Network Performance of Optical Burst/Packet Switching: The Impact of Dimensioning, Routing and Contention Resolution*

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Abstract

Optical burst switching (OBS) and Optical packet switching (OPS) are highly dynamic transport network architectures for a future optical Internet. As they both rely on statistical multiplexing network dimensioning, routing, and efficient contention resolution are key issues in order to achieve a low burst loss probability.

This paper first compares principal network dimensioning and fixed routing strategies in a US reference core network for the failure-free case and for selected single link failure cases. We show that dimensioning approaches, which take knowledge of traffic demands as well as of routing into account, combined with shortest path routing can achieve a better performance than uniform dimensioning with either shortest path or optimized explicit routing. However, for critical single link failure cases, the higher flexibility of explicit routing yields more homogeneous results. Then, we extend this comparison to alternative/deflection routing in the failure-free case. Finally, we present results for the impact of dimensioning in OBS/OPS networks which employ simple fiber-delay line buffers for contention resolution.

1 Introduction

Optical Burst Switching (OBS) and Optical Packet Switching (OPS) have been proposed as efficient and flexible switching paradigms for highly dynamic future optical data planes [1, 2, 3, 4]. So far, OBS/OPS research mostly concentrated on isolated nodes or on regular or simple network topologies. Only few work is available considering the interplay of dimensioning, routing and contention resolution for OBS/OPS in network scenarios [5, 6, 7, 8, 9].

In the network design phase, network resources are dimensioned to satisfy customer and application needs, e.g., traffic demands, QoS, or resilience requirements, as well as to comply with operational constraints, e.g., protocols and algorithms of the data and control plane. Then, in the network operations phase, traffic management, e.g., routing or bandwidth reservation, guarantees that service requirements are met.

Dimensioning and routing are closely related tasks as dimensioning determines resources based on traffic while routing allocates traffic to resources. Figure 1 illustrates both tasks and their input as well as output data. A close integration of dimensioning and routing is beneficial if data and algorithms applied in both tasks match or are at least similar. Still, dimensioning and routing for dynamic networks are often treated as separate sequential tasks although a single bottleneck link due to misdimensioning can dominate the performance of an entire network.

Even if the assumptions for dimensioning and routing match well during the regular operations phase, network failures may lead to a large and diverse set of network configurations for which these assumptions do not apply anymore. For instance, after a link failure traffic may be rerouted and then may use resources originally allocated to other traffic streams.

In this paper, we show the interdependence of dimensioning and routing algorithms in OBS/OPS networks for the first time. In OBS/OPS, the availability of proper resources is essential for effective contention resolution and acceptable burst loss probabilities. In a representative US core network topology, we compare bufferless OBS/OPS for two dimensioning schemes, which exploit knowledge of routing, and one isolated, uniform dimensioning approach. While the former approaches are first looked at for fixed shortest path routing only, the latter network dimensioning is also evaluated for an optimized explicit routing scheme [7]. In order to provide a balanced view, we consider the failure-free case as well as selected critical single link failure cases which are the dominant failure scenarios in telecommunication networks.

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Then, we extend our studies to deflection routing, a shortest path routing scheme with alternative paths, in the failure-free case. Finally, we include fiber delay line (FDL) buffers for contention resolution to reduce burst loss in case of fixed shortest path routing.

The remainder of this paper is structured as follows. In Section 2, we shortly introduce the OBS/OPS architectures and discuss contention resolution strategies. Section 3 then classifies and describes the dimensioning and routing approaches. The evaluation model and results are presented in Section 4. Finally, Section 5 summarizes this paper and provides an outlook to further work.

2 Optical Burst/Packet Switching

2.1 OBS/OPS Architectures

In OBS/OPS networks, the dynamics of traffic can be supported by edge nodes which aggregate traffic and assemble IP packets into variable length optical containers as well as by core nodes which switch these bursts. Originally, the definition of OBS was much more general and embraced a much wider set of architectures [1, 2]. However, technological and operational constraints helped to refine the applicable scenarios in the meantime [10].

