta_{\text{MAX}} : \text{non-negative integer}, \tag{15}$$

where σ^v is a binary variable that indicates if path v is used to carry bursts from node $s(v)$ to node $d(v)$. Constraint (13) states that one path must be found for each pair of nodes, and that path must be selected from the corresponding set $V_{s,d}$ of available paths. In constraint (14), where p_l^v is from the given pre-selected paths and $t_{s,d}$ is always 1 for a uniform all-to-all traffic matrix, the expected congestion at a link must not exceed ζ_{MAX}. With this algorithm, and for the scenario previously presented, we can see in Fig. 1(b) that the traffic is more evenly distributed, increasing the network utilization to avoid the highly congested situation presented in Fig. 1(a). However, it should be noted that on this attempt to spread the traffic throughout the network some paths can became longer (such as 2→3). This observation was the driving force behind the next strategy.

3. MEC Path Selection Strategy

This strategy is based on the idea that blocking may occur at any link traversed by a burst along the path. Therefore, paths for source-destination pairs should be selected so that demands have the lowest probability of contending with other demands at every link from source to destination, minimizing end-to-end blocking. This is achieved by the following ILP optimization problem, where φ_{MAX} denotes the value of the path having the highest number of contention:

$$\min \varphi_{\text{MAX}}, \tag{16}$$

subject to

$$\sum_{v \in V_{s,d}} \sigma^v = 1, \quad \forall s,d \in N, \tag{17}$$

$$\eta^{v,v'} \geq (\sigma^v + \sigma^{v'} - 1) \times q^{v,v'}, \\ \forall v \in V, \forall v' \in V \setminus V_{s(v),d(v)}, \tag{18}$$

$$t_{s,d} + \sum_{v \in V_{s,d}} \sum_{v' \in V \setminus V_{s,d}} \eta^{v,v'} \times t_{s(v'),d(v')} \leq \varphi_{\text{MAX}}, \\ \forall s,d \in N \tag{19}$$

$$\sigma^v, \eta^{v,v'} \in \{0,1\}, \ \varphi_{\text{MAX}} : \text{non-negative integer}, \tag{20}$$

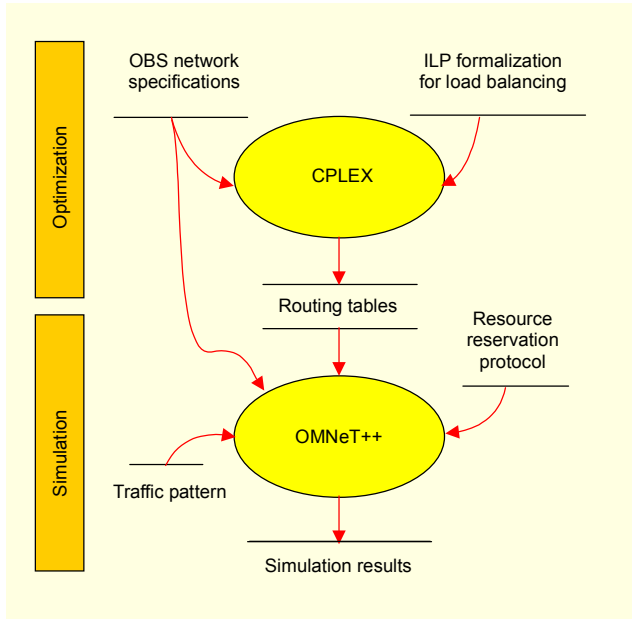where σ^v is a binary variable that indicates if v is used to carry

Fig. 2. Conceptual view of the simulation model.

Table 1. Network physical parameters.

