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Reactive and proactive routing in labelled optical burst switching networks

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Abstract: Optical burst switching architectures without buffering capabilities are sensitive to burst congestion. The existence of a few highly congested links may seriously aggravate the network throughput. Proper network routing may help in congestion reduction. The authors focus on adaptive routing strategies to be applied in labelled OBS networks, that is, with explicit routing paths. In particular, two isolated alternative routing algorithms that aim at network performance improvement because of reactive route selection are studied. Moreover, a nonlinear optimisation method for multi-path source-based routing, which aims at proactive congestion reduction is proposed. Comparative performance results are provided and some implementation issues are discussed.

1 Introduction

Optical burst switching (OBS) is a photonic network technology aiming at efficient transport of IP traffic [1]. In conventional OBS, the packets from the access networks are aggregated and assembled into large data bursts at the edge nodes. Meanwhile, the control information is transmitted out-of-band and delivered with some offset time prior to the data burst in such a way that the intermediate nodes have enough time, both to process this information and to reconfigure the switching matrix.

OBS architectures without buffering capabilities are sensitive to burst congestion. An overall burst loss probability (BLP), which adequately represents the congestion state of the entire network is the primary metric of interest in an OBS network. To reduce burst losses, both reactive and proactive routing techniques can be applied in the network. Reactive routing attempts to resolve the contention of bursts rather than to avoid it. Usually, it is based on local information at the node. Proactive routing reduces the number of burst contentions by routing traffic over a less-congested part of the network; for example, such routing may be controlled in the source by feedback information that indicates the congestion state of the network.

Routing of data bursts can be performed either hop-by-hop, like for example, in connectionless IP networks, or explicitly, like for example, in connection-oriented multi-protocol label switching (MPLS) networks. In the explicit routing a logical connection, also called label switched path (LSP), is set up first over an explicit physical route. Fast packet forwarding of MPLS together with its explicit route selection fit well to both high-speed processing requirements of node controllers and the need for constrained routing, in order to preserve the network from link overloads, in bufferless OBS networks. As a result, the use of labelled OBS (LOBS) has been proposed in [2] as a natural control and provisioning solution under the MPLS framework.

In this article, we address the problem of network routing in the context of burst loss performance and congestion reduction. At the beginning, we recall basic routing terminology that helps us to classify numerous routing strategies considered for OBS networks. Then, we are concerned with two adaptive routing strategies designed for an LOBS network. We study alternative routing, which is reactive-like routing, and multi-path source routing, which is proactive-like routing. We propose two isolated routing algorithms to be used with explicit alternative routing. Moreover, we introduce a novel optimisation framework to be used with centralised multi-path source routing. Obtained performance results enable us to compare the efficiency of reactive and proactive routing strategies in both small and large network scenarios.

2 Routing in OBS networks

2.1 Routing terminology

Routing in an OBS network involves two phases: route calculation and route selection [3]. The route calculation and selection can be either static or dynamic. In static-route calculation, one or more routes are calculated ahead of time. In dynamic-route calculation, the routes are computed periodically based on certain transient (dynamic) traffic information such as link congestion or number of burst contentions. Once the routes are computed, one of the routes is selected for the burst transmission.

In a static route selection, the traffic is split such that its fixed fraction is sent on each of the routing paths. Dynamic route-selection policies are based on feedback information of the network state. For each route, a given cost function (heuristic or optimised) is calculated such that the routes are ranked according to their congestion states. Then, a traffic splitting or a route-ranking technique reacts accordingly in order to shift some part of the traffic to less-loaded links.

In general, routing algorithms can be grouped into two major classes: non-adaptive (when both route calculation and selection are static) and adaptive (when some dynamic decisions are taken) [4]. In static routing the choice of routes does not change during the time. 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 information they use, namely centralised (or global), isolated (or local) and distributive routing (Fig. 1). Single-path or multi-path routing corresponds, respectively, to the routing scenarios with only one or more paths between each pair of nodes available. Generally, the decision of path selection in multi-path routing is taken at the source node and, hence, such routing can also be called source routing. A special case of multi-path routing is alternative (or deflection) routing. Alternative routing allows the selection of an alternative path at whatever capable node in case a default primary path is unavailable.