A key characteristic of OBS is the hybrid approach in which burst control packets are signaled out of band and processed electronically while data bursts stay in the optical domain until they reach their destination node. According to one-pass reservation in OBS, burst transmission is not delayed until an acknowledgment of successful end-to-end path setup is received but is initiated shortly after the burst was assembled and the control packet was sent out (this time difference is called offset).

In OPS, packets also stay in the optical domain on their way through the network but it is assumed that control information travels with the packet, e.g., in an inband or sub-band header. Usually, no offset schemes are assumed for OPS.

Due to the lack of end-to-end reservation and due to statistical multiplexing burst/packet loss can occur in case of contention and effective resolution strategies in core nodes are essential in order to achieve a low burst loss probability in the core network as required in transport networks.

OBS and OPS are both architectures in which data containers are switched in the optical domain. For the scenarios and topics studied in this paper, we modelled them and used an abstraction which allows to treat both in a unified way. For simplicity, we only use the term *OBS* in the following.

2.2 Contention Resolution

In principle, contention resolution in OBS networks can be performed in one of the three physical domains wavelength, space and time (c. f. [11, 12] for more detailed discussions). In this paper, following basic strategies and our further assumptions are considered (acronyms in parentheses):

- wavelength conversion can be performed without limitations regarding number of converters or tuning range (*Conv*)
- deflection routing selects an alternative, available output interface in each node in the order of shortest path length (*Defl*)
- buffering can be done in a shared FDL buffer with a single FDL in which several bursts can be buffered in parallel using wavelength division multiplexing WDM (*FDL*).

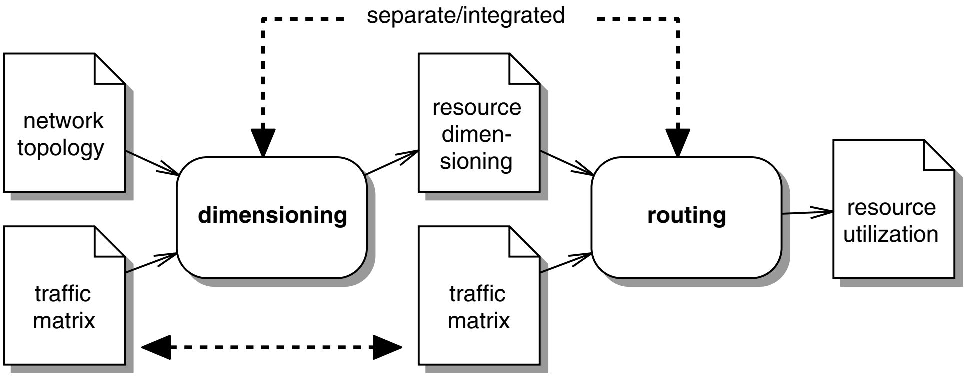


Figure 1: Dimensioning and routing: input and output data as well as interrelation of tasks

Apart from these basic strategies, also combinations of them can be applied. As the order in which these schemes are used is essential, they are named by a concatenation of their acronyms. E. g., *ConvFDL* refers to a scheme which tries conversion first, only if this fails it tries to buffer in an FDL. In case contention resolution for a burst finally fails, it is dropped.

Previous work showed that when combining full wavelength conversion with either FDL buffers or deflection routing conversion should always be used first [11, 12]. Consequently, we only consider such combinations.

Following the overall objectives of this paper, we will discuss the combination of conversion and deflection routing (ConvDefl) with a focus on routing, c.f. Section 3.3.

3 Dimensioning and Routing

3.1 Dimensioning Algorithms

Network resource dimensioning can be classified based on the kind of information used as input: While one class takes no knowledge of traffic demand distribution as well as of the routing strategy into account the other does.

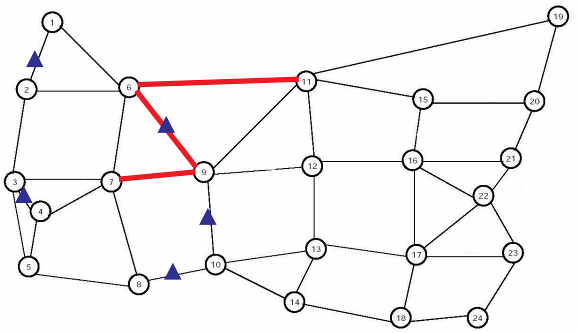
For the latter class, we describe two specific approaches, namely *linear* and *Erlang* dimensioning [13, 14], while for the former we only consider the uniform dimensioning case, i.e., all links have the same number of wavelengths. In literature, uniform dimensioning is often used [7, 9], e.g., as reference case.