Network	Num of nodes	Num of links	Degree		Physical connectivity
			av	stdev	
ARPAnet	20	62	3.1	0.45	0.16
NSFnet	14	42	3.0	0.55	0.23
Random12	12	42	3.5	0.67	0.32
COST239	11	52	4.7	0.65	0.47

Fig. 3. Adopted OBS architecture.

bursts from node $s(v)$ to node $d(v)$, and $\eta^{v,v'}$ is a binary variable that indicates if v and v' have both been selected to carry bursts and share at least one link. As in the previous strategy, (17) states that one path must be found for each pair of nodes. Constraint (18) forces $\eta^{v,v'}$ to be 1 if v and v' share a link and have both been selected to carry bursts. Otherwise, due to the minimizing nature of the objective function, $\eta^{v,v'}$ will be 0. Constraint (19) states that the contending value of a source-destination pair must not exceed φ_{MAX}. Still considering the scenario of subsection 2, we can observe in Fig. 1(c) that the longest path 2→3 in Fig. 1(b) no longer exists and that this algorithm also tries to maintain the traffic in a distributed manner.

III. Simulation Model

The simulation model described in this paper involves the two working stages conceptually represented in Fig. 2. In the first stage, the optimization problem is formulated and solved using ILP, and in the second stage, the OBS network simulation takes place. After the first stage, whose algorithms were presented in the previous section and from which an optimized routing solution is produced, the second stage uses the OMNeT++ event-driven platform for simulations [22] and some programming effort in C++.

The functional architecture of our OBS model [23] has the same characteristics as the one presented in [3], assuming that each node can support both the new input traffic generated by the client networks and the *in transitu* traffic passing all-
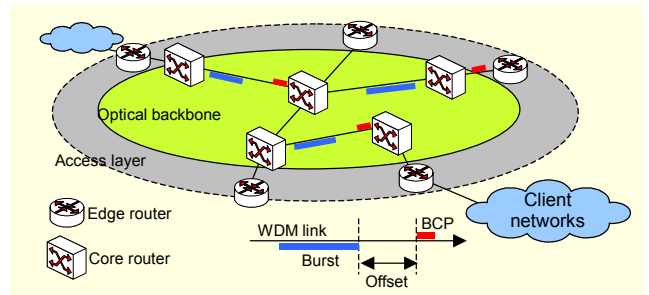
optically from source to final destination. This means that each node consists of both an edge router and a core router as shown in Fig. 3. The simulation study presented here uses each of the following networks: ARPAnet, NSFnet, Random12, and COST239. Their topologies and main physical parameters are presented in Fig. 4 and Table 1, where the average degree is considered the average number of physical connections per node, and the physical connectivity is defined as the normalized number of bidirectional links with respect to a physically fully connected network of the same size [24]. The nodes are connected by links representing optical fibers with the same characteristics, having 16 wavelengths per link with a transmission capacity of 10 gigabits per second (per wavelength).

The adopted traffic pattern is based on bursts assuming a Poisson arrival pattern with a threshold-based assembly method, generating messages that are 100×10^3 bytes. The bursts are forwarded through the core backbone reproducing the relevant actions of the just-enough-time (JET) [2] signaling scheme. The control information processing time is assumed to be 10 μs per core node, although other values from 12.5 μs to 1 μs could be adopted depending on the technology in place (current state-of-art or foreseeable in the near future).

The model employs source routing in which a complete routing decision is taken at the ingress edge node. Like the approach adopted in [13] and [15], the path over which the burst must travel is carried by the setup message that precedes the transmission of each data burst and is not modified by
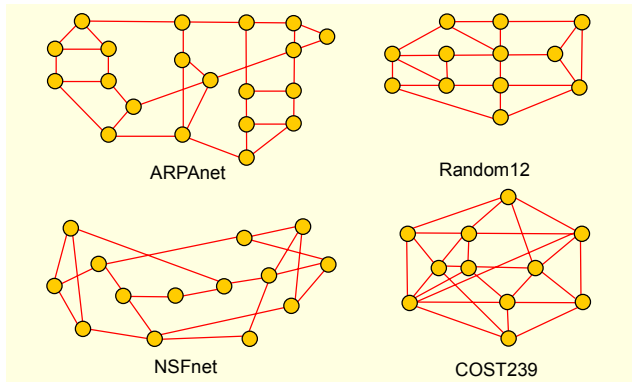
Fig. 4. Network topologies under test.