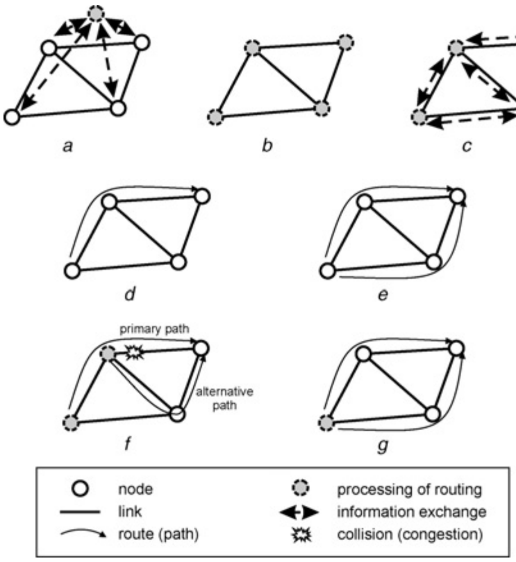

Figure 1 *Routing algorithms*

a Centralised
b Isolated
c Distributed
d Sing-path
e Multi-path
f Alternative
g Source

2.2 Review of routing methods in OBS networks

Static shortest path routing based on Dijkstra's algorithm is the primary routing method frequently explored in OBS networks [5]. Such routing reduces overall network utilisation when calculated with respect to the number of hops. On the other hand, some links may be overloaded, whereas others may be spare, leading to excessive burst losses. Therefore several reactive and proactive routing strategies, based on alternative, multi-path or single-path routing, have been proposed with the objective of the reduction of burst congestion.

Although alternative routing improves network performance under low-traffic conditions [6], it may intensify the burst losses under moderate and high loads [7]. Indeed the problem of alternative routing in bufferless OBS networks is over-utilisation of link resources, if an alternative route has more number of hops than a primary path. Hence, since the first proposals were based on static route calculation and selection [8–10], in the next step, the authors are concerned with the optimisation of the set of alternative routes [12, 13] as well as the introduction of adaptive path selection techniques [14, 15]. Assigning lower priorities to deflected bursts is another important technique, which preserves the network from excessive burst losses on primary routes [16].

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Multi-path routing represents another group of routing strategies, which aim at traffic load balancing in OBS networks. Most of the proposals are based on a static calculation of the set of equally important routes with Dijkstra's algorithm [17]. Then, the path selection proceeds adaptively according to some heuristic [3, 18] or optimised cost function [19, 20]. Both traffic splitting [21, 22] and path ranking [23–25] techniques are used in the path selection process.

Network congestion avoidance in single-path routing is achieved thanks to a proactive route calculation. Since most of the strategies proposed for OBS networks consider centralised single route calculation [19, 26, 27] some authors study distributed routing algorithm [28–30]. Both optimisation [31, 32] and heuristic [33, 34] methods are used.

3 Reactive and proactive routing methods

In this section, we focus on adaptive routing methods to be used in LOBS networks. We consider that the route calculation is static, that is, there are preestablished LSPs between network nodes, and the route selection is limited to these paths only. Moreover, the network is enhanced in a full wavelength conversion capability in each switching node.

Our first method applies a simple reactive deflection routing principle; that is, in case there is no wavelength available on the primary LSP, the routing algorithm can select an alternative LSP. The routing decision is taken only using information of the local (isolated) output link state.

In the second approach – multi-path source routing – we aim at optimised, proactive traffic distribution in order to improve overall network performance. The optimisation methods used in OBS routing are usually based on linear programming formulations with piecewise linear approximations of the overall BLP function [19] even it has nonlinear character [35]. Thus, in order to complete the study, we formulate and solve a nonlinear optimisation problem for an OBS network with multi-path source routing.

3.1 Isolated alternative routing

We propose two isolated alternative routing algorithms, namely, a path excluding routing (PER) algorithm and a by-pass routing (BPR) algorithm. Notice that both of them have been already considered in the context of optical packet switching networks [36].

3.1.1 PER algorithm: In PER algorithm, the edge node selects the first available path from the set of paths to the destination. This selection determines the next hop and excludes from the set of available paths all those paths that do not include this hop in their route. Hence, from the k original paths, each node removes some paths as there long as remains only one path.

Figs. 2*a* and 2*b* show an example. A burst is generated in node A and destined to node E. $k = 3$ paths are set up: the shortest ones are 1. $A - D - E$, then 2. $A - B - C - E$ and 3. $A - D - F - E$. If the first (shortest) path from the list is congested on its output port, A selects the $A - B - C - E$ path definitely excluding the other possibilities. This means that the rest of the nodes in the selected path cannot take other routing decisions. If the output port of A towards D is not congested, both $A - D - E$ and $A - D - F - E$ are selected, whereas the other is removed. The next node D will take the path decision in the same way. If the output port of D towards node E is not congested, it chooses the path $D - E$; otherwise, $D - F - E$ is selected. It is evident that when all output ports are congested, the burst is lost.