For the approaches *linear* and *Erlang*, end-to-end traffic demands are routed through the network according to the specified routing scheme and thus translated into offered load on network links. For all links, we calculate the sum $A_{i,j}$ of traffic routed over them and neglect path blocking for dimensioning. Based on these values, the number of wavelengths on a link is dimensioned applying one of the following two algorithms:

- **linear dimensioning**: For offered link traffic $A_{i,j}$ on network link (i, j), $n_{i,j} = \lceil A_{i,j} \rceil$ describes the number of wavelengths on this link.
- **Erlang dimensioning**: Here, each link is modeled as a loss system with $n_{i,j}$ servers and general service time distribution to which the traffic $A_{i,j}$ arrives according to a Poisson process. The same target loss probability B is specified for all links and the number of wavelength channels $n_{i,j}$ is calculated by numerically solving the Erlang-B formula

  $$B(A, n) = \frac{A^n/n!}{\sum_{i=0}^{n} A^i/i!}.$$

  We choose the loss probability B for all node pairs such that the total number of wavelength hops in the network is equal to a predefined number W.



(a)

```
{ 0, 4, 0, 0, 0,19, 0, 0, 0, 0, …
{ 4, 0,18, 0, 0,27, 0, 0, 0, 0, …
{ 0,18, 0, 3,22, 0,12, 0, 0, 0, …
{ 0, 0, 3, 0, 9, 0,11, 0, 0, 0, …
{ 0, 0,22, 9, 0, 0, 0,26, 0, 0, …
{19,27, 0, 0, 0, 0,17, 0,36, 0, …
{ 0, 0,12,11, 0,17, 0,18,23, 0, …
{ 0, 0, 0, 0,26, 0,18, 0, 0,37, …
{ 0, 0, 0, 0, 0,36,23, 0, 0,42, …
{ 0, 0, 0, 0, 0, 0, 0,37,42, 0, …
…
```

(b) linear

```
{ 0, 6, 0, 0, 0,19, 0, 0, 0, 0, …
{ 6, 0,18, 0, 0,26, 0, 0, 0, 0, …
{ 0,18, 0, 5,22, 0,13, 0, 0, 0, …
{ 0, 0, 5, 0,10, 0,12, 0, 0, 0, …
{ 0, 0,22,10, 0, 0, 0,25, 0, 0, …
{19,26, 0, 0, 0, 0,17, 0,34, 0, …
{ 0, 0,13,12, 0,17, 0,18,23, 0, …
{ 0, 0, 0, 0,25, 0,18, 0, 0,35, …
{ 0, 0, 0, 0, 0,34,23, 0, 0,39, …
{ 0, 0, 0, 0, 0, 0, 0,35,39, 0, …
…
```

(c) Erlang

Figure 2: (a) Network topology graph with 24 nodes, 43 bidirectional links and parts of the link dimensioning matrices for links (i,j), i,j = 1…10, with linear (b) and Erlang (c) dimensioning

While the linear approach does not consider traffic dynamics, the Erlang approach also comprises this factor and models the performance of OBS/OPS quite well for several scenarios [2].

In this paper, we only consider link dimensioning and assume node dimensioning, e.g. the number of add/drop ports, to be no limiting factor. In [13], results are reported applying these dimensioning techniques also to node resources in SDH/WDM multilayer networks.

3.2 Dimensioning of the Studied Network

For all studies in this paper, we used a representative US core network with 24 nodes and 43 bidirectional links which is illustrated in Figure 2a.