Fig. 5. Screenshot of the OBS simulation model (simplified version with (a) edge node and (b) core node using only 3 wavelengths).

downstream nodes. Here, the adopted path is fetched from the edge node's routing tables previously populated by the results of the path selection strategies discussed in section II. The core nodes do not employ any buffering in the data path and they do not use deflection routing, but we assume that the nodes are capable of performing a full wavelength conversion. Thus, a burst is blocked only if there are no free wavelengths available to accomplish the next hop on a predetermined path to a certain destination. If scheduling fails, the burst is simply dropped and no further contention resolution method is adopted. Together with the network topology description, the OBS simulation model, which is essentially composed of OBS capable nodes interconnected by optical fibers, is based on two main compound modules, namely, edge node and core node modules. These modules will be presented from the functional point of view in the next subsections.

1. Edge Node

Edge nodes connect multiple subnetworks running on top of legacy link layer protocols to the OBS network. They can be considered either ingress or egress nodes. When acting as ingress nodes, edge nodes are responsible for aggregating the incoming packets into bursts, for taking the initial (and here also permanent) routing decision, and for scheduling the bursts for transmission on outgoing channels. When acting as egress nodes, they perform the inverse operation; that is, they are responsible for disassembling bursts back into packets and for sending them to upper layers for processing. In our model, we assume *the burst* as the basic transport unit of interest. Hence, the issue of the packet aggregation policies is beyond the scope in this paper. It is worth noting that the traffic generator developed here is already a burst generator, generating messages based on a Poisson process with a symmetric all-to-all traffic matrix. Thus, whenever a Poisson process timer expires, a new burst is generated, a destination address is chosen at random between all other nodes in the network, a
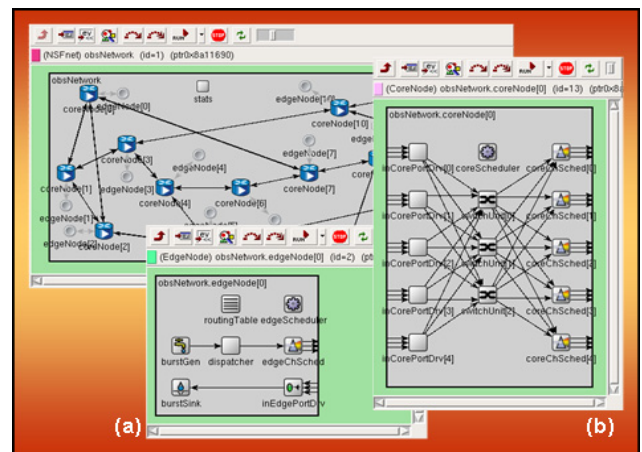
route to the destination node is taken from the source node's optimized routing table, and an initial wavelength is selected among the free ones. Note that source-based routing decision is our first way of addressing contentions with an *a priori* action on the network space domain. The burst, together with all its relevant information, is then retained in a system queue organized by destination address, and the signaling process starts with the sending of a burst control packet (BCP) on the appropriate dedicated channel. The BCP is always transmitted before the corresponding burst and separated from it by an adequate offset time. The model calculates this offset time in order to allow the BCP to be processed at each subsequent node before the burst arrival and in such a way that an optical path can be properly reserved for burst delivery.

A simplified version of the internal structure of the edge node is shown in Fig. 5(a), and its functionality is implemented by the following submodules.

RoutingTable holds the routing information of the node and all the related protected and public functions. The routing information comprises complete paths from source to destination extracted from the solution of the optimization problem previously presented, and stored into STL vectors loaded during the initialization phase of the simulation. The module takes two parameters: the path selection strategy (SP, MCL, or MEC) and the number of routes to be considered to each source destination pair.