3.1.2 BPR algorithm: In the BPR algorithm, for each burst, the source node selects a single path as a function of the state of its output queues. The route can be modified only when a travelling burst finds a congested link. In this case, the node tries to by-pass it using the shortest available path to the destination. The behaviour of the BPR algorithm is like that of any non-constrained (to the number of hops) deflection routing algorithm with the only difference that the deflected path is selected from the set of available (pre-established) paths.

Fig. 2*c* shows an example of this algorithm behaviour. Node A transmits a burst to node D with the destination node E (the path is $A - D - E$). When the burst arrives at node D, no resources are available to reach node E. Therefore node D finds two by-pass paths in its forwarding table: $D - C - E$, and $D - F - E$. It selects the first available one.

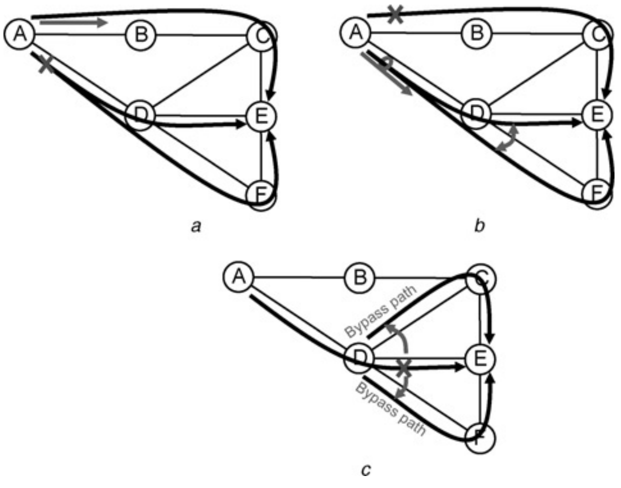

Figure 2 *Isolated alternative routing algorithms*

a PER (case 1)
b PER (case 2)
c BPR

3.2 Multi-path source routing

Let $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ 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. $\mathcal{P}$ defines a set of all paths predefined between each of the source nodes s and destination nodes d, where $s, d \in \mathcal{V}$ and $s \neq d$. Each individual path $p \in \mathcal{P}$ is identified with a subset $p \subseteq \mathcal{E}$. Subset $P_{sd} \subseteq \mathcal{P}$ identifies all paths from source s to destination d. Subset $Q_e \subseteq \mathcal{P}$ identifies all paths that go through link e.

The reservation (holding) times on each link are independent and identically distributed (i.i.d.) 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 the given node d arrive at node s according to a Poisson process of (long-term) rate $t_{sd}/h = t_{sd}$.

Our multi-path source routing is defined as follows:

1. each subset P_{sd} comprises a (small) number of paths and a burst can follow one of them,

2. the source node determines the path of a burst that enters the network (Fig. 3), and

3. path selection is performed according to the given traffic splitting factor x_p, such that

$$0 \le x_p \le 1, \quad p \in \mathcal{P} \tag{1}$$

$$\sum_{p \in P_{sd}} x_p = 1, \quad s, d \in \mathcal{V}, \quad s \neq d \tag{2}$$

According to such definition, traffic v_p offered to path $p \in P_{sd}$ can be calculated as

$$v_p = x_p \tau_p \tag{3}$$

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

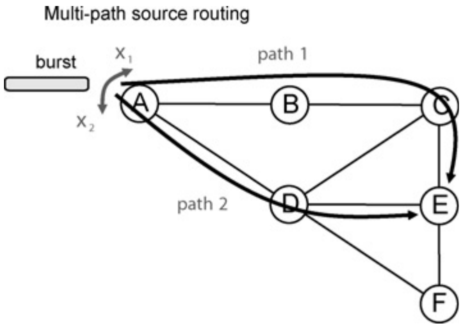

Figure 3 *Example of OBS network with source-based routing; x_1 and x_2 are the traffic splitting factors and $x_1 + x_2 = 1$*

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

We solve such a multi-path routing problem as a nonlinear optimisation problem [37]. In particular, we formulate a cost function which is a simplified overall BLP function. The main modelling steps include the calculation of:

1. a non-reduced link load, where the traffic offered to link e is calculated as a sum of the traffic offered to all the paths that cross this link

$$\rho_e = \sum_{p \in Q_e} v_p, \quad e \in \mathcal{E} \tag{4}$$

2. BLPs E_e on links, given by the Erlang loss formula

$$E_e = E(\rho_e, C_e) = \frac{\rho_e^{C_e}}{C_e!} \left[\sum_{i=0}^{C_e} \frac{\rho_e^i}{i!} \right]^{-1}, \quad e \in \mathcal{E} \tag{5}$$