In order to fairly compare the different dimensioning approaches, the total number of wavelength hops W is (practically) kept constant in all cases. For a uniform traffic demand equivalent to 1 lightpath per node pair and using the mean hop distance of 3.0, a total of $24 \cdot (24 - 1) \cdot 3.0 = 1656.0$ wavelengths hops would be required (on shortest paths for the topology in Figure 2a). In average, this amounts for 19.25 wavelengths per link.

For the linear approach, a dimensioning solution can be found for a total of 1652 wavelength hops (avg. 19.20 wavelengths per link), for the Erlang approach for a total of 1654 (avg. 19.23 wavelengths per link). The uniform dimensioning could be either chosen to have19 or 20 wavelengths per link. In order to be conservative regarding the benefit of including routing information already in the dimensioning step we use 20, i.e., a total of 1720 wavelength hops (3.9% more).

For the linear and Erlang dimensioning, respectively, Figure 2b and Figure 2c list illustrative sections of the link dimensioning matrices of links (i, j), $i, j = 1 \ldots 10$, i.e., only the Western part of the network. Comparing the two matrices, the benefit of Erlang dimensioning for dynamic traffic can be seen. The underlined elements, to which the links marked with the triangles in Figure 2a belong, show that the Erlang approach assigns more bandwidth to smaller links and less bandwidth to larger links. While the absolute differences look rather insignificant (1–3), the relative numbers of up to 50% more wavelengths on small links but only up to 7% less wavelengths on large links are far more important. The relative values indicate that statistical multiplexing is greatly improved for small links but only marginally reduced for large links.

3.3 Routing Strategies

Routing strategies can be classified based on the flexibility of routes into static (fixed and alternative) and dynamic (adaptive and non-adaptive). An additional dimension is given by explicit source-to-destination (e.g. applied in connection-oriented networks like MPLS) vs. hop-by-hop routing (e.g. applied in connectionless networks like IP). Finally, criteria for identifying suitable paths, e.g., shortest or widest path, or minimized link utilization, are often used for classification.

In this paper, we first consider fixed hop-by-hop routing on shortest paths as well as fixed explicit routing resulting from a minimization of link utilizations [7]. The latter approach minimizes the sum of consumed bandwidth on all links for which the utilization is larger than a certain critical utilization watermark level. The paths are obtained using the ILP formulation published in [7].

We study both the failure-free case as well as single link failure cases separately in stationary models. It is assumed that the network reacted on the single link failure by triggering a rerouting. In the case of fixed hop-by-hop routing, new shortest path routing tables are used. In the case of fixed explicit routing, optimized paths are pre-planned (offline) for each single link failure scenario [8].

Secondly, we compare fixed hop-by-hop routing with alternative hop-by-hop routing. A representative of this scheme is our realization of deflection routing as outlined in Section 2. Our previous evaluations showed that for deflection routing improvements and penalties due to limitations regarding the number of deflections, the number of paths, and even loops were marginal as long as a reasonable amount of flexibility is allowed. Thus, we do not apply any of these extended strategies in this paper.

For the following performance studies, we will abbreviate fixed hop-by-hop shortest-path routing by *SP* and the fixed explicit optimized routing by *ER*. As deflection routing is most often referred to as a contention resolution scheme we use the abbreviation *ConvDefl.*

In [9], optimized non-shortest path routing in OBS is discussed for a uniform network dimensioning under uniform as well as distance-dependent traffic demands. In contrast to [7], the routing algorithm formulated there considers link congestion based on an Erlang loss model. Evaluations are for Poisson and non-Poisson traffic but only look at the failure-free case.

4 Performance Studies

4.1 Evaluation Model

Performance of the different dimensioning, routing and contention resolution strategies is evaluated by event-driven simulation. Both for the dimensioning and operation phase, a uniform demand matrix is assumed. Bursts are generated based on a Poisson process and burst length is exponentially distributed with mean 100 kbit, i. e., a mean burst duration of $h = 10$ µs for 10 Gbps line-rate.