BurstGen is responsible for the traffic that each node generates. This traffic represents already aggregated IP packets assembled into burst units on the access network. The traffic pattern and the loading factor are among the relevant parameters of this submodule.

Dispatcher initiates the signaling process and manages a system of queues where bursts are retained for a certain offset

time. The offset time is calculated based on the delays introduced by the core nodes on the downstream and the number of hops on that path.

EdgeChSched is the output port driver of the edge node. This submodule transmits BCPs and bursts to the core backbone after finding a free wavelength. The number of available wavelengths and the presence of devices with wavelength conversion capability are among the relevant parameters of this submodule of the access network.

InEdgePortDrv receives BCPs and bursts from the core backbone. It is the signaling end point, establishing the locations from which the BCP related statistics are obtained and from which data bursts are forwarded to be disassembled.

BurstSink is the submodule that receives the data bursts and collects some data burst related statistics. This submodule represents the place where bursts are disassembled back into IP packets.

2. Core Node

Core nodes are responsible for processing BCP signaling messages, for switching the bursts from an input to an output port without OEO conversion, and for handling contentions. Signaling in OBS is typically implemented using one out-of-band channel, meaning that BCPs are transmitted on a different wavelength from the group of wavelengths used to transmit data bursts. This model uses λ_0 for the transmission of BCPs. Several signaling schemes have been proposed for burst scheduling but just-in-time (JIT) and JET are two of the most popular protocols using distributed signaling on OBS. These are both one-way and source-initiated signaling schemes, which means that the bursts are sent to the core network without waiting for acknowledgments regarding the success or failure of the reservation attempts. Although they are closely related, they differ in the duration of the reservations. The JIT protocol uses immediate reservation with the data channel being reserved as soon as the BCP reaches the node, while JET delays the channel reservation until the burst arrival. This technique, together with the implicit release, makes JET more efficient than JIT regarding bandwidth utilization, resulting in lower blocking rates and low end-to-end delay [5]. For these reasons our model runs under a JET-type behavior scheme, but it can easily be converted to JIT-type behavior.

Together with burst forwarding without leaving the optical domain, core nodes are also responsible for taking contention resolution actions. Contention occurs when multiple bursts from different sources are destined for the same output port at the same time [25]. In addition to the initial path selection strategies adopted on the edge nodes, in handling burst contentions, the core nodes are assumed by default to be equipped with devices having full wavelength conversion capability. This means that no end-to-end wavelength continuity constraint exists, and that any incoming wavelength can be shifted to any outgoing wavelength. As a result, only if there is no wavelength available on the output port the burst will be dropped without any further contention resolution action.

The internal structure of the core node is illustrated in Fig. 5(b) with a simplified configuration. Its functions are implemented by the following submodules.

InCorePortDrv is the entry point of the core backbone. It is an input port driver that receives both BCPs and bursts from the access network and forwards them, after an increment in the number of hops counter, to the proper switch unit. This submodule is also the place from which information related to the node demands is obtained.

SwitchUnit is the submodule where switching takes place and the incoming BCPs and data bursts are directed to the proper output ports towards their next hops. Although for data bursts this is done in the optical domain, for BCPs OEO conversion is involved. This submodule holds an internal switching table, which is loaded during the initialization phase of the simulation and is stored in an STL map, which relates the target address with its correspondent gate identification. The BCP processing delay and the number of ports are among its most important parameters.

CoreChSched is the output port driver of the core node. This submodule forwards BCPs and bursts to the next core node of the backbone or to the local edge (egress) node of the current core node. In doing this, it schedules bursts in the order of their arrival [26] and tries to find a free wavelength by checking an availability word of flags implemented through the use of an STL bit set. This is also the place where contention for output resources occurs and the number of drops is obtained. The total number of wavelengths and the presence of wavelength converters are among the relevant parameters of this submodule.