3. loss probabilities L_p of bursts offered to paths

$$L_\mathrm{p} = 1 - \prod_{e \in p} (1 - E_e), \quad p \in \mathcal{P} \tag{6}$$

4. and the overall BLP B

$$B = \sum_{p \in \mathcal{P}} v_p L_\mathrm{p} \left[\sum_{p \in \mathcal{P}} v_p \right]^{-1} \tag{7}$$

From (3) and (7), we define a cost function to be the subject of optimisation

$$B(\boldsymbol{x}) = \sum_{p \in \mathcal{P}} x_p \tau_p L_\mathrm{p} \tag{8}$$

The optimisation problem is formulated as follows

$$\min B(\boldsymbol{x}) \tag{9}$$

subject to the constraints given by (1) and (2).

Since the overall BLP is a nonlinear function of vector $\boldsymbol{x}$, the cost function is nonlinear as well. To solve such optimisation problem, we can use for instance the modified reduced gradient method described in [38].

Gradient methods need to employ the calculation of partial derivatives of the cost function. In [37], we provide a straightforward derivation of the partial derivative of B with respect to x_q, $q \in \mathcal{P}$. In particular, for each path $q \in \mathcal{P}$ we have

$$\frac{\partial}{\partial x_q} B(\boldsymbol{x}) = \tau_q \Big[L_q + \sum\nolimits_{e \in q} c_e\Big] \tag{10}$$

where c_e is defined for each link $e \in \mathcal{E}$ as

$$c_e = \eta_e \sum\nolimits_{p \in Q_e} v_p(1 - L_{\mathrm{p}}) \tag{11}$$

and for each link $e \in \mathcal{E}$

$$\eta_e = E(\rho_e, C_e - 1) - E(\rho_e, C_e) \tag{12}$$

4 Performance evaluation

4.1 Simulation environment

The evaluation of our routing methods is performed in an ad hoc, event-driven OBS network simulator written in C language. The simulator manages three types of events at the network nodes: (1) the generation of a new burst at the source nodes, (2) the burst arrival at the core nodes and (3) the burst arrival at the destination nodes. The burst events are terminated either if they reach the destination node or the wavelength resources cannot be found. Whereas type 2 and 3 events only perform the functions dedicated to the resource reservation and routing look-up, type 1 event further generates another arrival event till the simulation ends.

Additionally, for the multi-path source routing scenario, we use the solver `fmincon` for constrained nonlinear multi-variable functions available in the MATLAB environment in order to find a splitting vector $\bar{x}$. Once calculated, the vector is applied to the network simulator.

It is worth mentioning that all simulation results have 99% level of confidence. It is achieved by means of at least ten repetitions of the same simulation scenario.

The details of the implemented node, network and traffic scenarios are presented in the next section.

4.2 Network and traffic scenario

We consider an OBS network with a one-way signalling protocol [1], the Horizon resource reservation [39] and the latest available unused channel scheduling policy [40]. We assume the delay for burst control packet processing is compensated by a short extra fibre delay coil of appropriate length at the input port of the node. Thus, offset violation because of excessive deflections is no issue [41].

Each network node is both an edge node and a core switching node capable of generating bursts destined to any other nodes. We assume the source nodes do not buffer the bursts after completing their aggregation. The nodes are not enhanced with FDL buffers.

We evaluate the routing algorithms in three logical network topologies (Fig. 4):

- the SIMPLE mesh network topology of six nodes and eight links,
- the NSFNET network topology of 15 nodes and 23 links, which represents an American backbone network [42] and
- the EON network topology of 28 nodes and 41 links, which is a pan-European network defined in European COST 266 action [43].

Network links are dimensioned with the same number of wavelengths c; in particular, each link has $c = 32$ data wavelengths in SIMPLE and NSFNET networks, and $c = 64$ wavelengths in the EON network. Transmission bitrate in the data wavelength is 10 Gbps.