The number of add/drop ports in OBS nodes is not limited. The delay for burst control packet processing is compensated by a short extra FDL of appropriate length at the input of the node. Thus, neither effects of offset reduction

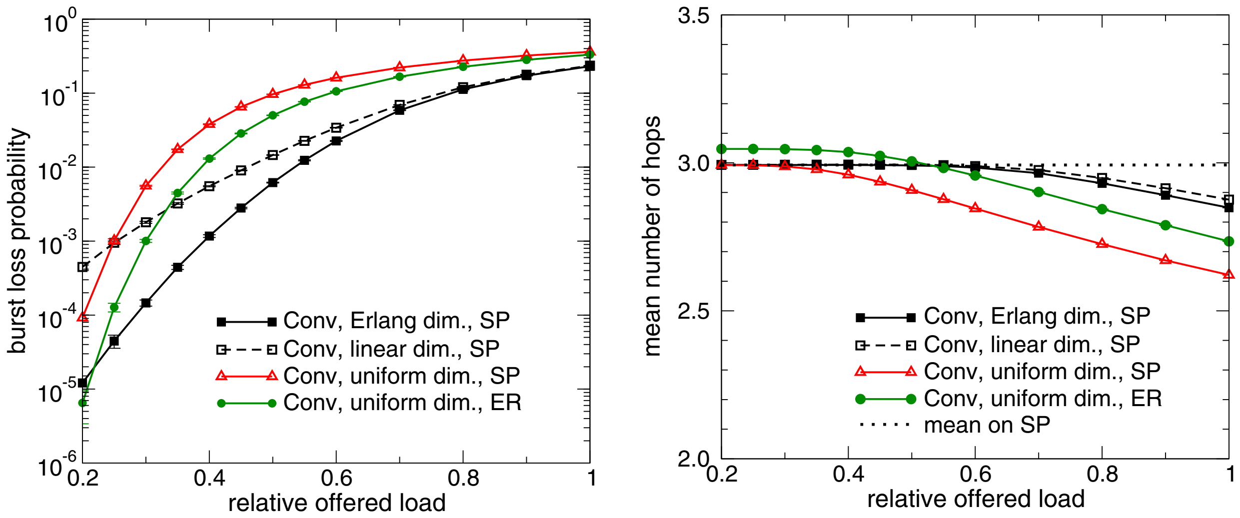


Figure 3: Burst loss probability (left) and mean number of hops (right) vs. offered load for different combinations of dimensioning and routing strategies in the failure-free case

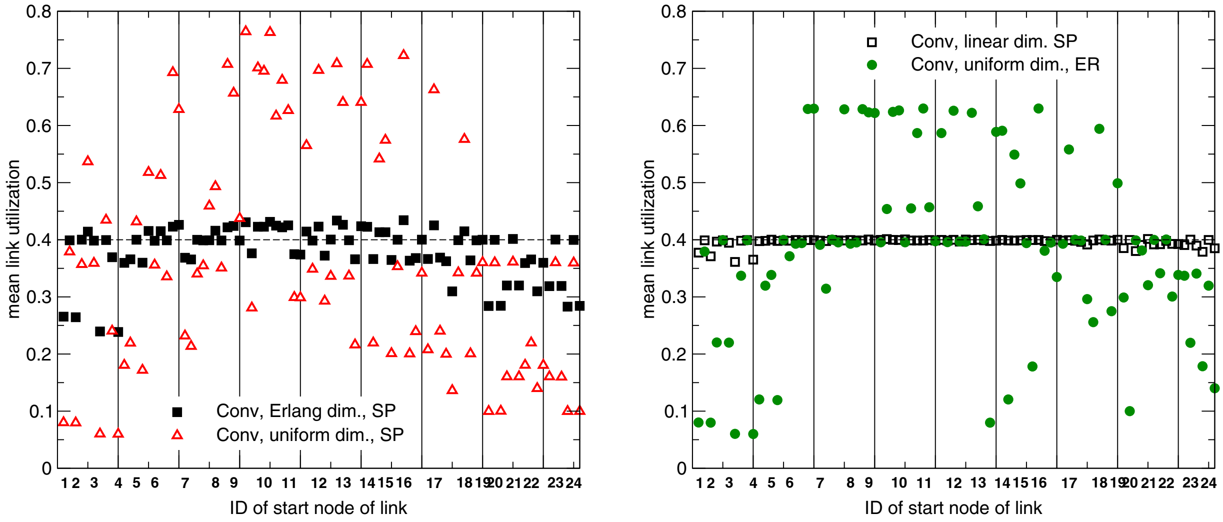


Figure 4: Comparison of mean link utilization of all links for different dimensioning (all unidirectional links (i,j) starting from a node i are listed on the horizontal axis following i in the order of increasing end node ID j)

along the path nor offset violation due to excessive deflections are considered.