IV. Evaluation

In this section, we provide simulation results and compare the performance of our proposed path selection schemes with the shortest path approach. For all the four networks represented in Fig. 4, simulations were done under similar conditions with regard to the total number of bursts generated per source node (1×10^6), arrival pattern, traffic load variation, and the number of shortest paths (per pair of nodes) being provided to the path selection strategies (assuming k=2, k=3, and k=4). Figure 6 presents the average number of burst drops for all the loads considered and for the different path selection
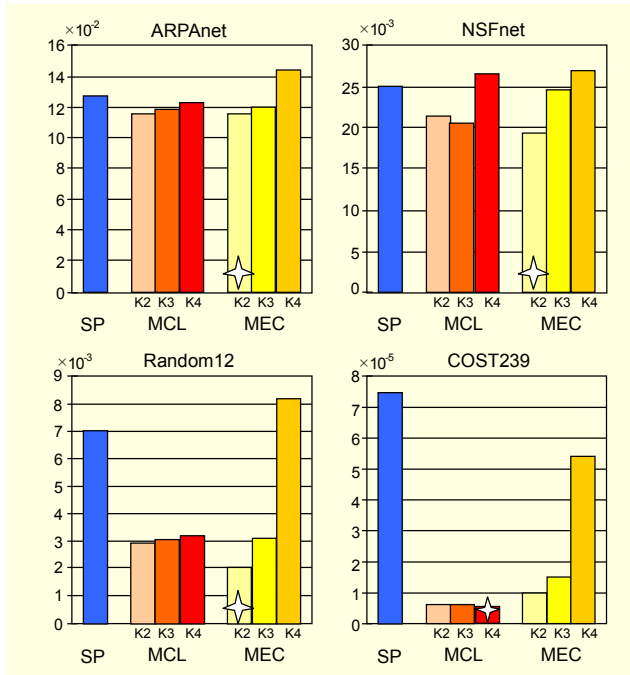
Fig. 6. Normalized burst loss on the OBS backbone (K2, K3, and K4 denote the number of eligible SPs provided to MCL and MEC. The star indicates the best result for the network).

Table 2. Average number of hops.

Network	SP		MCL		MEC	
	av	stdev	av	stdev	av	stdev
ARPAnet	2.71	1.14	2.76	1.18	2.80	1.21
NSFnet	2.13	0.75	2.32	0.93	2.17	0.79
Random12	1.92	0.73	2.02	0.78	1.92	0.73
COST239	1.56	0.55	1.65	0.57	1.59	0.56

schemes. The values are normalized to the number of bursts that enter the network. As the figure shows, in the majority of the cases, the proposed algorithms behave better than the shortest path (SP). From the 24 simulations done using MCL or MEC routing paths, 20 present lower than average dropping values, the best of which are highlighted with a star. From these results, it is also possible to conclude that, generally, when K increases, there is a certain degradation of performance, indicating that the algorithms do not benefit from the alternative paths given as input. This means that when longer paths are adopted, this can become a disadvantage resulting in less gain. This was expected since burst scheduling is required at each intermediate node, and the longer paths determined by higher values of K also correspond to a greater possibility of contention. The statistical values of Table 2 support this conclusion where, for instance, network topologies with lower

Table 3. Average end-to-end delay (ms).

Network	SP		MCL		MEC	
	av	stdev	av	Stdev	av	stdev
ARPAnet	10.93	0.0046	11.16	0.0047	11.33	0.0049
NSFnet	8.70	0.0045	9.00	0.0047	8.71	0.0046
Random12	7.78	0.0029	8.19	0.0031	7.79	0.0029
COST239	6.35	0.0022	6.68	0.0023	6.46	0.0022

connectivity present higher numbers of average hops and higher standard deviations when compared with the more connected ones. The exception to this is the case of the COST239 network under the MCL with $k=4$. This is probably because its high connectivity makes it possible to obtain alternative paths with a similar number of hops.

Similar features are found when we observe the simulated end-to-end delay values presented in Table 3. Since queuing is restricted to the edge nodes, burst transfer in these bufferless networks is predominantly determined by propagation, which is fixed for a path. These results show that the increase in delay resultant from the alternative paths is minimal and does not compromise the improvements obtained from the proposed strategies.