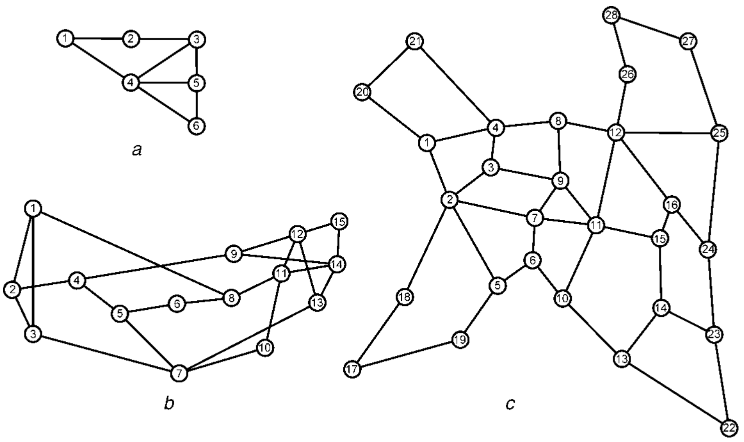

Figure 4 *Network topologies*

a SIMPLE
b NSFNET
c EON

The traffic is uniformly distributed between network nodes. We assume that each edge node offers the same amount of burst traffic to the network; this offered traffic is normalised to the transmission bitrate and expressed in Erlangs. In our context, an Erlang corresponds to an amount of traffic that occupies an entire data wavelength, for example, 51.2 Erlangs indicate that each edge node generates 512 Gbps.

The bursts are generated according to a Poisson arrival process and have exponentially distributed lengths. The mean burst duration is 1 ms. All simulations are performed under a static traffic scenario, that is, the traffic demands do not change during a simulation.

The routing paths are calculated according to Dijkstra's shortest hop algorithm. There are k pre-established LSPs between each source-destination pairs of nodes. The routes are not necessarily disjoint.

An LSP can be selected in any network node in alternative routing, while it is assigned to the bursts in the source node in multi-path routing. In both cases, we consider per-burst routing decision. As a reference we use a simple shortest hop routing (SPR) algorithm.

4.3 Results

4.3.1 Isolated alternative routing: Our isolated alternative routing is evaluated in the scenarios with $k = \{2, 4, 6\}$ LSPs available between each pair of nodes in SIMPLE and NSFNET networks, and $k = \{2, 4, 6, 8, 10\}$ LSPs in EON network.

In the following figures, we study the BLP as a function of the offered traffic. In Figs. 5*a*–*f*, we present the impact of the number of available paths (LSPs) on overall BLP performance under PER and BPR algorithms.

First, we can see that both PER and BPR\ outperform SPR under low and moderate traffic loads in each scenario. Moreover, the performance of PER under high loads can still be better than that of SPR, whereas the performance of BPR is worse. These results are consistent with the observations presented in [7]. In particular, the BPR algorithm, which has not constraint on the number of deflections allowed, can increase the network load, and hence the burst blocking significantly. On the other hand, the number of deflections in PER is limited, at most, to the number of available paths k. The network can hardly be overloaded in such case.

The next conclusion is that by increasing the number of LSPs we can improve the network performance, which is obvious since there are more chances for a deflection in case of unavailability of resources in the primary paths. The performance improvement can be really high under the BPR algorithm, especially in smaller networks (Fig. 5*d*). BPR with a high number of LSPs available behaves like hot-potato routing; the burst is likely to be sent even to the previous node (loops possible). Nevertheless, the selection of the set of LSPs should be reasonable in order to preserve the network from the use of too-long routing paths, as for example, in Fig. 5*f*, where the performance with $k = 10$ is worse than with $k = 8$.

In general, BPR offers better performance than PER (excepting high-load traffic conditions). Again, it is clear since BPR has more chances for a successful deflection in each intermediate node.

4.3.2 Optimised multi-path source routing: We consider two LSPs available from each source to each destination in our optimised multi-path routing (OR) algorithm.

In Fig. 6, we show the overall BLP as a function of the offered traffic load ρ. We can see that OR achieves significantly lower losses than SPR in each network scenario. Moreover, we validate that the analytical results [OR (an) in the figure] calculated from the model match the simulation ones very well [OR (sim)].

4.3.3 Comparison of routing methods: In the next step, we compare the performance of proactive multi-path routing with reactive alternative routing. In Fig. 7, we evaluate the overall BLP performance as a function of the offered traffic. To enable a discussion on the effect of the network topology and traffic load on routing performance, we provide results obtained in different network scenarios. We consider $k = 2$ LSPs per each pair of source-destination nodes in the OR algorithm, where as $k = 2$, $k = 6$, or $k = 10$ in the case of the PER and BPR algorithms.

Our first observation is that in most of the cases with the same number of paths k available, the OR performs better than the corresponding alternative routing strategies. The fact can be explained by better global knowledge of the network congestion state in our multi-path routing than in the isolated alternative routing. This knowledge allows to distribute the traffic over the paths that traverse underutilised network links and, thus, it preserves the network from the use of overloaded links.