If an FDL buffer is used, there is a single shared FDL with a delay of $2h = 20$ µs and there are 20 wavelengths in the FDL. Thus, as in realistic WAN scenarios, FDL delay is small compared to link delay [10].

In all figures, a relative offered load of 1.0 represents the situation, in which the traffic demand between any node pair is equivalent to the capacity of one wavelength channel. Graphs contain 95%-confidence intervals based on the batch-means simulation method.

4.2 Dimensioning and Fixed Routing in Failure-Free Cases

In this section, we first compare the performance of shortest path routing with uniform, linear, and Erlang link dimensioning as well as explicit routing with uniform dimensioning. Here, we only consider wavelength conversion for contention resolution, i.e., no FDL buffers.

Figure 3 (left) depicts the burst loss probability in the network vs. the relative offered load for the four combinations. For high and medium values of load, the curves are grouped according to dimensioning with routing knowledge (linear and Erlang) and without (uniform). There is

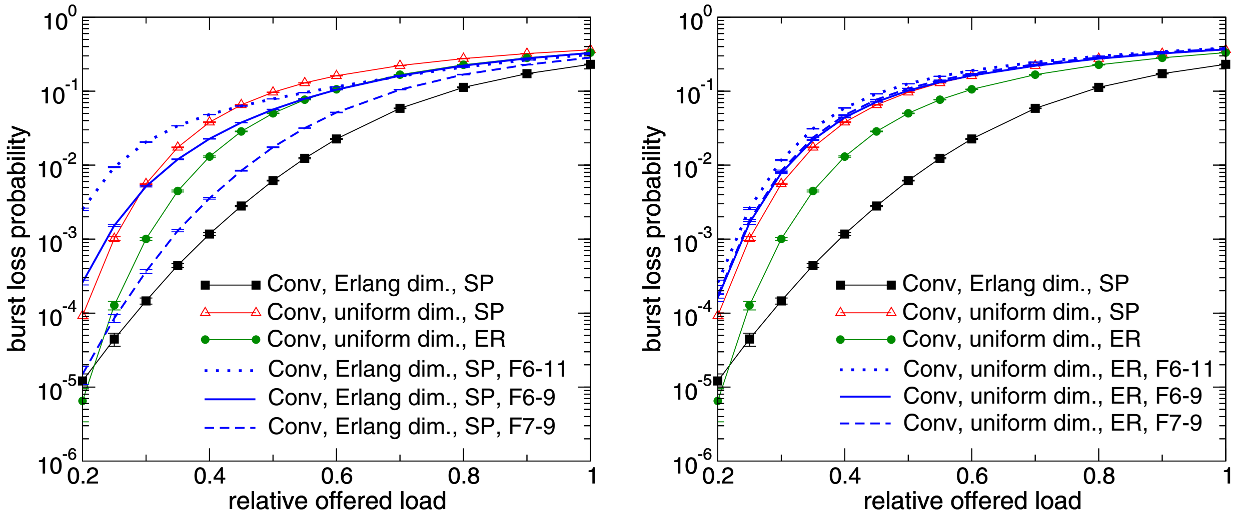


Figure 5: Burst loss probability vs. offered load for Erlang dimensioning and shortest path routing (left) and uniform dimensioning and explicit routing (right) for the failure-free and selected single link failure cases

up to an order of magnitude between the uniform and the Erlang curves. Only for low loads, the linear approach performs worse than the uniform.

For the uniform dimensioning, explicit routing is clearly advantageous. For shortest path routing, the smarter Erlang resource distribution clearly pays off for low and medium values of load.