The best results were obtained with each algorithm for each network as follows: for ARPAnet, MCL with $k=2$ and MEC with $k=2$; for NSFnet, MCL with $k=3$ and MEC with $k=2$; for Random12, MCL with $k=2$ and MEC with $k=2$; and for COST239, MCL with $k=4$ and MEC with $k=2$. The following evaluation will compare these best cases with the shortest path approach. In each of the 28 simulations performed, 15 runs were executed with gradually increasing traffic loads, ranging from 0.3 to 0.95 (Erlangs) in steps of 0.05.

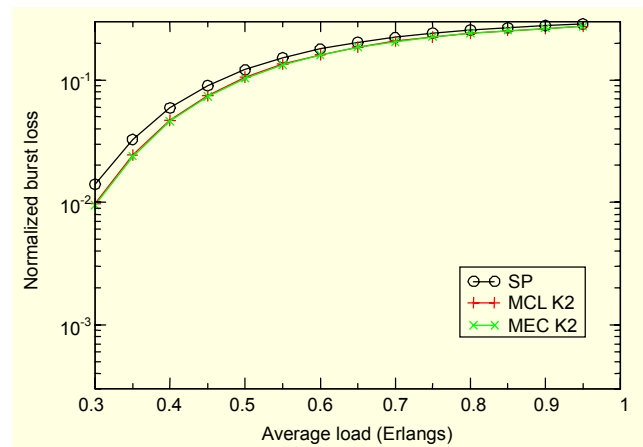Figures 8 to 11 present the results of these runs, plotting the

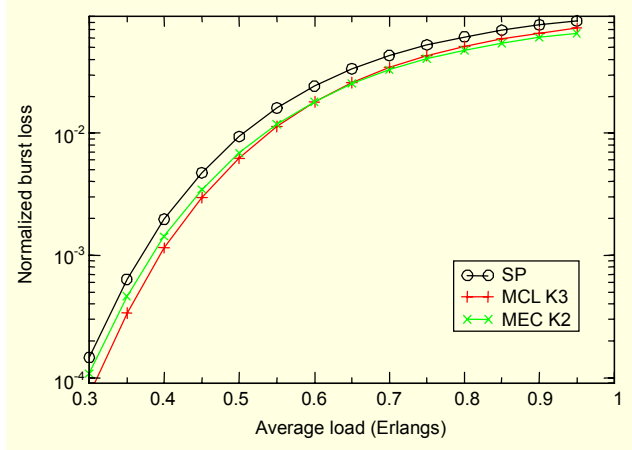Fig. 8. Proposed schemes versus SP for ARPAnet.
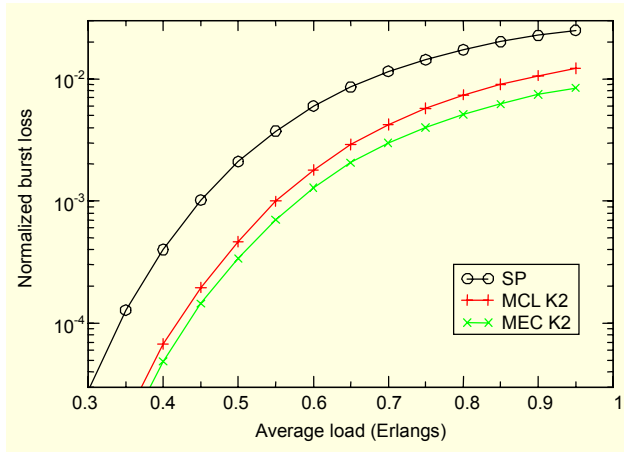
Fig. 9. Proposed schemes versus SP for NSFnet.
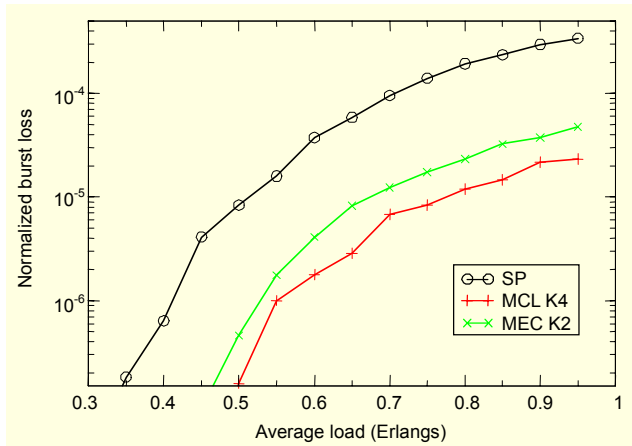