In a small network of relatively high connectivity (Fig. 7*a*), we can see that both alternative routing algorithms take advantage of their reactive contention resolution feature if the number of LSPs they can access is high ($k = 6$). This gain is particularly high – of a few orders of magnitude – when compared with SPR, under low and moderate traffic load conditions. The OR algorithm competes with alternative routing algorithms under either high traffic loads or the same number of LSPs (as already discussed above).

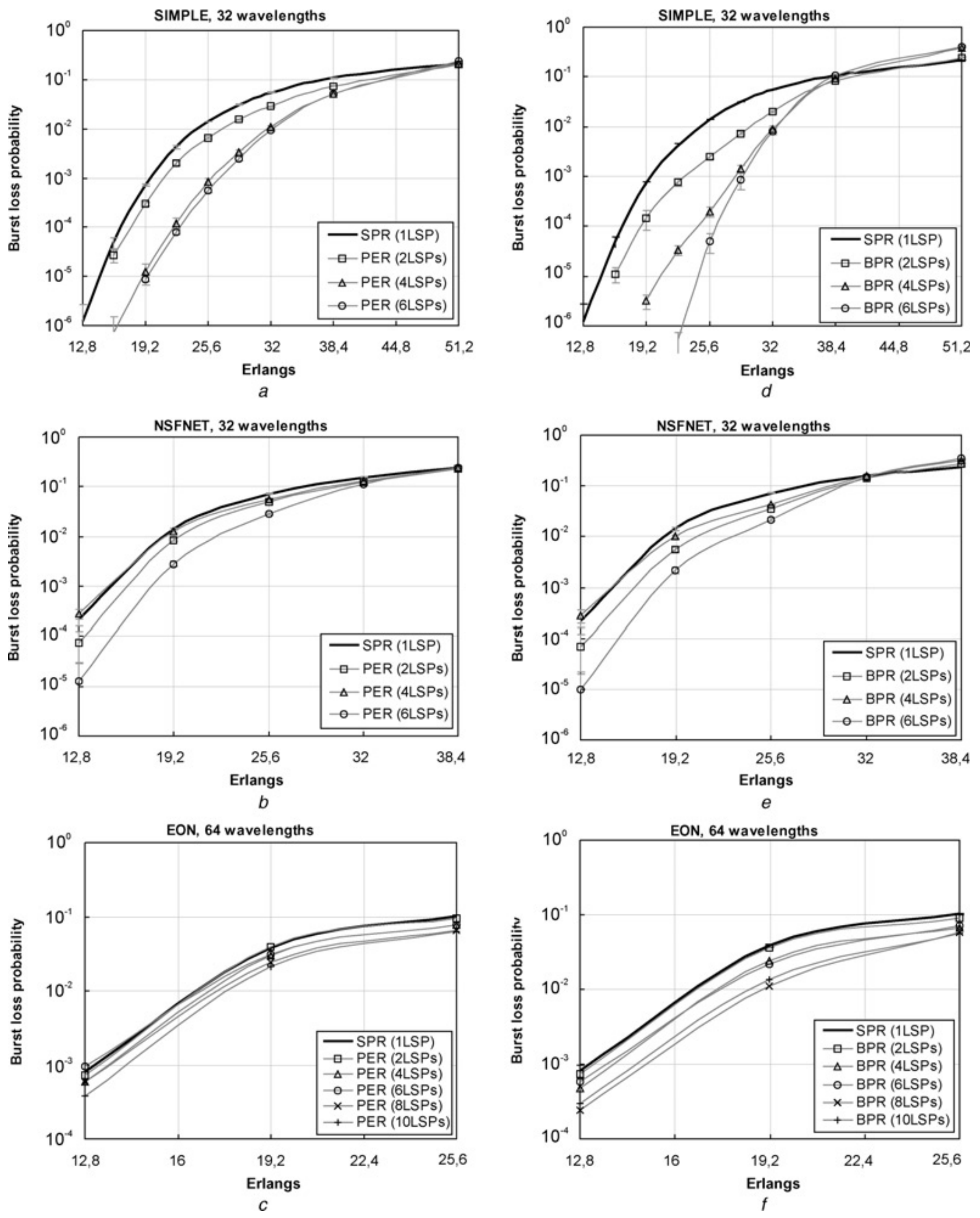

Figure 5 *Burst loss probability of PER and BPR in SIMPLE (32λ), NSFNET (32λ), and EON (64λ) networks*

In a medium-size network (Fig. 7*b*), the performance gain of reactive routing is no longer as considerable as in the small network case, even under low traffic load conditions. The performance gain of OR is kept almost unchanged with respect to the previous case.