Figure 3 (right) shows that the smaller loss probability of explicit routing compared to shortest path routing in the uniform dimensioning does not come at the cost of a severely increased mean hop distance. The decreasing mean hop distance for high loads is due to the well-known effect that bursts travelling over more hops experience a higher loss probability.

The impact of the different dimensioning approaches on network utilization can be seen in Figure 4 for a relative offered load of 40%. The figures show the mean link utilization of all 86 unidirectional links. While the almost homogenous link utilizations for linear and Erlang dimensioning reveal the routing knowledge in the dimensioning step, the very heterogeneous values for the uniform dimensioning have the opposite reason.

The lower utilization values for Erlang dimensioning on some links for small and high node IDs is due to the overprovisioning on small links as discussed in detail in Section 3.2. The lower utilization on a link with low statistical multiplexing gain allows to reduce loss significantly. This yields the overall better performance of Erlang compared to linear in the previous figures.

Also, minimizing link utilization in explicit routing yields more homogenous values than shortest path routing for uniform dimensioning. Also the impact of the utilization watermark around 0.63 can be seen.

4.3 Dimensioning and Fixed Routing in Failure Cases

The previous studies considered the failure-free case only. Regarding the integration of routing knowledge into dimensioning, this can be considered an optimal case as the information for the planning and the operation phase match. However, in the case of failures, this no longer holds and the detailed assumptions made in the dimensioning process or the restrictions of shortest path routing may turn out to be problematic.

Figure 5 depicts the performance degradation for 3 selected critical single link failures. The selected single link failures affect the bidirectional links 6-9, 6-11, and 7-9 which are marked by thick lines in Figure 2. These links were also identified to be critical in [7] as they belong to a cut of the topology graph over which a lot of traffic flows (namely all the coast-to-coast traffic).

For Erlang dimensioning with SP, which performed best so far, it can be seen that, the impact of failures is very heterogeneous, e.g., the failure of link 6-11 (30 wavelengths) has detrimental consequences while failure of link 7-9 (23 wavelengths) only yields minor performance degradation.

In contrast, for uniform dimensioning with ER, the performance after a link failure is very homogenous and approximately in the vicinity of the failure-free case with SP.

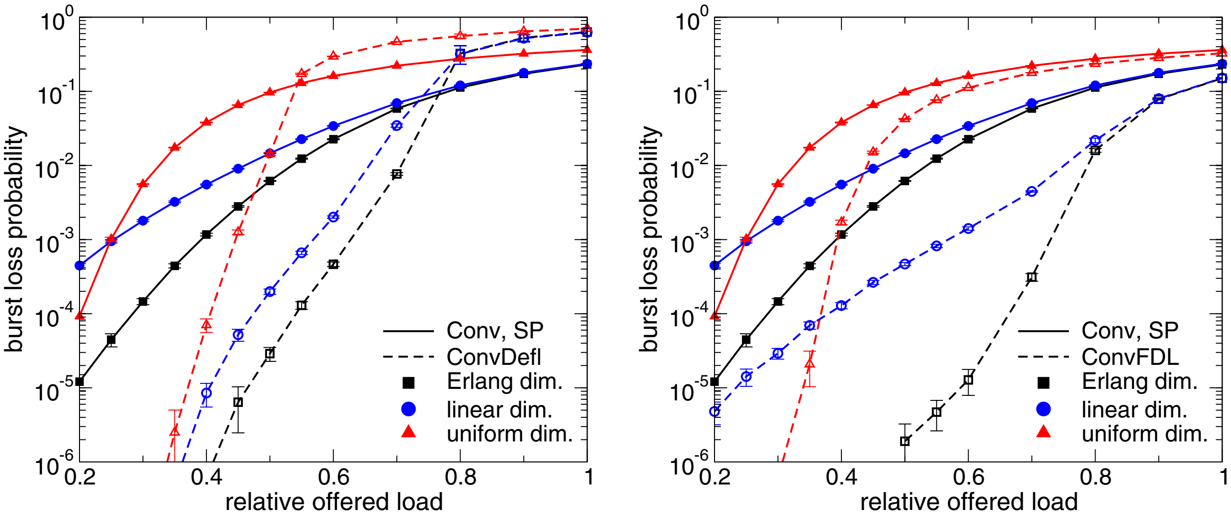


Figure 6: Comparison of fixed and alternative routing (left) and contention resolution with and without FDL buffer (right) for Erlang, linear, and uniform dimensioning

This difference is not only due to the potential failure of larger links in the Erlang case. It is also due to the more flexible and fine-grain ER which can better bypass failures. An indication for this ability and a very minor performance penalty of ER is an increase in mean hop distance by approx. 0.2 hops (15%) after failures not shown here.