Fig. 10. Proposed schemes versus SP for Random12.

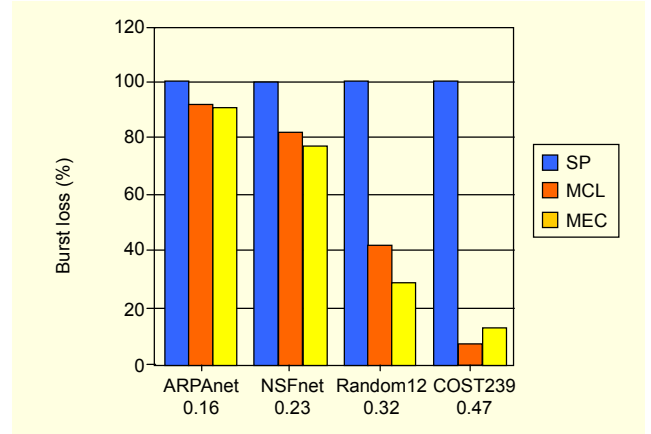Fig. 11. Proposed schemes versus SP for COST239.

Fig. 12. Gain in burst loss reduction.

increases for both MCL and MEC from Fig. 8 to Fig. 11. Considering that these graphics are presented in ascending order of physical connectivity and the same amount of traffic is being generated at each node with the same arrival pattern, we assume that the gain of the proposed algorithms is also related to the way links are connected in OBS networks. This effect corroborates the work presented in [27]. This means that MCL and MEC are more efficient in highly connected networks, and this explains why they provide better results for the COST239 topology than for the ARPAnet topology. The gain of these algorithms is graphically presented in Fig. 12, where the reduction in burst dropping is easily seen, showing that the MCL and MEC routings clearly outperform the results achieved with the SP.

V. Conclusion

In this paper, we considered the problem of routing path selection in OBS networks to minimize the overall burst loss. We took a traffic engineering approach which substantially reduces contention using only topological information. We demonstrated that data burst loss can be minimized by appropriately choosing the paths that bursts must follow. That is, an effective choice of paths can lead to an overall network performance improvement. Although the resolution of an ILP problem is involved in the process, since eligible paths are provided as input for the path selection strategies, the solutions can be promptly reached, meaning that they can admit updates if bounded by the reconfiguration requirements of the optical backbones, whose topologies typically last for long time scales. Our results also show that the achieved performance improvement depends on the physical connectivity of the network. More highly connected networks show better performance. This happens because the proposed algorithms take advantage of more, short, alternative paths. Our approach

normalized burst loss against the average load. From these graphics it is possible to see that the SP curves are in agreement with the ones generally presented in literature [13] and that the values of burst loss for MCL and MEC are always lower than those for SP routing. Moreover, the burst loss improvement

achieves an initial stage of improved performance, measured in terms of burst loss reduction without incurring state dissemination protocol penalties. However, it should be noted that other contention avoidance strategies, including dynamic resolution schemes, can be combined with this offline load balancing methodology.

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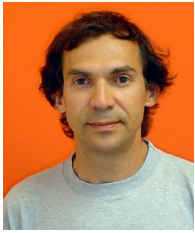
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