Finally, in a large network (Fig. 7*c*), isolated alternative routing has some difficulty with the reduction of the burst blocking and it needs a high number of LSPs ($k = 10$) in order to improve the performance. On the contrary, the optimised multi-path routing can cope with the network congestion even if the number of available paths is small ($k = 2$).

Taking into account these observations, we attempt to suggest some criteria that make the deployment of the proposed algorithms viable. In particular, reactive isolated alternative routing algorithms might be appropriate for small and medium networks as long as the maintenance of higher number of LSPs does not significantly increase the network complexity. On the other hand, larger networks may require some proactive routing function that collects the information about the network state and accordingly distributes the traffic over the network.

In the next section, we extend the discussion to some implementation issues of the analysed routing algorithms.

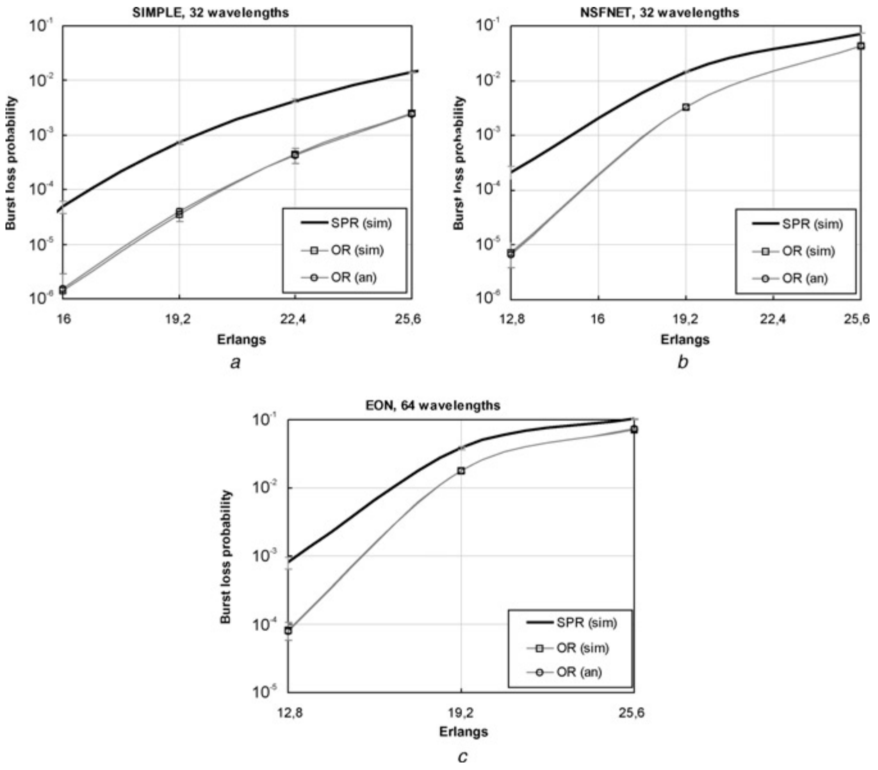

Figure 6 *Burst loss probability OR-NR*

a SIMPLE (32λ)
b NSFNET (32λ)
c EON (64λ)