Based on the results of this section, an interesting extension for future work will be the combination of Erlang dimensioning and ER for failure-free and especially link failure cases.

4.4 Dimensioning and Alternative Routing in Failure-Free Cases

In Figure 6 (left), we now compare fixed and alternative (deflection) hop-by-hop shortest path routing for Erlang, linear and uniform dimensioning. In contrast to fixed routing (Conv, SP), deflection routing (ConvDefl) can bypass overloaded links using alternative routes.

Although ConvDefl yields increased burst losses for high values of load, it also significantly improves performance for low and medium values of load. From the fact that linear and Erlang dimensioning yield very similar results, it can be seen that the flexibility in routing can be effectively used to bypass bottleneck links. Thus, the penalty due to the less suitable dimensioning can be almost entirely compensated here.

In contrast, uniform dimensioning does not benefit as much from deflection routing as linear dimensioning. Here, some links remain overloaded up to low values of load as deflections (on in average longer paths) occur frequently.

The overall steep decrease in loss towards low load values is a well-known phenomena [15]: ConvDefl has a large number of possibilities for deflecting a burst in case of contention. Below a certain threshold, the probability of contention is very low and almost all bursts traverse the network on a shortest path. Above the threshold, the probability for contention raises very fast due to positive feedback. Then, many bursts are deflected.

4.5 Dimensioning and FDL buffers

While we have concentrated on the interplay of dimensioning and routing in the previous studies and only looked at the case without buffering, we will now focus on the impact of dimensioning on combined contention resolution by conversion and buffering. Not only can buffering with fixed routing achieve low burst loss probabilities, also it can be an attractive solution if alternative routing has to be avoided due to network control policies.

Figure 6 (right) depicts the burst loss probabilities with Erlang, linear and uniform dimensioning for the case with and without FDL buffer, (ConvFDL) and (Conv, SP).

Both for Erlang and linear dimensioning, the additional FDL in ConvFDL significantly reduces burst loss probability up to load values of approx. 0.8. However, the improvement for Erlang is much greater than for linear.

As we explained in Section 3.2, linear dimensioning can lead to bottlenecks on small links which can be avoided by Erlang dimensioning (also c.f. performance comparison of specific nodes in a network in [6]).

For uniform dimensioning, ConvFDL only yields improvements for values of load less than approx. 0.5 with very large reductions for low loads. Only then, there are no overloaded links left and buffering can become effective.

Results for a combination of conversion, deflection routing, and buffering in two reference network scenarios of Germany [16] and Europe [17] with Erlang dimensioning can be found in [5, 6].

5 Conclusions and Outlook

In this paper, we first compare principal network dimensioning and fixed routing strategies in a US reference core network for the failure-free case and for selected single link failure cases. We show that dimensioning approaches, which take knowledge of traffic demand distribution as well as of routing into account, combined with shortest path routing can achieve a better performance than uniform dimensioning with either shortest path or optimized explicit routing. However, for critical single link failure cases, the higher flexibility of explicit routing yields more homogeneous results.

Then, we extend this comparison to alternative/deflection routing in the failure-free case. Here, different dimensioning approaches yield rather similar results as the increased routing flexibility can effectively bypass bottleneck links, i.e., the penalty due to a less suitable dimensioning can be almost entirely compensated. Finally, we present results for the impact of dimensioning in OBS/OPS networks which employ simple fiber-delay line buffers for contention resolution. Here, improved dimensioning approaches can help to avoid bottleneck links and make buffering even more effective.

Future work should consider the combination of Erlang dimensioning and explicit routing. Also, studies should be extended to other network scenarios and traffic models to cover a wider set of application scenarios.

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