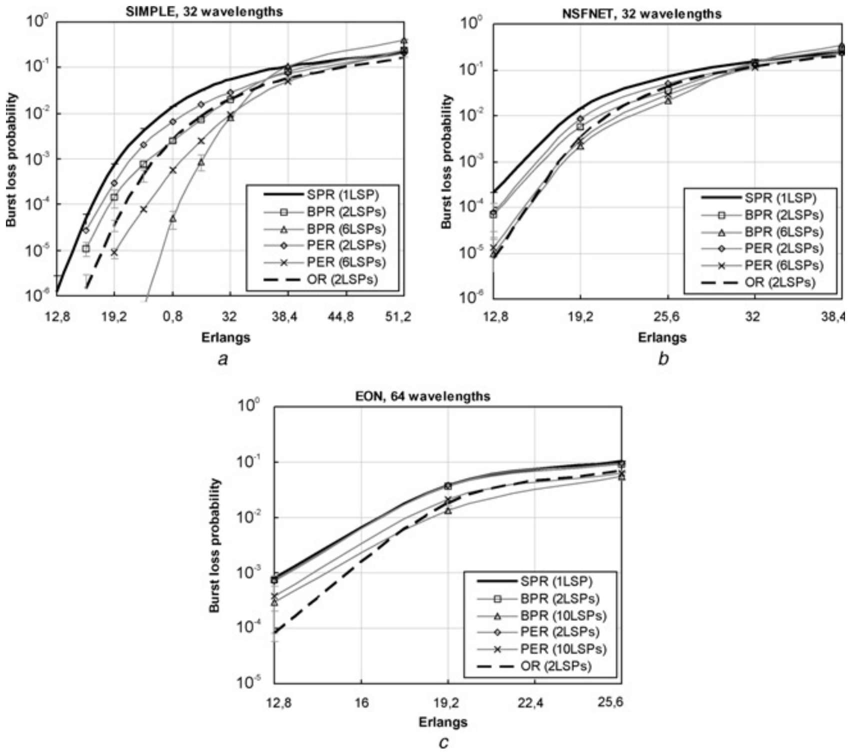

Figure 7 *Comparison of optimised multi-path source routing with isolated alternative routing strategies*

a SIMPLE (32λ)
b NSFNET (32λ)
c EON (64λ)

5 Implementation issues

The advantage of isolated alternative routing is its relatively easy implementation. Indeed, the route selection is performed based on local node state information only and, thus, no additional signalling is required. Nevertheless, in an OBS network, there is the issue of offset time management. Particularly, in a conventional OBS, the setup of offset times in the edge node should take into account the number of hops the burst is going to proceed with in order to preserve the burst from an insufficient offset effect [41]. The problem concerns any deflection routing algorithm, which does not have a constraint on the number of permitted deflections, like for instance the BPR algorithm. Application of an offset time-emulated OBS [41] may facilitate alternative routing as long as the offsets are introduced in core switching nodes. Notice that the mentioned problem does not concern the PER algorithm, in which the maximum burst routing path is limited by the length of the longest LSP (it results from the routing algorithm).

Another problem of alternative routing is the out-of-order burst arrival. The bursts, which are deflected over the paths of different lengths, may arrive at the destination in an unsettled sequence. The BPR algorithm with its unlimited deflection is particularly sensitive to this problem. Another important issue is the increase of burst delay because of additional propagation delay on alternative paths. Thus, BPR might require some constraints on the maximum number of deflections allowed. Also, the application of BPR might be reasonable only in the networks with low loads, where the percentage of deflected bursts is small. To support the PER algorithm at the out-of-order burst arrival problem, one could try to establish the LSPs of similar lengths. In this way, the deflected bursts would experience comparative propagation delays as on the primary paths.

Our nonlinear optimisation method of multi-path routing can be used, in particular, for static (pre-planned) routing, where the traffic distribution is calculated based on a given (long term) traffic demand matrix. Then, either a periodic or a threshold-triggered update of the splitting vector can be performed if the traffic demand matrix is subject to a change. The optimisation framework can be possibly extended to a distributed routing scenario; nevertheless, such an approach is left for future study.

The problem of burst reordering is also common for multi-path routing. To cope with it, some dedicated mechanisms should be used [17, 21, 23].

6 Conclusions

In this article, we addressed the problem of adaptive routing in connection-oriented LOBS networks. Our objective was to reduce an overall BLP. To achieve this goal, we proposed two distinct solutions; one of them is based on isolated alternative routing with reactive path selection, whereas the other applies multi-path source routing with proactive traffic splitting.

We studied two alternative routing algorithms: the PER and the BPR. We showed that BPR significantly improves the performance of a small- or medium-size network under low and moderate traffic loads. Although the performance of PER is slightly worse in such scenarios (compared with BPR), it behaves better under high loads as well as it brings some operational advantages.

The multi-path source routing takes advantage of nonlinear optimisation theory. In our method, we calculate a traffic splitting vector that determines a near-optimal distribution of traffic over routing paths. The presented formulae for partial derivatives are straightforward and very fast to compute; it makes the proposed nonlinear optimisation method a viable alternative for linear programming formulations based on piecewise linear approximations.

The simulation results demonstrate that our routing methods effectively distribute the traffic over the network. As a result, the network-wide BLP is reduced compared with the shortest path routing. When comparing proactive with reactive routing techniques, we can see that multi-path source routing outperforms alternative routing as long as the number of available paths is the same or it is done in larger networks. On the other hand, reactive techniques even if suboptimal, as they are based only on local node state information, can be characterised by lower complexity (no need for signalling) and inherent adaptability to traffic changes. Therefore a preferred dynamic routing strategy for OBS networks will probably need to involve both proactive and reactive techniques. Such a solution is left for future study.

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